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Economic development, social consequences, and technological innovation under climate change COVID-19 pandemic conditions

Edited by
Cem Işık, Asif Razzaq and Vishal Dagar

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Economic development, social consequences, and technological innovation under climate change COVID-19 pandemic conditions

Topic editors
Cem Işık — Anadolu University, Türkiye
Asif Razzaq — Dalian University of Technology, China
Vishal Dagar — Great Lakes Institute of Management, India

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BRIEF RESEARCH REPORT
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Research on the Impact of COVID-19 on Import and Export Strategies

Wenguang Tang[1], Jian Hu[1], Geovanny Genaro Reivan Ortiz[2], Fatma Mabrouk[3] and Jinghuan Li[1]*

[1]College of Science, Tianjin University of Commerce, Tianjin, China, [2]Laboratory of Basic Psychology, Behavioral Analysis and Programmatic Development PAD-LAB, Catholic University of Cuenca, Cuenca, Ecuador, [3]Department of Economics, College of Business Administration, Princess Nourah Bint Abdulrahman University, Riyadh, Saudi Arabia

Due to the spread of COVID-19, the public health crisis is bound to have a huge impact on the world economy and international trade. How to study the import and export strategies under the coronavirus pandemic has become a major issue that many scholars need to solve urgently. Therefore, a two-stage game model is constructed, and the reverse solution method is used to obtain the optimal output of enterprises in importing countries and exporting countries before and after the outbreak of pandemic, as well as the optimal subsidies for enterprises from exporting countries and the optimal import quarantine rate for importing countries. Based on the game between the two countries without the pandemic outbreak, the impact of the pandemic on the output, profits, and social welfare of enterprises in the two countries was compared. Enterprises in exporting countries face double threats from the pandemic and import quarantine fees. The increase in import quarantine fees reduces the social welfare of exporting countries. In order to effectively control the spread of the pandemic, subsidies are an effective means to restore exports to normal. Reasonable collection of import quarantine fees by importing countries can promote bilateral trade, but an excessive collection will be counterproductive. The governments of exporting countries should establish emergency mechanisms and relevant subsidy policies, and enterprises should continuously improve their competitiveness. At the same time, countries should abandon the concept of trade protection and negotiate and cooperate to jointly deal with the pandemic.

Keywords: COVID-19, stackelberg game, import and export, import quarantine fee, strategies

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Ural Federal University, Russia

Correspondence:
Wenguang Tang
lxytwg@tjcu.edu.cn

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INTRODUCTION

With the ongoing global pandemic of COVID-19, the unprecedented public health crisis is bound to have a huge negative impact on the world economy, environment and international economic and trade cooperation (Razzaq et al., 2020; Khan et al., 2021; Yu et al., 2021; Irfan et al., 2022). The forecast report released by the World Trade Organization in 2020 pointed out that the pandemic will significantly shrink global trade. After the pandemic outbreak, the scale of global import and export trade showed a sharp decline amid fluctuations. In the first half of 2020, the year-on-year decline in global import and export trade scale reached 11.98% and 13.48%, respectively. The above-mentioned restrictive measures will lead to an obvious trade-inhibitory effect, the direct consequence of which is to weaken the degree of trade liberalization between countries, leading to high market access barriers, sharp rise in trade costs, and may even induce trade protectionism (Shahzad et al., 2021). Therefore, under the impact of the Coronavirus pandemic, how to alleviate the adverse impact of the pandemic

to promote international trade to enter the fast lane of recovery has become a major issue that the international community urgently needs to deal with.

Due to the rapid spread of COVID-19 worldwide, countries worldwide have to take trade protection measures (Xuefeng et al., 2021), the international free trade system is increasingly fragile, and new trade barriers are gradually formed. Taking China as an example, in foreign trade, statistics from the General Administration of Customs show that most enterprises with actual import and export results in 2019 are private enterprises, with the number reaching 406,000. In addition, among the export-oriented enterprises in China, small, medium and micro enterprises contribute about 60% of the total national import and export (Zhang, 2020). The addition of such an entry quarantine fee by foreign governments is a severe blow to many export-oriented enterprises facing difficulties in China at the moment. Therefore, export-oriented enterprises must not expand their production blindly because of a series of favorable policies introduced by the state. Each enterprise should reasonably adjust its output and set the optimal production decision according to the international market situation.

The COVID-19 is characterized by high risk, suddenness, and rapid spread and is a typical global public health emergency. It is well known that sudden major public health events usually affect the normal operation of political, economic, and social activities, some scholars conduct research on sudden public health events in the context of social emergency management (Sun et al., 2014; Liang et al., 2019; Xi and Zang, 2020). Numerous scholars have argued that this COVID-19 has created potential trade barriers and negatively impacted exports. (Duan et al., 2020). noted that more than 18 million SMEs in China were severely affected by the pandemic, most of which have export-led businesses. (Baldwin and Di Mauro, 2020). argued that this COVID-19 pandemic will have a more severe impact on the economy and environment than any other pandemic since World War II, with border closures and factory shutdowns, which will cause a significant drop in exports of the corresponding industries in the countries where the pandemic occurred. Meanwhile, some scholars have proposed policy recommendations for the government to respond to major public health events such as the pandemic from the perspective of maintaining foreign trade. For example Wang and Zhang (2020), point out that the pandemic may cause significant losses to export country's economies and trade, and is a major test of national governance system and governance capacity. According to (Shen, 2020), countries need to "stabilize foreign trade" and support import and employment growth by stabilizing the export market, and the government should help enterprises to resume work and production in an orderly manner and introduce policies such as tax reduction and fee reduction. However, these studies usually focus on studying the situation in a single country and fail to consider the interactions between the two countries in terms of import and export.

The related research on the analysis of oligopoly competition strategy is one of the commonly used methods to construct an application scenario model based on game theory, analyze the influence of different strategic behaviors and the changing trend of important variables by means of numerical simulation. Based on the US Rice Export Program to Japan and South Korea (Lee and Kennedy, 2006), attempted to analyze both import markets incorporating econometric estimates and public choice theory in a game-theoretic framework. Du and Wang (2018) proposed a multi-level threshold public goods game model to research how income redistribution affects the evolution of global cooperation. The effect of different thresholds on the strategy was investigated by numerical simulation. Andoni et al. (2021) modeled the problem of deducing how much capacity each player should build as a non-cooperative Stackelberg-Cournot game. Using data-driven analysis to analyze investor decision-making. Based on the game theory (Yang et al., 2021), analyzed the behavior of countries when carrying out regional cooperation to govern the epidemic and put forward specific cooperative income distribution schemes according to the different attributes of the countries. Using numerical simulations, they analyze the effect of the variation of different parameters on the utility of the two countries in different cooperation situations.

Scholars have also conducted many studies on the use of game theory to study bilateral trade. Ferreira and Ferreira (2009) considered an international trade under the Bertrand model with differentiated products and unknown production costs. The impact of tariff changes on corporate profits is analyzed. Yang and Wei (2013) constructed a three-stage game model for the continuation of the United States carbon tariff policy based on a two-stage game model in which the United States implemented a carbon tax policy only on its domestic enterprises and introduced a carbon tariff on imports from China. The impact of carbon tariffs on trade between China and the United States is analyzed. Xie et al. (2016) construct a theoretical game model in which a domestic firm exports to a third country through an intermediary in the third country and competes with a firm located in another country that exports directly to the third country. It is analyzed whether the bargaining power affects the choice of a country's strategic trade policy when a country firm chooses a third-country intermediary to export its products. Xie et al. (2018) constructed a model of duopoly international market competition in which producers compete on price against the background of product quality differences and with the actual situation of Chinese exporters. And on this basis, using game theory, a country's optimal strategic trade policy is explored in terms of trade benefits and social welfare. Mizuno and Takauchi (2020) considered a third-market model with a vertical trading structure. The change in optimal export policy as product-substitutability increases is examined, along with a discussion of welfare comparisons between the downstream Gounod and Bertrand cases.

In order to study the impact of the pandemic on import and export strategies and the changes in the profits and social welfare of companies in various countries under the pandemic, we used game theory to model the import and export strategies under the impact of the pandemic. Compared with the existing literature, the contributions of this paper are mainly reflected in the following aspects: under the pandemic, we examined the impact of the collection of import quarantine fees on the

TABLE 1 | Model notations and variables.

Variables	Descriptions
Q_E	The output of enterprises in the exporting *E* country (decision variable)
Q_I	The output of enterprises in the importing *I* country (decision variable)
s	Subsidy given by exporting country per unit of product (decision variable)
a	Potential price of the product
b	The sensitivity of price to output
c_E	The marginal cost of production for the exporting country
c_I	The marginal cost of production for the importing country ($c_I > c_E > 0$)
τ	Import quarantine fee per unit of product
s	Export enterprises relevant subsidy

production strategies of importing and exporting countries; under the pandemic, we have given the optimal subsidy strategy of exporting countries based on their own social welfare; under the pandemic, we compared the changes in the enterprises' profits and social welfare of the respective governments after the game between importing and exporting countries, and analyzed the measures that importers and exporters should take to deal with the impact of the pandemic jointly.

THEORETICAL MODEL

Problem Description and Assumptions

Consider two countries: an exporter (E country) and an importer (I country). Similar to the setting in Xie et al. (2018), Tang et al. (2020), Mizuno and Takauchi (2020), Tang et al. (2020), we assume that each of them has only one enterprise (enterprise E and enterprise I, respectively) that produces a homogeneous product. The products produced by the exporting enterprise E are all exported to the importing I country, and the products of the importing enterprise I can only be sold in its own market, i.e., the importing country is the only consumer of the product. There are two sources of supply in the production market: in addition to the domestic enterprises, they can also import from the exporting E country. We further make the following assumptions. The marginal cost of production, transportation, and tariffs for the exporting country is c_E, and the marginal cost of production for the importing country is c_I. Since enterprises in the exporting country have relatively low costs, this paper assumes that $0 < c_E < c_I$. Since consumers in the importing I country consume only one homogeneous product, the demand function for the product is:

$$P = a - b(Q_E + Q_I),$$

where $a > 0$ is the potential price of the product, $b > 0$ is the sensitivity of price to output, Q_E and Q_I represent the output of enterprises in the exporting E country and importing I country, respectively.

When a pandemic occurs in the exporting country, the government of the importing country, to protect its national health and the share of its own enterprises in the market, will enhance the exporting country enterprises to impose a unit of production import quarantine fee $\tau > 0$. At this point, the government of the exporting country, in order to maintain the normal operation of export enterprises, will choose to encourage exports in the short term by giving export enterprises relevant subsidy $s > 0$. These assumptions are mostly common practices, thus can be made without the loss of generality of this study. The notations and variables used in our analysis are shown in **Table 1**.

Game Model of Two Enterprises in the Absence of a Pandemic

When there is no pandemic, the enterprises of the two countries compete in Cournot game in the consuming country I (importing country). Enterprises' profits $\pi_E(Q_E, Q_I)$ and $\pi_I(Q_E, Q_I)$ are given by (see Fernanda A.)

$$\begin{cases} \pi_E(Q_E, Q_I) = (P - c_E)Q_E \\ \pi_I(Q_E, Q_I) = (P - c_I)Q_I \end{cases}.$$

The enterprises of each country determine the optimal output by maximizing their profits, and the maximization problem can be expressed as:

$$\begin{cases} \max_{Q_E, Q_I} \pi_E(Q_E, Q_I) = (P - c_E)Q_E \\ \max_{Q_E, Q_I} \pi_I(Q_E, Q_I) = (P - c_I)Q_I \end{cases} \tag{1}$$

$$s.t. \begin{cases} Q_E \geq 0 \\ Q_I \geq 0 \end{cases}$$

From the first-order condition of the optimization problem (**Eq. 1**) equation, we know that when $a > 2c_I - c_E$, the optimal output of the enterprises in the two countries are:

$$Q_E^* = \frac{a - 2c_E + c_I}{3b}, \; Q_I^* = \frac{a + 2c_E - 2c_I}{3b},$$

This leads to the optimal price of the product and the optimal profit of the two enterprises, respectively:

$$\begin{cases} P^* = \dfrac{a + c_E + c_I}{3} \\ \pi_E^* = \dfrac{(a - 2c_E + c_I)^2}{9b} \\ \pi_I^* = \dfrac{(a + c_E - 2c_I)^2}{9b} \end{cases}$$

Property 1. In the absence of a pandemic, the enterprise's optimal output is a decreasing function of the marginal cost of products from domestic enterprise, is an increasing function of the marginal cost of products of the enterprise from other country; the product price is an increasing function of the marginal cost of the product of the enterprise from both countries.

Since $Q_E^* - Q_I^* = \frac{c_I - c_E}{b}$ and $\pi_E^* - \pi_I^* = \frac{(2a - c_E - c_I)(c_I - c_E)}{9b}$, and since $c_I > c_E$ and $a > 2c_I - c_E$, we obtain the following property.

Property 2. Enterprises in exporting country have higher output and profit than enterprises in importing countries due to their lower marginal costs, i.e.,

$$Q_E^* > Q_I^*,\ \ \pi_E^* > \pi_I^*.$$

Game Model of Two Countries When a Pandemic Occurs in the Exporting Country

When a pandemic occurs in the exporting country, on the one hand, the importing country will impose an additional import quarantine fee τ, and the exporting country will give enterprises subsidy s, the profit structure of exporting enterprises changes. On the other hand, the price of raw materials rises and additional protective equipment lead to an increase in the marginal cost of exporting enterprises, which is recorded as c_E^m, and $c_E^m > c_E$. At this point, the game process between the two governments and enterprises is divided into two stages: in the first stage, due to the pandemic in the exporting country, the exporting government determines the optimal subsidy s^* to the exporting enterprise based on maximizing its social welfare after learning that the importing country imposes import quarantine fees τ on the exporting enterprise; in the second stage, after the enterprises observe the optimal subsidies given to the enterprises of the exporting country, the enterprises of the two countries conduct the Cournot game to determine their respective optimal output. For this two-stage Stackelberg game, we use the inverse solution method to find the optimal solutions of each stage with reference to Tang et al. (2020), Tang et al. (2021), and the superscript denotes the game with pandemic.

Consider the game process of the second stage. The enterprise's profit is given by

$$\pi_E^m\left(Q_E^m, Q_I^m, \middle| s\right) = \left(P^m - c_E^m + s - \tau\right) Q_E^m,$$

at this time, the profit per unit product of the exporting country's enterprise has changed. The enterprises in both countries maximize the profits to determine their optimal output Q_E^{m*}, Q_I^{m*}, the game model is:

$$\begin{cases} \max_{Q_E, Q_I} \pi_E^m\left(Q_E^m, Q_I^m, \middle| s\right) = \left(P^m - c_E^m + s - \tau\right) Q_E^m \\ \max_{Q_E, Q_I} \pi_I^m\left(Q_E^m, Q_I^m, \middle| s\right) = \left(P^m - c_I\right) Q_I^m \end{cases} \quad (2)$$

$$s.t. \begin{cases} Q_E^m(s) \ge 0 \\ Q_I^m(s) \ge 0 \end{cases}$$

where the demand function for the product is $P^m = a - b\left(Q_E^m + Q_I^m\right)$; τ is a constant, which indicates the import quarantine fees levied by the government of the importing country for enterprises in the exporting country.

From the first-order conditions of the optimization problem (2), the optimal price of the product and the optimal output of the two enterprises are obtained as:

$$\begin{cases} P^{m*}(s) = \dfrac{a + c_E^m + c_I - s + \tau}{3} \\ Q_E^{m*}(s) = \dfrac{a - 2c_E^m + c_I + 2s - 2\tau}{3b} \\ Q_I^{m*}(s) = \dfrac{a + c_E^m - 2c_I - s + \tau}{3b} \end{cases} \quad (3)$$

Property 3. When a pandemic occurs in the exporting country, the exporting country's subsidies for its own enterprises will increase the export volume of its own enterprises, reduce the output of the importing enterprises, and lower the price of the product; the import quarantine fees imposed by the importing country on the exporting country will reduce the export of the exporting country, increase the output of its own enterprises, and increase the price of the product.

Since $Q_E^{m*}(s) - Q_E^{m*}(s) = \frac{-c_E^m + c_I + s - \tau}{b}$, the following property can be obtained.

Property 4. When a pandemic occurs in the exporting country

(1) If $s < c_E^m - c_I + \tau$, the output of enterprises in the exporting country is less than the output of enterprises in the importing country.
(2) If $s > c_E^m - c_I + \tau$, the output of the enterprises in the exporting country is greater than the output of the enterprises in the importing country.

Consider the game process of the first stage. The exporting country government maximizes its social welfare to determine the optimal subsidy to enterprises, and the social welfare function is:

$$\omega_E^m(s) = \pi_E^{m*}(s) - sQ_E^{m*}(s) \quad (4)$$

It consists of the profits of enterprises minus subsidy expenses.

Substituting the conclusion from **Eq. 3** into **Eq. 4** yields:

$$\omega_E^m(s) = \frac{-2s^2 + s\left(a - 2c_E^m + c_I - 2\tau\right) + \left(a - 2c_E^m + c_I - 2\tau\right)^2}{9b}$$

the optimal subsidy from the government of the exporting country to the enterprises should satisfy

$$\frac{\mathrm{d}\omega_E^m(s)}{ds} = 0$$

From the fact that the second order derivative is less than 0, there exists an unique optimal solution when $a > 2c_E^m - c_I + 2\tau$:

$$s^* = \frac{a - 2c_E^m + c_I - 2\tau}{4}$$

Due to the uncertainty of the pandemic, subsidy policy should be adjusted depending on the situation of the pandemic. Reasonable subsidies will also avoid trade protection by importing countries and promote healthy trade relations between the two countries. However, suppose high export subsidies are given to enterprises across the board for a long period of time. In that case, it will not only harm the interests of enterprises in the importing countries and cause unfair trade

competition, but also inhibit technological innovation and weaken the intrinsic motivation of enterprises.

Property 5. When a pandemic occurs in the exporting country, the optimal subsidy from the government of the exporting country to the enterprises is a decreasing function of the import quarantine fees in the importing country, a decreasing function of the marginal cost of the product of the enterprises in the exporting country, and an increasing function of the marginal production cost of the enterprises in the importing country.

Substituting s^* into **Eq. 3** yields the optimal output of the two enterprises in the case of a pandemic in the exporting country when $\frac{-a+3c_I}{2} - c_E^m < \tau < \frac{a+c_I}{2} - c_E^m$, respectively:

$$\begin{cases} Q_E^{m*} = \dfrac{a - 2c_E^m + c_I - 2\tau}{2b} \\ Q_I^{m*} = \dfrac{a + 2c_E^m - 3c_I + 2\tau}{4b} \end{cases}$$

Since the social welfare function of the importing country is:

$$\omega_I^m(s) = \pi_I^{m*}(s) + CS(Q^{m*}) + \tau Q_E^{m*}(s) \quad (5)$$

it consists of the profit of domestic enterprises, consumer surplus and import inspection and quarantine fee income, where $CS(Q^{m*})$ indicates consumer surplus

$$CS(Q^{m*}) = \int_0^{Q_E^{m*}+Q_I^{m*}} (P^m - P^{m*})\mathrm{d}Q = \frac{b}{2}\left(Q_E^{m*}(s) + Q_I^{m*}(s)\right)^2$$

The optimal price of the product, the profit of the two firms and the social welfare of the two countries can be obtained as:

$$\begin{cases} P^{m*} = \dfrac{a + 2c_E^m + c_I + 2\tau}{4} \\ \pi_E^{m*} = \dfrac{4\tau^2 - 4\tau\left(a - 2c_E^m + c_I\right) + \left(a - 2c_E^m + c_I\right)^2}{4b} \\ \pi_I^{m*} = \dfrac{4\tau^2 + 4\tau\left(a + 2c_E^m - 3c_I\right) + \left(a + 2c_E^m - 3c_I\right)^2}{16b} \\ \omega_E^{m*} = \dfrac{4\tau^2 - 4\tau\left(a - 2c_E^m + c_I\right) + \left(a - 2c_E^m + c_I\right)^2}{8b} \\ \omega_I^{m*} = \dfrac{-20\tau^2 + 4\tau\left(3a - 2c_E^m - c_I\right) + 2\left(a + 2c_E^m - 3c_I\right)^2 + \left(3a - 2c_E^m - c_I\right)^2}{32b} \end{cases}$$

Property 6. When a pandemic occurs in the exporting country, the optimal output of enterprises in the exporting country, the profits of enterprises and the social welfare of the exporting country are all decreasing functions of import quarantine fees; the optimal output of enterprises in the importing country, the profits of enterprises and the prices of products are all increasing functions of import quarantine fees; when $\tau < \frac{3a-2c_E^m-c_I}{10}$, the social welfare of the importing country is an increasing function of import quarantine fees, and when $\tau > \frac{3a-2c_E^m-c_I}{10}$, the social welfare of the importing country is a decreasing function of import quarantine fees.

COMPARISON OF EFFECTS IN EXPORTING COUNTRIES WITHOUT AND WITH PANDEMIC

Using the absence of a pandemic as a benchmark, we compare the impact on product prices, production and profits of enterprises in both countries, and social welfare in both countries under the scenario of a pandemic in the exporting country.

Impact on Production, Product Prices and Corporate Profits of Enterprises in Both Countries

The optimal output of enterprises in both countries, the optimal price of the product and the social welfare of the governments in both countries are compared for the two scenarios, and the results are as follows:

$$Q_E^{m*} - Q_E^* = \frac{a - 6\left(c_E^m + \tau\right) + 4c_E + c_I}{6b}$$

$$Q_I^{m*} - Q_I^* = \frac{-a + 6\left(c_E^m + \tau\right) - 4c_E - c_I}{12b}$$

$$P^{m*} - P^m = \frac{-a + 6\left(c_E^m + \tau\right) - 4c_E - c_I}{12}$$

$$\pi_E^{m*} - \pi_E^* = \frac{\left[5a - 6\left(c_E^m + \tau\right) - 4c_E^m + 5c_I\right]\left[a - 6\left(c_E^m + \tau\right) + 4c_E^m + c_I\right]}{36b}$$

$$\pi_I^{m*} - \pi_I^* = \frac{\left[7a + 6\left(c_E^m + \tau\right) + 4c_E^m - 17c_I\right]\left[-a + 6\left(c_E^m + \tau\right) - 4c_E^m - c_I\right]}{144b}$$

Property 7.

(1) If $c_E^m + \tau < \frac{a+4c_E^m+c_I}{6}$, the impact of the pandemic on exporters is small, and timely and effective subsidies from the exporting country's government lead to an increase in production and profits for the exporting country's enterprises, a decrease in optimal production and profits for the importing country's enterprises, and a decrease in product prices.

(2) If $\frac{a+c_I}{2} > c_E^m + \tau > \frac{a+4c_E^m+c_I}{6}$, the impact of the pandemic on exporters is greater at this time. The occurrence of the pandemic in the exporting country will lead to a reduction in production and profits of enterprises in the exporting country, an increase in production and profits of enterprises in the importing country, and a rise in product prices.

Impact on Social Welfare

To further analyze the impact of the COVID-19 on social welfare in both countries, numerical simulation is presented. Simulation explored the effect of import quarantine rates and the marginal cost of exporting enterprises on social welfare. For this quantitative demonstration, we assigned values to each parameter based on the assumptions described in the previous sections and the practical implications. The parameters $a = 10$, $b = 3$, $c_E = 1$, $c_I = 3.5$ were used as the benchmark case when there is no pandemic. By calculating the optimal social welfare (ω_E^{m*}) of exporting countries with

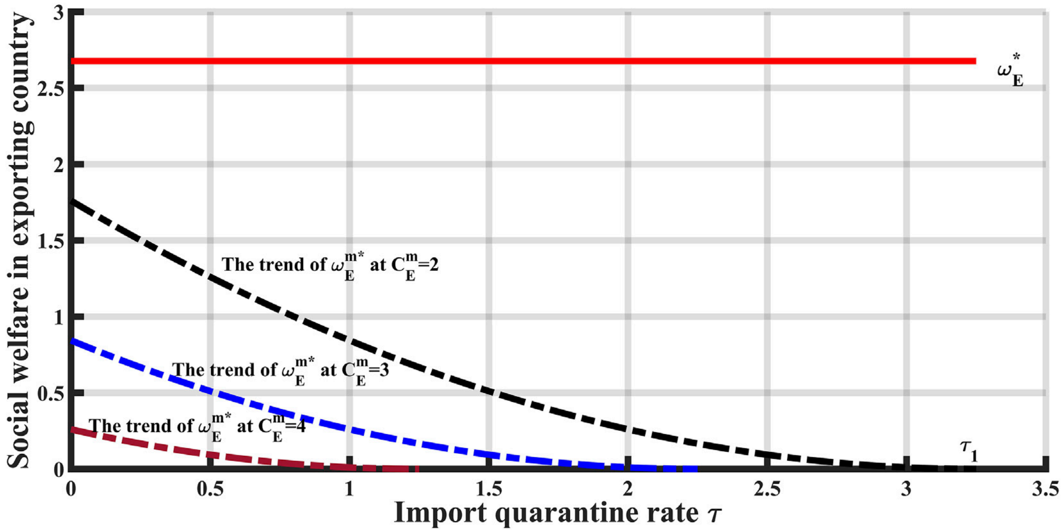

FIGURE 1 | Trend of social welfare changes in exporting country. (Source: Simulation data for numerical calculations).

different c_E^m and τ, we draw **Figure 1** as follows, which describes the trend of social welfare of exporting countries with the import quarantine fee and different production cost.

The upper horizontal line in **Figure 1** is the social welfare of the exporting country in the absence of the pandemic, which is independent of τ and c_E^m. The lower three curves show the decreasing trend of social welfare in the exporting country for $c_E^m = 2, 3, 4$, respectively. In addition, the increase of import quarantine fees brings a double blow to exporters; social welfare will be further reduced and decreases as τ increases. With $c_E^m = 2$, for example, the social welfare of exporting countries decreases with the increase of import quarantine rate, and the levy of quarantine fees has a great impact on exporting countries. It is clear from the figure that when the quarantine rate is low, i.e., $\tau < \tau_1$, exporters will still export, but when the quarantine rate exceeds τ_1, exporters will not be able to afford the excessive tax and stop exporting, and trade is terminated.

In the face of the impact of the pandemic and the import quarantine fees imposed by importing countries, the government should strive to improve the competitiveness of its enterprises. Exporters should accelerate the pace of transformation and upgrading, reduce the marginal cost of production, continuously improve logistics efficiency, review the situation to improve their own management capacity and risk resistance and enhance the position of their products in the industrial chain and the competitiveness of the international market.

The trends of social welfare (ω_E^{m*}) in importing countries with τ and c_E^m are shown in **Figure 2**.

The horizontal line in **Figure 2** is the social welfare of the importing country in the absence of the pandemic, which is independent of τ and c_E^m. The three curves show the change of social welfare of importing countries with τ when $c_E^m = 2, 3, 4$, respectively, and the curves show an increasing and then decreasing trend. Taking $c_E^m = 3$ as an example, it can be clearly seen that: 1) When $\tau < \tau_2$ The social welfare of the importing country is an increasing function of the import quarantine fee, and increasing the import quarantine fee will increase the social welfare. When $\tau_2 < \tau < \tau_4$, the social welfare of the importing country is a decreasing function of the import quarantine fee, and increasing the import quarantine fee at this time will make the social welfare decrease, indicating that the high quarantine fee does not improve the social welfare of the importing country; 2) And when $\tau < \tau_1$ or $\tau_3 < \tau < \tau_4$, the social welfare is lower than that of in the absence of pandemic, indicating that when the quarantine fee is too low or too high, the social welfare of the importing country due to the pandemic will lower; and when $\tau_1 < \tau < \tau_3$, the social welfare of the importing country is higher than before the pandemic, indicating that an appropriate import quarantine fee will increase the social welfare of the importing country; 3) When $\tau > \tau_4$, the exporting country will not export the product due to the high import quarantine fee and the trade between the importing and exporting countries will stop.

To avoid trade frictions between bilateral countries and to avoid the increase of product prices in the domestic market and the reduction of consumer surplus, the importing country should only reasonably levy import quarantine fees to improve the market competitiveness of domestic enterprises, thereby increasing corporate profits and social welfare. However, the import quarantine fee levied by the importing country cannot be too high, otherwise, it will not only seriously damage the social welfare of the exporting country but also reduce the social welfare of the importing country itself, which is not conducive to the upgrading and transformation of domestic enterprises and the adjustment of industrial structure.

The trend in total social welfare ($\omega_E^{m*} + \omega_I^{m*}$) for both countries with τ and c_E^m is shown in **Figure 3**.

The horizontal line in **Figure 3** is the sum of social welfare in the absence of the pandemic, which is independent of τ and c_E^m. The three curves show the change of the total of social welfare of the two countries with τ when $c_E^m = 2, 3, 4$, and the

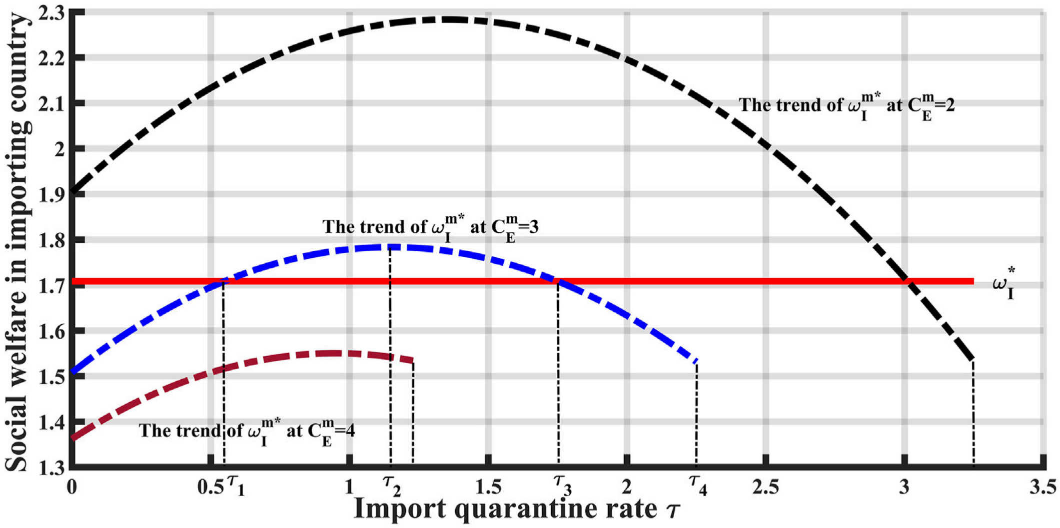

FIGURE 2 | Trends of social welfare changes in importing countries. (Source: Simulation data for numerical calculations).

curves show a decreasing trend. Affected by the pandemic, the social welfare of both countries are greatly reduced, and the greater the c_E^m, the more social welfare reduced; It can be seen from this that on the one hand, exporting countries should actively take measures to restore production capacity as soon as possible and reduce the cost of enterprises in the face of the pandemic; Social welfare has had a negative impact on the normal trade and economy of the two countries. The importing country should abandon trade protection and proceed from the overall situation of the trade between the two countries to jointly deal with the pandemic and achieve a win-win situation.

The government should be fully aware of the long-term nature and complexity of the game between the two countries and should respond to the WTO-compliant import quarantine fees imposed by the importing countries with a normal heart, and establish an early warning and response mechanism promptly, with the relevant subsidy policies for exporters. Both the governments and enterprises must actively negotiate with relevant governments and enterprises from both domestic and international perspectives and take the initiative to bear the impact of the pandemic on domestic and foreign trade.

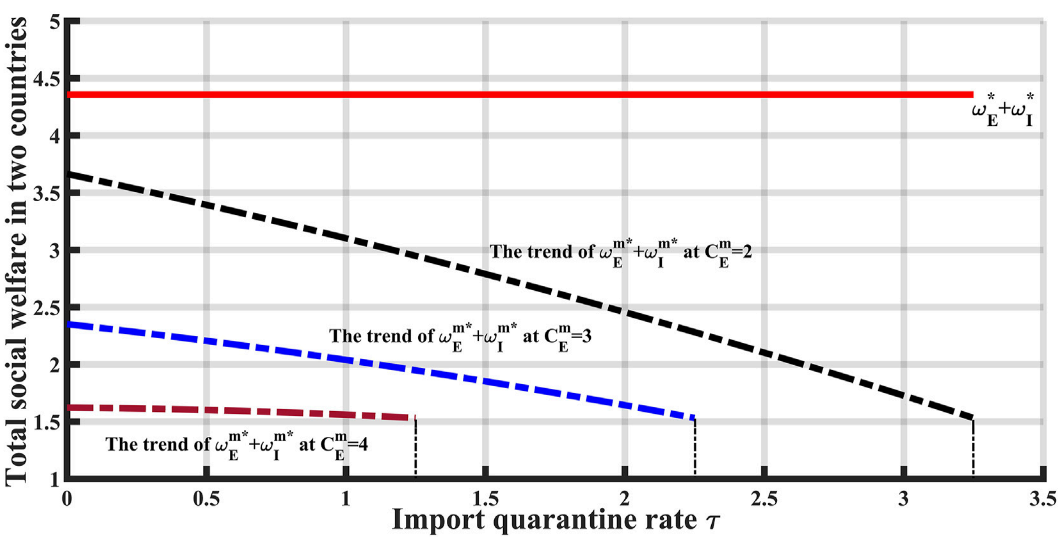

FIGURE 3 | Trend of total social welfare in two countries. (Source: Simulation data for numerical calculations).

RESULTS

In the face of the pandemic, exporting countries must first control the spread of the pandemic to reduce the costs of their enterprises. The tax exemption method or lowering export tax rate is a desirable fiscal policy to prevent enterprises from breaking their capital chains and help them smoothly overcome the hard times. Controlling the spread of the pandemic and subsidizing enterprises are effective means for exporting countries to restore the economy. However, it should not be overlooked that exporting countries make every effort to subsidize export enterprises, which will lead to unfair trade competition in the markets of importing countries, i.e., low-price competition of products, which reduces the profits of enterprises in exporting countries and reduces the profits of enterprises in importing countries, which is not conducive to the sustainable development of economy and trade.

The reasonable increase in import quarantine fees imposed by importing countries is conducive to enhancing the market competitiveness of their enterprises. However, when the importing country imposes higher import inspection and quarantine fees, not only seriously undermines the social welfare of the exporting country, bringing the possibility of trade friction between the two countries and promoting the increase in the price of products on the domestic market. Consumer surplus is reduced, which counterproductively reduces the country's social welfare and is not conducive to the upgrading and industrial restructuring of domestic enterprises themselves. Therefore, the importing country should impose lower import quarantine fees to promote their social welfare and corporate profits. Importing countries should take other positive trade measures and exporting countries should cooperate fully to achieve a win-win situation.

When the pandemic comes, all countries should abandon trade protection, eliminate trade barriers, unblock trade channels, reasonably build stable supply chains and industrial chains, and commit to developing an equal, balanced, mutually beneficial and win-win trade partnership. Both exporting and importing countries must establish subsidies and import quarantine taxes that align with their own national conditions. On the one hand, they can promote healthy competition in the consumer market, and on the other hand, they must jointly respond to the negative impact of the pandemic on the economies of both countries. The two countries should actively conduct in-depth diplomatic consultations on the impact of the pandemic, promote the signing of bilateral border health and quarantine cooperation documents, and avoid the deterioration of trade relations and escalation of trade frictions caused by the pandemic. All countries should focus on long-term trade cooperation, adhere to the deeply intertwined model of mutually beneficial cooperation, clearly express their attitude and position to work together to overcome the pandemic, and resolutely oppose unilateral trade protection.

DISCUSSION

The research further enriches bilateral trade strategies' theoretical connotation and practice under the pandemic. We only consider the situation of international duopoly competition. Still, the motive involving government intervention in the import and export of enterprises has always existed in the situation of multi-oligopoly competition. In particular, when the number of enterprises participating in international competition is more than one, the exporting country needs to consider the actual situation and negotiating power of each enterprise in formulating subsidy policies and balancing the competition effect among various enterprises. In addition, we only studied the pandemic situation in the exporting country and did not consider the pandemic situation in the importing country, nor did we consider the information asymmetry between enterprises and enterprises and between enterprises and governments. As future research, our model can be extended to multi-oligopoly competition while considering the asymmetry between firms and governments, making the model more realistic and challenging. Finally, the model is based on static decision-making, and we can also extend it to a dynamic decision-making model, that is, to study and analyze the evolution of import and export strategies over time. These deficiencies are left for future research to address.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

WT issued the idea and design for the research. JH and JL analyzed the model and drafted the manuscript. GR and FM revised the manuscript along with other authors.

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Understanding the Role of Sustainable-Oriented and Process Innovation With Lean Practices in Achieving Sustainability Paradigm: A Chinese Perspective

Guodong Liu[1], Yuan Ding[2], Chen Wen[3]*, Ke Gao[1,4]*, Tao Wang[5] and Ruiqi Sun[6]*

[1]Development Research Center of Shandong Provincial People's Government, Jinan, China, [2]School of Management, Ocean University of China, Qingdao, China, [3]Olin Business School, Washington University in St. Louis, St. Louis, MO, United States, [4]School of Economics, Peking University, Beijing, China, [5]School of Public Finance and Taxation, Capital University of Economics and Business, Beijing, China, [6]The Center for Economic Research, Shandong University, Jinan, China

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Kiran Batool,
North China Electric Power University, China
Arooj Fatima,
Yanshan University, China

****Correspondence:***
Yuan Ding
49706713@qq.com
Ke Gao
chen.wen@wutl.edu
Chen Wen
gkfly@126.com

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The organizational development following the philosophy of sustainability is becoming the prerequisite for companies, which urges and emphasizes them to incorporate social, economic, and environmental aspects into their manufacturing and operations. Despite plethora of researches exploring lean practices as the solution for improving productivity, it is limited to the operational aspects only, thus ignoring the other aspects of sustainability. Moreover, there is a dearth of studies that explored the combined effect of sustainable innovation, process innovation, and lean practices on the three aspects of sustainability. The current study is an attempt and contribution in the existing literature through the sample of 431 respondents from ISO 14001 certified Chinese organizations during COVID-19 pandemic conditions. The estimations were performed through the Partial Least Squares–Structural Equation Modeling. The results revealed a positive association among the proposed hypothesis of aforementioned studied phenomena. In addition, the current study explores the role of sustainable innovation as a mediator between lean and three dimensions of the sustainability, which is reportedly found to be a partial mediator as both direct and indirect effects are found to be statistically significant. Through the findings of the current study, the managers and decision makers can comprehend the potential of the possible benefits which can be reaped by incorporating both lean and sustainability within their operations.

Keywords: lean practices, innovation, sustainability, environment, economic, social

1 INTRODUCTION

The concept of sustainability has jolted and startled the world since its inception in late 1980s by the "World Commission of Environment and Development" (WCED) (Khodeir and Othman, 2018). The concept of sustainability predominately covers three aspects that include economic, social, and ecology (Dagar et al., 2021; Tang et al., 2022). The ecological aspects cover and address the concerns caused to the environment because of the non-environment friendly operations including manufacturing, transportation, and so on (Liu et al., 2020; Bhardwaj et al., 2022). The social

aspects cover the concerns that are related to the welfare of the stakeholders including employees, customers, strategic partners, and all stakeholders (Hao et al., 2021; Elavarasan et al., 2021a; Elavarasan et al., 2021b; Razzaq et al., 2021; Irfan et al., 2022). The economic aspects cover the concerns through which the excessive and unnecessary wastage of financial resources are controlled and accordingly invested into profitable avenues (Resta et al., 2016; Khan et al., 2021; Rauf et al., 2021; Huang et al., 2022; Islam et al., 2022).

A recent study by The United Nation Global Compact (2016) recommended that through the improvement in the environmental-oriented performance, the supply chain of an organization will become capable to improve their processes, whereas this will also result in reduction in costs, enhancement of productivity, and improvement in the outcomes that includes financial as well as societal. Therefore, achieving sustainable innovation through which the cost to the environments is reduced as well as societal wellbeing is ensured is the need of the time (Chen et al., 2006; Burki et al., 2018). Moreover, through the integration of the operations and processes that are environment friendly, organizations can become greener and sustainable (Burki et al., 2018; Wu et al., 2021). The sustainable objectives can be achieved, through mutual collaboration among the related stakeholders, which is beneficial not only for the organization itself but also for the whole supply chain partners and the society (Thoo et al., 2013; Yumei et al., 2021).

Apart from sustainability, there are various management principles and philosophies that have urged to have maximum utilization of resources either by specialization of labor or by improving the productivity (Ahmad et al., 2021; Ali et al., 2021; Abbasi et al., 2022). One of the most studied, followed, and implemented solution is the philosophy of lean that was originated from the assembly line of automobile industry. Initially it was proposed to improve the level of productivity in the production operations by reducing different kind of non-value-added activities and wastes (Herron and Hicks, 2008). Despite the similarity within the philosophies of lean and sustainability, they are in contrast with certain aspects. For instance, lean is focused on improving the level of productivity by reducing the excess resources including inventory, whereas the theme of sustainability revolves around the efficiency without compromising the responsiveness (Jum'a et al., 2022). Similarly, the exploration of both these philosophies is conventionally limited to operational efficiency only, thus ignoring the aspects of environment and social wellbeing (Stamenkov and Dika, 2019; De et al., 2020), which however need equal attention and exploration (Piercy and Rich, 2015).

In addition, despite the similarities between lean and sustainability, there is dearth of researchers that have explored the integration of both of these philosophies within the manufacturing operations at the same time (Reich-Weiser and Dornfeld, 2009; Hartini and Ciptomulyono, 2015). The few evidences that have explored this stream include Dey et al. (2020) who as explored an integrated model covering the aspects of lean, corporate social responsibility, and innovation; however, they have integrated for exploring the economic performance only. Similarly, Ikram et al. (2019) also assessed the role of sustainability exclusive certification including SA8000, ISO 9001, and ISO 14001 in enhancing the level of exports and economic development. Similarly, different researchers have explored different performance outcomes, including Bandehnezhad et al. (2012) exploring environmental outcome, Hofer et al. (2012) exploring financial performance, Yang et al. (2011) exploring organizational performance, and Iranmanesh et al. (2019) and De et al. (2020) exploring sustainability performance.

Furthermore, the exploration of the linkage between lean practices with the any single aspect of sustainability has been reported by numerous researchers (Iranmanesh et al., 2019; Dieste et al., 2020). In addition, the relationship between sustainable innovation with the performance of the sustainability is also being documented (Adams et al., 2016; Khurana et al., 2021). In addition, the role of innovation based on the principles of sustainability is considered integral for bringing change in the existing operations and play the role of a connector in establishing linkage between advancement and sustainability without creating excessive financial burden (Adams et al., 2016). On the other hand, the integration of lean and sustainability can create synergy and harmony in achieving the objectives of the sustainability, although being explored by the researchers; however, their findings are either limited to a certain aspect of sustainability (as mentioned earlier) or the conclusions drawn are inconclusive. In addition, a systematic review by Carvajal-Arango et al. (2019) covering 117 research articles revealed that only 16% of these studied are based on the exploration of the phenomena through interviews and survey methodology. This is one of the potential contributions that the current study intends to fill by exploring the relationships among the studied phenomena through following the survey methodology (discussed in greater detail in **Section 3**).

Therefore, the current study is an attempt to search for the answers to the following research questions:

RQ1: To what extent sustainable innovation and lean manufacturing practices enhance the levels of the three sustainability aspects (environment, social, and economic)?

RQ2: To what extent sustainable innovation mediates the association between lean manufacturing practices and the three sustainability aspects (environment, social, and economic)?

For drawing the conclusions for the aforementioned research questions, the section comprised the literature review, followed by the methodology, statistical estimations, and outcome, whereas in the end the recommendations are proposed.

2 LITERATURE REVIEW

2.1 Aspects of Sustainability

As already mentioned, through the phenomena of sustainability, the world has been taken by storm since its proposition in 1987 by the "World Commission of Environment and Development" (WCED) (Khodeir and Othman, 2018). Moreover, in accordance with the objectives of the studies, the researchers have been using different aspects of it. For instance, in the context

of construction, the findings of Carvajal-Arango et al. (2019) had listed around 27 dimensions, which should be covered within the umbrella of sustainability. However, the majority is of the researchers who categorize, operationalize, consider, and cover only three aspects of sustainability which are social, economic, and environmental, which are also referred as the triple bottom line (TBL) (Elkington, 2013), as validated by numerous researchers (Martínez-Jurado and Moyano-Fuentes, 2014; Resta et al., 2016; Ikram et al., 2021). At the business level, among the available conceptualizations, the concise definition of sustainability is presented by Martínez-Jurado and Moyano-Fuentes (2014); according to them, the sustainability is "meeting the needs of a firm's direct and indirect stakeholders, without compromising its ability to meet the needs of future stakeholders." Considering the three predominately studied aspects, the environmental aspect of sustainability covers reduction in the obliteration cause to the ecology by efficient management of resources, waste disposal, energy consumption, and safeguarding of natural resources (Martínez León and Calvo-Amodio, 2017). In addition, the economic aspect covers efficient management and utilization of financial resources, whereas the social aspect covers welfare, wellbeing, and prosperity of all the internal and external stakeholders including employees, customers, society, and so on (Martínez León and Calvo-Amodio, 2017). Despite the consensus among the researchers regarding the three predominately aspects of sustainability, there is still a presence of vacuum in terms of exploration of all these aspects hence required further exploration (Burawat, 2019; Iranmanesh et al., 2019; Singh et al., 2020).

2.2 Process Innovation

Innovation has been considered as an integral element and prerequisite in order to improve value of the organization as well as its performance (Montes et al., 2005; Bowen et al., 2010). However, within the innovation, it is also essential at which level innovation is required so that it tickles down the expenses and expedite the economic condition of the organization (Li et al., 2007). Among them, the level where innovation can be far more beneficial is in the process termed as process innovation (PIN) as through this other innovation can also be triggered, for instance at the product level (Li et al., 2007; Camisón and Villar-López, 2014). Moreover, Oke (2007) also considered PIN as the driving force, which has the capability to improve the manufacturing and related operations resulting in improving the product offerings. Organizations that are progressive and proactive heavily strive in bringing in the PIN so that they can not only just improve their product offerings (Ahmed et al., 2020) but also such offerings tend to improve the other aspects of sustainability (Burki et al., 2018; Jum'a et al., 2022). Hence based on these discussions, it is assumed that when there is PIN it will reduce overconsumption and costs to the environment through which the environmental aspect is improved, reduces the excessive resources through which the financial aspect is improved, and improved the distribution of the all tangible and intangible resources through which the social aspects are improved. Therefore, it is anticipated that

H1: Process innovation enhances the environmental aspect of sustainability;
H2: Process innovation enhances the economic aspect of sustainability;
H3: Process innovation enhances the social aspect of sustainability.

2.3 Lean Manufacturing Practices

The inception of lean manufacturing and its practices was originally made in the automobile industry by the Toyota production system (TPS); however, its benefits and contribution toward profits makes it a standard for every organization to be followed (Jum'a et al., 2022). By the help of this philosophy, the organizations are stimulated to improve their level of productivity within their manufacturing operations and processes (Lee and Jo, 2007). Therefore, researches have listed different practices covering the LMP through which the overall productivity of the organizations can be improved. For instance, according to Vinodh et al. (2011), for LMP, the major processes include implementation of the 5S framework, manufacturing design that follows the cellular layout, maintenance at preventive level, demand management through pull approach, and continuous improvement such as Kaizen, sig sigma, perceptual mapping of the value stream, and so on. On the other hand, Bandehnezhad et al. (2012) have emphasized on the incorporation of human element in it. They urge to include employee engagement, customer satisfaction, supplier integration, and all other relevant sustainable practices that cover the human resources.

Similarly, Godinho Filho et al. (2016), Resta et al. (2016), Iranmanesh et al. (2019), and Dey et al. (2020) have explored different practices that are covered within the philosophy of LMP. Among all of them, the common practices that are validated by majority of the researchers include just-in-time flow, quality management, and employee involvement as they are true representation of maximization of the efficiency during production and the regular elimination of waste (Yang et al., 2011; Jum'a et al., 2022). Precisely, the just-in-time flow is the set of interrelated activities which ensure that only right quantity of material and products are made available, which enables reduction of excessive inventory, elimination of inventory waste, and improves the overall product flow across the manufacturing facility (Yang et al., 2011; Jum'a et al., 2022). In addition, quality management not only just covers the government and monitoring and maintenance of the quality but also assists in improving the processes and operation through the continuous improvement program, which assists in reducing the non-value-added activities (Yang et al., 2011; Jum'a et al., 2022). On the other hand, employee involvement covers the aspect related to human resource, which is actually the back bone of any organization and entails the needs of training, development of procedures that assist in creating systems and processes, development of groups for problem solving, and so on (Yang et al., 2011; Jum'a et al., 2022). Therefore, when all these practices are implemented, it is assumed that there will be a reduction in costs to the environment through which the environmental aspect is improved, reduction in the excessive resources through which the financial aspect is improved, and improvement in the distribution of the all tangible and intangible

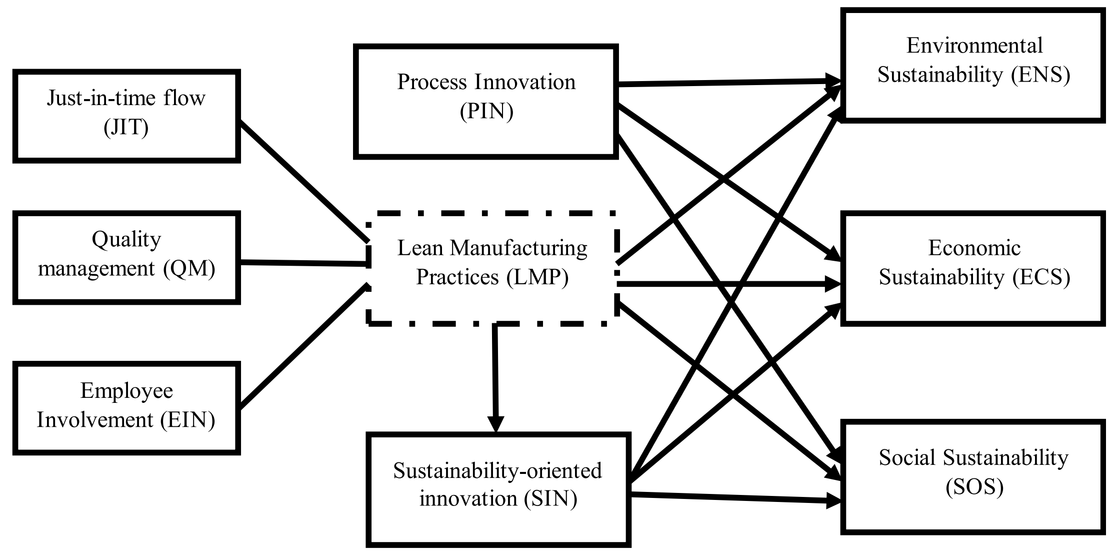

FIGURE 1 | Framework of the study.

resources through which the social aspects are improved. Hence, it is anticipated that

H4: Lean manufacturing practices enhances the sustainability-oriented innovation;
H5: Lean manufacturing practices enhances the environmental aspect of sustainability;
H6: Lean manufacturing practices enhances the economic aspect of sustainability;
H7: Lean manufacturing practices enhances the social aspect of sustainability.

2.4 Sustainability-Oriented Innovation

SOI has been explained as the combination of operations and processes that are involved in the development of the product following the principles of sustainability, with an objective to meet the objectives of the organization that covers ecological, financial, and social aspects (Klewitz and Hansen, 2014). In addition, SOI also highlight the areas where an organization need to made changes through the incorporation of practices that are aligned with sustainability, which leads to environmental, financial, and social wellbeing (Adams et al., 2016; Ikram et al., 2020a). Despite the potential benefits brought in by following the principles of sustainability, it is in contrast in terms of its nature when compared with the lean philosophy (De et al., 2020). For instance, in lean, the organization emphasizes on productivity and efficiency, whereas in SOI, it strives for improving responsiveness (Jum'a et al., 2022). However, if they both are implemented within the organization, then the synergy and harmony that is created through the integration can reap multiple sustainable benefits (Dey et al., 2020). In addition, an attempt was made by multiple researchers in explaining the level of association between the SOI and three studied aspects of sustainability (Klewitz and Hansen, 2014; Adams et al., 2016). Therefore, when there is a presence and incorporation of SOI, it is assumed that there will be a reduction in costs to the environment through which the environmental aspect is improved, reduction in the excessive resources through which the financial aspect is improved, and improvement in the distribution of the all tangible and intangible resources through which the social aspects are improved. Hence, it is anticipated that

H8: Sustainability-oriented innovation enhances the environmental aspect of sustainability;
H9: Sustainability-oriented innovation enhances the economic aspect of sustainability;
H10: Sustainability-oriented innovation enhances the social aspect of sustainability.

The proposed hypotheses in terms of their relationships are graphically illustrated in **Figure 1**.

3 METHODOLOGY

In the light of the discussed objectives and proposed hypotheses, the most suitable and relevant research approach is the quantitative research approach. This research enables the researchers to reach the logical conclusion from the collected numerical data through the application of statistical analysis, which are relatively more objective when compared to the qualitative methodologies that are extremely subjective. Moreover, within the quantitative research approaches, there are multiple research designs, whereas for the current study, the researchers have chosen a survey research design. This research design enables the researchers to have the data collected through a structured research questionnaire. Through the help of collected data, which is relatively small compared to the whole population, the findings can be generalized to the larger portion of the population (Cooper et al., 2006).

TABLE 1 | Source of measures.

Constructs	Number of items	Sources
Just-in-time flow	3	Yang et al. (2011)
Quality management	3	Yang et al. (2011)
Employee involvement	3	Yang et al. (2011)
Process innovation	4	Burki et al. (2020)
Sustainability-oriented innovation	5	Dey et al. (2020)
Environmental sustainability	6	Iranmanesh et al. (2019)
Social sustainability	5	Iranmanesh et al. (2019)
Economic sustainability	6	Iranmanesh et al. (2019)

In addition, the quality of the research and the collected data is highly dependent on the research questionnaire that has been used for the data collection purpose. If such research questionnaire contains any ambiguity or errors, the same will be reflected in the outcome generated from the collected data. Therefore, the development of questionnaire is the crucial phase and hence need to be conducted with due care and diligence. Hence, for employing the survey methodology, the guidelines discussed by Hulland et al. (2018) were followed. The developed questionnaire predominantly comprises two sections: **section 1**, which comprises the questions that are intended to measure the studied phenomena that are shown in **Figure 1**, whereas the second section comprises questions that are intended to ask for gauging the demographic profiles of the respondents.

Regarding **Section 1**, the questions that were asked to measure the studied phenomena were based on the questions that are adapted from the existing literature. As these questions are crucial enough to determine the outcome, it is important to have those scales that have justified their validity in any other geographical context. Hence, the sources and details of the adapted scales are listed in **Table 1**. It should be noted that all of these questions were measured on the Likert Scales having five points in which "1 represents Strongly Disagree," "2 represents Disagree," "3 represents neither Disagree nor Agree," "4 represents Agree," and "5 represents Strongly Agree."

Despite validation being made in the other studied, the face and content validity of these adapted questions were again ensured by a panel of five experts. The panel includes both linguistics and subject experts. The reason for ensuring the face and content validity again is that the current study is conducted on the manufacturing companies of China, where English is not easily understood by the masses. However, since the nature of the study demands to have responses from the qualified professional, a questionnaire being designed in the simple and easy to understand English language, could serve the purpose. Nevertheless, the panel validated the questionnaire as simple and easy to understand and recommended go-ahead data collection.

On the other hand, since environment is the most important aspect of sustainability, therefore for the current study, only those professionals are suited that belong to the manufacturing companies being ISO 14001 certified. This requirement serves as a pre-requisite to qualify for the sample of the current study. Moreover, around 1,000 questionnaire were mailed to the respondents that fit within the objectives of the current study due to the ongoing COVID-19 situation. Therefore, sending questionnaire through email is the best way of data collection. Among them, 490 were returned, which reached the response rate of 49% that is extremely good in the context of studies involving survey methodologies. Among those 490, 59 responses were eliminated as they were identified as univariate and multivariate outliers, following the procedures discussed by Hair et al. (2010). Comrey and Lee (1992) recommended the following scale to determine the adequacy of sample size: (very poor—50), (poor—100), (fair—300), (very good—500), and (excellent—1000 or more). According to this scale, the size of our study sample (431 respondents) falls under the "very good" category, ensuring that the sample is representative for this research.

Among the collected 431 responses, 241 that form 56% of the data were collected from males, whereas the rest 190 that forms 44% of the data were collected from females. The division of data in terms of age includes 141 responses that forms 33% were collected from the group of people having age 30 or less years, 164 responses that forms 38% were collected from the group of people having age 31–40 years, 81 responses that forms 19% were collected from the group of people having age 41–50 years, and 45 responses that forms 10% were collected from the group of people having age 51 and above. In terms of scale and size of the organization in terms of employees, 123 responses that forms 29% were collected from the group of organizations having employees less than 100, 142 responses that forms 33% were collected from the group of organizations having employees between 101–250, 94 responses that forms 22% were collected from the group of organizations having employees between 251–450, and 72 responses that forms 17% were collected from the group of organizations having employees more than 450. In terms of the industry from where the company belongs, 89 responses that forms 21% were collected from the group of the organizations from automobile industry, 161 responses that forms 37% were collected from the group of the organizations from electronics industry, 74 responses that forms 17% were collected from the group of the organizations from chemical industry, 64 responses that forms 15% were collected from the group of the organizations from pharmaceutical industry, and 43 responses that forms 10% were collected from the group of the organizations other than mentioned earlier. The demographic list of final samples is mentioned in **Table 2**.

In addition, there are certain biases which usually arise in the quantitative studies, and hence need to be ascertained. Such biases lead to inflated variance which can easily deteriorate the

TABLE 2 | Descriptive statistics.

		Frequency	Percentage
Gender	Male	241	56%
	Female	190	44%
	Total	431	100%
		Frequency	Percentage
Age	30 or less years	141	33%
	31–40 years	164	38%
	41–50 years	81	19%
	51 and above	45	10%
	Total	431	100%
		Frequency	Percentage
Size (number of employees)	Less than 100	123	29%
	101–250	142	33%
	251–450	94	22%
	More than 450	72	17%
	Total	431	100%
		Frequency	Percentage
Industry	Automobile	89	21%
	Electronics	161	37%
	Chemical	74	17%
	Pharmaceutical	64	15%
	Others	43	10%
	Total	431	100%

Source: Authors estimation.

quality of generated outcome (Podsakoff et al., 2003). Therefore, following the operational remedies proposed by Podsakoff et al. (2012), the possibility of having the method variance is reduced. In addition, the presence of method variance was also assessed statistically through Harman (1967) single factor test and through the values of correlations among the construct as highlighted in Najmi and Ahmed (2018). Both of the measure negates the presence of method variance. Thus, the current data are apparently found to be free from the methodological unwanted variances.

4 ESTIMATIONS AND RESULTS

In the researches involving complex research frameworks and the objective of maximum explanation of the variance, as the case of the current study is, the application of Partial Least Squares–Structural Equation Modeling (PLS-SEM) is highly recommended (Hair et al., 2019). This is because of the fact that PLS-SEM belongs to the category of second-generation techniques and has the capability to incorporate multiple predictors and criteria in one go. Hence, through the help of SmartPLS software, which is the easiest to handle software having simple interface, the application of PLS-SEM was made possible. In addition, Hair et al. (2016) suggested that the application of PLS-SEM must be done in a dual-step method. In this dual step, the first step covers the assessment of the outer model in which the relationships of the observed variables with the latent variables are being assessed. The second step covers the assessment of the inner model in which the relationships between latent variables are assessed. Once both assessments are done, then the researchers will be in a position to evaluate the proposed hypotheses and their respective relationships. The assessment is discussed in the following sections.

4.1 Assessment of Outer Model

As already discussed, the assessment of the outer model covers the relationships of the observed variables with the latent variables. Within the outer model, the assessment of the relationships between the observed variables with their respective latent variables is termed as convergent validity, whereas the assessment of the relationships between the observed variables of a latent variable with the other latent variables is termed as discriminant validity (Mehmood and Najmi, 2017).

Considering the convergent validity, the current study ensures the presence of convergence by the help of three different parameters, which includes factor loadings, internal consistency (through Cronbach's Alpha and Composite Reliability), and through the value of average variance extracted (AVE). For factor loadings, the recommendations by Hair et al. (2016) is that it should be larger than 0.7. The values listed in **Table 3** clearly shows that the observed values of factor loadings are larger than 0.7. For internal consistency, which is further assessed through Cronbach's Alpha and Composite Reliability, the recommendations by Hair et al. (2016) is that these should be larger than 0.7. The values listed in **Table 3** clearly shows that the observed values of Cronbach's Alpha and Composite Reliability are larger than 0.7. For AVE, the recommendations by Hair et al. (2016) is that it should be larger than 0.5. The values listed in **Table 3** clearly shows that the observed values of AVE are larger than 0.5.

Considering the discriminant validity, this is assessed by three different criteria including cross loadings, Fornell–Larcker criterion, and "Heterotrait–Monotrait ratio of correlations" (HTMT). Cross loading is the representation of a factor loading within a particular construct along with the loadings of this factor into other constructs. Theoretically and statistically, a factor loading of a construct should be highly loaded into its own construct. Moreover, Gefen and Straub (2005) have stated the acceptable difference of a factor loadings into other constructs which is the cross loadings. According to them, the acceptable difference should be higher than 0.1, which is found in the current study as the outcome listed in **Table 4**.

The second criterion is the one which is most commonly applied in the researches assessing discriminant validity and is known as the Fornell and Larcker (1981) criterion proposed by the authors in their own name. As per them, a particular factor's square root of AVE should be much higher while comparing it with the values of the correlations among the constructs. The outcome mentioned in **Table 5** outlines the meeting of the said proposition as the diagonal values are the factor's square root of AVE, whereas all other values represents correlations among the constructs. The outcome outlined in **Table 5** clearly satisfies the meeting of the Fornell and Larcker (1981) criterion.

The third and the most recent criteria by which the discriminant validity is assessed in the present study is of HTMT proposed by Henseler et al. (2015). As per this criterion, the value of the HTMT at which there is the

TABLE 3 | Measurement model results (first order variables).

Variables	Items	Factor loadings	Cronbach's alpha	Composite reliability	AVE
Just-in-time flow	JIT1	0.880	0.753	0.766	0.572
	JIT2	0.746			
	JIT3	0.746			
Quality management	QM1	0.791	0.759	0.784	0.696
	QM2	0.837			
	QM3	0.882			
Employee involvement	EIN1	0.783	0.714	0.782	0.598
	EIN2	0.793			
	EIN3	0.769			
Process innovation	PIN1	0.758	0.779	0.799	0.593
	PIN2	0.727			
	PIN3	0.798			
	PIN4	0.722			
Sustainability-oriented innovation	SIN1	0.882	0.794	0.780	0.677
	SIN2	0.851			
	SIN3	0.806			
	SIN4	0.756			
	SIN5	0.735			
Environmental sustainability	ENS1	0.855	0.716	0.807	0.585
	ENS2	0.841			
	ENS3	0.747			
	ENS4	0.745			
	ENS5	0.723			
	ENS6	0.764			
Social sustainability	SOS1	0.725	0.758	0.779	0.661
	SOS2	0.817			
	SOS3	0.729			
	SOS4	0.774			
	SOS5	0.794			
	SOS6	0.799			
Economic sustainability	ECS1	0.778	0.791	0.731	0.594
	ECS2	0.855			
	ECS3	0.772			
	ECS4	0.781			
	ECS5	0.877			

Source: Authors estimation.

establishment of discriminant validity is 0.85; however, any value below one is also considered as acceptable. The outcome outlined in **Table 6** clearly satisfies the meeting of the HTMT criterion.

4.2 Assessment of Inner Model

After the assessment of outer model, the second step involves the assessment of inner model in which the relevancy and predictability of the model which is the reflection of the exploration of variance from the dependent variable through the independent variables. The assessment was done through "coefficient of determination" and "Cross-Validated Redundancy" which is gauged through R-Square and Q-Square. Particularly for R-Square, Cohen (1988) stated that it is highly rely on the nature and attributional quality of the independent variable that successfully explain the dependent variable; however, if the value of R-Square is found to be below 0.02 then it is considered as low, whereas if it is found between 0.02 and 0.25 then it is moderate and will be termed as substantial if it is higher than 0.26. On the other hand, for Q-Square which is the reflection of "Cross-Validated Redundancy" is computed through the methodological framework of Stone–Geisser's value. According to this criterion, any value beyond the number of zero is acceptable for it. The outcome outlined in **Table 7** shows the assessment of R-Square and Q-Square criterion.

4.3 Hypotheses Testing

For the computation of significance of the relationship among the variables, the application of PLS-SEM is used because of an edge on the comparative statistical analysis (**Figure 2**). The edge is because of the significance computation following the framework of bootstrapping. In this methodology, the significance is computed after drawing multiple subsamples from the data set of which Hair et al. (2016) have recommended the number of 5,000 subsamples. Nevertheless, through computing significance after drawing 5,000 subsamples, the legitimacy and reliability of the outcomes is ascertained which is outlined in **Table 8**.

First, about the relationships of process innovation with the different criterion variables reflecting three aspects of sustainability. For environmental aspect of sustainability, process innovation is reported to affect environmental aspect of sustainability positively and significantly at level of significance

TABLE 4 | Results of loadings and cross loadings.

Variable	JIT	QM	EIN	PIN	SIN	ENS	SOS	ECS
Just-in-time flow	0.880	0.298	0.342	0.361	0.316	0.324	0.308	0.355
	0.746	0.355	0.301	0.383	0.330	0.339	0.330	0.297
	0.746	0.341	0.374	0.377	0.365	0.322	0.304	0.396
Quality management	0.375	0.791	0.294	0.393	0.301	0.390	0.387	0.357
	0.330	0.837	0.359	0.298	0.397	0.343	0.371	0.388
	0.362	0.882	0.372	0.366	0.344	0.307	0.351	0.384
Employee involvement	0.313	0.322	0.783	0.290	0.335	0.336	0.355	0.355
	0.324	0.336	0.793	0.368	0.296	0.320	0.292	0.352
	0.345	0.292	0.769	0.307	0.296	0.392	0.311	0.292
Process innovation	0.327	0.338	0.356	0.758	0.372	0.340	0.292	0.328
	0.343	0.313	0.350	0.727	0.397	0.388	0.317	0.372
	0.332	0.347	0.344	0.798	0.383	0.341	0.304	0.308
	0.376	0.349	0.349	0.722	0.314	0.321	0.290	0.300
Sustainability-oriented innovation	0.342	0.308	0.304	0.308	0.882	0.357	0.335	0.379
	0.331	0.290	0.319	0.370	0.851	0.335	0.366	0.340
	0.339	0.375	0.392	0.348	0.806	0.343	0.320	0.312
	0.369	0.332	0.358	0.312	0.756	0.368	0.340	0.385
	0.355	0.351	0.348	0.316	0.735	0.314	0.355	0.349
Environmental sustainability	0.334	0.340	0.383	0.314	0.302	0.855	0.370	0.295
	0.343	0.315	0.388	0.376	0.342	0.841	0.342	0.352
	0.339	0.363	0.394	0.294	0.376	0.747	0.341	0.359
	0.333	0.353	0.366	0.294	0.387	0.745	0.318	0.369
	0.306	0.346	0.383	0.380	0.327	0.723	0.322	0.371
	0.383	0.391	0.345	0.361	0.329	0.764	0.389	0.398
Social sustainability	0.309	0.326	0.328	0.386	0.334	0.310	0.725	0.357
	0.323	0.313	0.385	0.320	0.366	0.301	0.817	0.354
	0.334	0.384	0.315	0.373	0.354	0.331	0.729	0.306
	0.324	0.362	0.374	0.379	0.301	0.292	0.774	0.346
	0.293	0.321	0.326	0.300	0.380	0.398	0.794	0.377
	0.336	0.366	0.378	0.315	0.359	0.304	0.799	0.346
Economic sustainability	0.298	0.319	0.349	0.306	0.373	0.359	0.377	0.778
	0.371	0.295	0.337	0.371	0.362	0.379	0.365	0.855
	0.324	0.369	0.328	0.346	0.369	0.354	0.368	0.772
	0.388	0.347	0.302	0.330	0.390	0.398	0.375	0.781
	0.363	0.294	0.347	0.339	0.352	0.300	0.366	0.877

Source: Authors estimation.

TABLE 5 | Discriminant validity of the Fornell–Larcker criterion.

	JIT	QM	EIN	PIN	SIN	ENS	SOS	ECS
JIT	0.756							
QM	0.628	0.834						
EIN	0.627	0.560	0.774					
PIN	0.576	0.550	0.586	0.770				
SIN	0.550	0.527	0.646	0.555	0.823			
ENS	0.534	0.603	0.582	0.525	0.633	0.765		
SOS	0.621	0.541	0.528	0.553	0.537	0.572	0.813	
ECS	0.570	0.599	0.645	0.533	0.532	0.628	0.536	0.771

Source: Authors estimation.

TABLE 6 | Results of HTMT ratio of correlations.

	JIT	QM	EIN	PIN	SIN	ENS	SOS	ECS
JIT								
QM	0.584							
EIN	0.733	0.650						
PIN	0.676	0.614	0.571					
SIN	0.745	0.634	0.639	0.585				
ENS	0.560	0.739	0.637	0.640	0.636			
SOS	0.735	0.616	0.684	0.725	0.605	0.708		
ECS	0.637	0.722	0.713	0.676	0.599	0.592	0.688	

Source: Authors estimation.

of 1%. This is the reflection of the level of expansion environmental aspect of sustainability can have by 26.1%, through the level of expansion in the process innovation. This relationship is explained as when organizations improve the processes through the innovation, there will be optimization of the resources and minimization of the waste. As an outcome, there will be a comparatively lesser effect to the environment as process innovation will lead to less consumption of resources

TABLE 7 | Predictive power of construct.

	R-Square	Q-square
SIN	0.192	0.110
ENS	0.288	0.099
ECS	0.235	0.103
SOS	0.239	0.097

Source: Authors estimation.

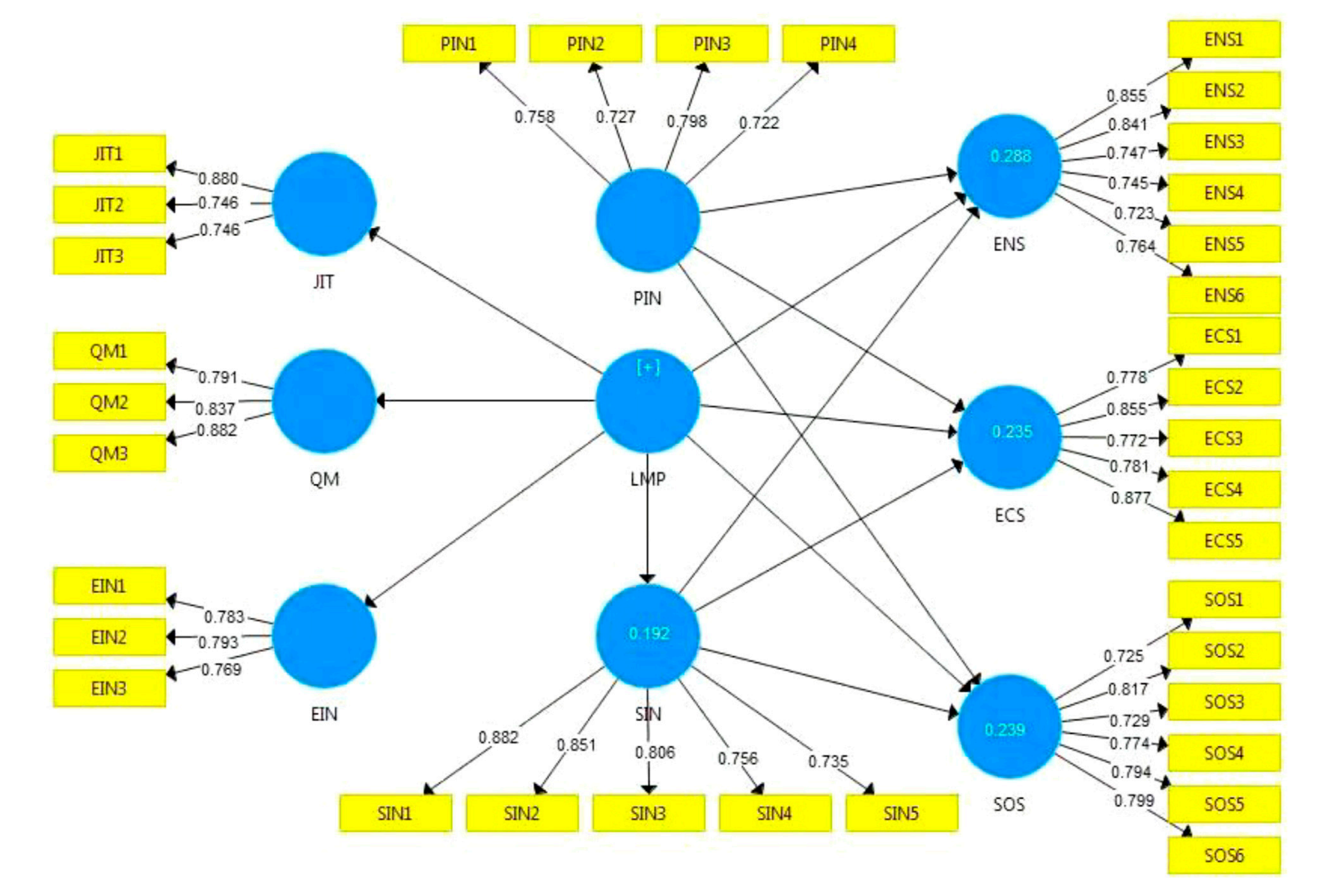

FIGURE 2 | Structural model assessment.

TABLE 8 | Results of path coefficients (direct effects).

Hypothesized path	Path coefficient	C.R	p-value	Remarks
PIN → ENS	0.261	8.700	0.000	Supported
PIN → ECS	0.278	8.879	0.000	Supported
PIN → SOS	0.270	8.372	0.000	Supported
LMP → SIN	0.288	12.948	0.000	Supported
LMP → ENS	0.262	11.774	0.000	Supported
LMP → ECS	0.286	7.501	0.000	Supported
LMP → SOS	0.372	10.512	0.000	Supported
SIN → ENS	0.346	8.223	0.000	Supported
SIN → ECS	0.317	11.233	0.000	Supported
SIN → SOS	0.332	9.963	0.000	Supported

Level of significance (5%, i.e., 0.050).
Source: Authors' estimation.

TABLE 9 | Results of path coefficients (indirect effects).

Hypothesized path	Path coefficient	C.R	p-value	Remarks
LMP → SIN → ENS	0.187	9.471	0.000	Supported
LMP → SIN → ECS	0.152	10.729	0.000	Supported
LMP → SIN → SOS	0.170	10.981	0.000	Supported

Level of eignificance (5%, i.e., 0.050).
Source: Authors' estimation.

causing least possible cost to the environment. For economic aspect of sustainability, process innovation is reported to affect economic aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion economic aspect of sustainability can have by 27.8%, through the level of expansion in the process innovation. This relationship is explained as when organizations improve the processes through the innovation, there will be optimization of the resources and minimization of the waste. As an outcome, there will be a comparatively lesser level of consumption of financial resources. Through this, firms can save the finances which can further be invested in other possible profitable avenues when needed. For social aspect of sustainability, process innovation is reported to affect social aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion social aspect of sustainability can have by 27%, through the level of expansion in the process innovation. This relationship is explained as when organizations improve the processes through the innovation, there will be optimization of the resources and minimization of the waste. As an outcome, firms can realign those resources for the welfare of the society through which firms can improve the social aspect of sustainability.

Second, the relationships of lean manufacturing practices are reflected by three criteria, namely, involvement of the employees, just-in-time flow of the products, and quality management across the manufacturing processes, with the different criterion variables reflecting three aspects of sustainability and sustainable innovation. For sustainable innovation, lean manufacturing practices are reported to affect sustainable innovation positively and significantly at level of significance of 1%. This is the reflection of the level of expansion sustainable innovation can have by 28.8%, through the level of expansion in the lean manufacturing practices. This is because when there is higher level of involvement by the employees and quality management across all of the manufacturing practices, followed by lesser level of inventory due to following the just-in-time approach, organization can have enough room of improvement in terms of sustainable innovation, which is also reflected though the outcome estimated. These findings validate the outcome reported by earlier researchers (Piercy and Rich, 2015; De et al., 2020). For environmental aspect of sustainability, lean manufacturing practices are reported to affect environmental aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion environmental aspect of sustainability can have by 26.2%, through the level of expansion in the lean manufacturing practices. This is because when there is higher level of involvement by the employees and quality management across all of the manufacturing practices, followed by lesser level of inventory due to following the just-in-time approach, organization can reduce the possible environment costs which lead to increase the environmental aspect of sustainability. These findings validate the outcome reported by earlier researchers (Bandehnezhad et al., 2012; Baliga et al., 2019; Dieste et al., 2020).

Moreover, for economic aspect of sustainability, lean manufacturing practices are reported to affect economic aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion economic aspect of sustainability can have by 28.6%, through the level of expansion in the lean manufacturing practices. This is because when there is higher level of involvement by the employees and quality management across all of the manufacturing practices, followed by lesser level of inventory due to following the just-in-time approach, organization can reduce the possible economic costs through taking out the unnecessary finances which lead to increase the economic aspect of sustainability. These findings validate the outcome reported by earlier researchers (Hofer et al., 2012; Dey et al., 2020). Furthermore, for social aspect of sustainability, lean manufacturing practices are reported to affect economic aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion social aspect of sustainability can have by 37.2%, through the level of expansion in the lean manufacturing practices. This is because when there is higher level of involvement by the employees and quality management across all of the manufacturing practices, followed by lesser level of inventory due to following the just-in-time approach, organization can reduce the possible social costs through taking out the unnecessary finances which will be available to be invested for social wellbeing for the employees, society and other relevant stakeholders. These findings validate the outcome reported by earlier researchers (Dey et al., 2020; Singh et al., 2020).

Third about the relationships of sustainable innovation with the different criterion variables reflecting three aspects of sustainability. For environmental aspect of sustainability, sustainable innovation is reported to affect environmental aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion environmental aspect of sustainability can have by 34.6%, through the level of expansion in the sustainable innovation. This relationship is explained as when organizations improves the processes through the innovation keeping in mind the social, ecological and financial aspects, there will be optimization of the resources and minimization of the waste. As an outcome, there will be a comparatively lesser effect to the environment as sustainable innovation will lead to less consumption of resources causing least possible cost to the environment. For economic aspect of sustainability, sustainable innovation is reported to affect economic aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion economic aspect of sustainability can have by 31.7%, through the level of expansion in the sustainable innovation. This relationship is explained as when organizations improves the processes through the social, ecological and financial aspects of innovation, there will be optimization of the resources and minimization of the waste. As an outcome, there will be a comparatively lesser level of consumption of financial resources. Through this, firms can save the finances which can further be invested in other possible profitable social, ecological and financial aspects and avenues when needed. For social aspect of sustainability, sustainable innovation is reported to affect social aspect of sustainability positively and significantly at level of significance of 1%. This is the reflection of the level of expansion social aspect of sustainability can have by 33.2%, through the level of expansion in the sustainable innovation. This relationship is explained as when organizations improves the processes through the social, ecological and financial aspects of innovation, there will be optimization of the resources and minimization of the waste. As an outcome, firms can realign those resources for the welfare of the society through which firms can improve the social aspect of sustainability.

Considering the relationship of sustainable innovation as mediator between lean practices and the three dimensions of sustainability, the sustainable innovation was found to act as the mediator in all of the proposed relationships. In addition, since the both direct and indirect relationships are reportedly found statistically significant therefore, the kind of mediation is said to be partial between predictors, mediator and criterion variables. It means that the presence of sustainable innovation will play a beneficial role for lean practices while transforming them in enhancing all the dimensions of sustainability.

5 CONCLUSION AND RECOMMENDATIONS

Despite plethora of researches exploring lean as the solution for improving productivity, it is limited to the operational aspects only, thus ignoring the other aspects of sustainability. The current

study is an attempt and contribution in the existing literature through the sample of 431 respondents from ISO 14001 certified Chinese organizations. The estimations were performed through the Partial Least Squares–Structural Equation Modeling whereas the outcome reported a positive association among the proposed hypothesis of aforementioned studied phenomena. The findings of the present study draw the conclusion that implementation of lean and innovation that comply to the principles of sustainability can significantly enhance all the three levels of sustainability (including environmental, social and economic) among the Chinese firms. Since the SIN is also reported as the partial mediator, it draws the in the presence of LMP, the SIN can enhance the aspects of sustainability.

Considering the LMP which in present study is measured through three subdimensions, which are employee engagement, quality management and just-in-time flow, there are multiple recommendations. For employee engagement, organizations need to look into means by which the level of engagement can be increased. This includes implementation of incentive and reward systems where additional rewards are awarded to the employee contributing to the sustainability of the organizations. Moreover, provision of educational trainings and certifications can also act as the catalyst whereas taking employees on board even at the stage of the product development can also enhance their level of engagement. For quality management, implementation of quality programs like being accredited by internal certifications like ISO 9001 and compliance to the Total Quality Management policies can also make the difference. For just-in-time flow, implementation of systems like Kanban can improve the product flow by reducing the excessive inventory and lead times. For innovation, implementation of green initiatives can increase the level of compliance toward sustainability. This includes implementation of green procurement, green transportation, green warehousing and green logistics. In addition, organizations need to invest in the research and development of the initiatives that comply to the principles of lean as well as sustainability.

In terms of limitations, following are the future research recommendations. Firstly, current study only explores the three subdimensions of lean however, there are several other dimensions as well which includes like 5S, six sigma, value stream mapping and so on. In addition, the current study though based on the sample size which is large but it is based on the companies from China only, hence the generalizability will be issue. Lastly, the current study is among the few limited studies that explores the synergy between lean and sustainability, more empirical survey methodology-based studies are required in order to broaden the literature further.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Institutional Review Board of Ocean University of China (protocol code 674-3 on 18 October 2021). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

GL: conceptualization, writing—original draft, and methodology. YD: supervision. CW: formal analysis. KG: variable construction. TW: funding acquisition. RS: data handling. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL RESEARCH
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Determining Farmers' Awareness About Climate Change Mitigation and Wastewater Irrigation: A Pathway Toward Green and Sustainable Development

Muhammad Tayyab Sohail[1], Eslam B. Elkaeed[2], Muhammad Irfan[3]*, Ángel Acevedo-Duque[4] and Sohaib Mustafa[5]**

[1]School of Public Administration, Xiangtan University, Hunan Xiangtan, China, [2]Department of Pharmaceutical Sciences, College of Pharmacy, AlMaarefa University, Riyadh, Saudi Arabia, [3]Faculty of Management Science, Department of Business Administration, ILMA University, Karachi, Pakistan, [4]Public Policy Observatory Faculty of Business and Administration, Universidad Autónoma de Chile, Santiago, Chile, [5]Department of Management, National College of Business Administration and Economics (NCBA&E), Lahore, Pakistan

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Beijing University of Technology, China

***Correspondence:**
Muhammad Tayyab Sohail
tayyabsohail@yahoo.com
Muhammad Irfan
irfansahar2010@gmail.com
Sohaib Mustafa
gillsohaib@yahoo.com

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The present study was conducted in one of the major agriculture areas to check farmers' awareness of climate change, adaptation measurements, and use of wastewater for irrigation. A semi-structured questionnaire was adopted from the existing literature, it was divided into different parts such as demographic information, use of wastewater for irrigation, farmer's livelihood assets, climate change deciding factors, and adaptation measures, and some statistical tools (correlation and regression) were used to analyze the data. The farmers with enough resources and assets regarded themselves as safer and have enough capacity to bear the negative impacts of climate change. Farmers' assets (FA) with determinants of climate change (DCC) and adaption measures (AM) are highly significant with the correlation values of 0.440 and 0.466, respectively, and DCC with AM (0.269). The correlation values for other variables are: gender with cultivated land 0.202, wastewater use (WWU) 0.419, farmers' assets (FA) 0.766, determinants of climate change (DCC) 0.381, and adaption measures (AM) 0.449. Floods and droughts variables have shown a significant relationship with adaption measures at p-value 0.000 and coefficient 0.176 and p-value 0.021 and coefficient 0.063, respectively. The study will aid in the implementation of effective monitoring and public policies to promote integrated and sustainable water development.

Keywords: farmers, climate, change, development, green, sustainable and resilient

INTRODUCTION

Climate change is a global environmental challenge (Hao et al., 2021; Huang et al., 2022; Shi et al., 2022), and to minimize its negative impact (Razzaq et al., 2020; 2021; 2022), governments are implementing environmentally friendly technologies worldwide (Tang et al., 2022; Wen et al., 2022; Xiang et al., 2022). Many developing countries are affected by climate change due to lack of effective policies or insufficient capacity to deal with it (Elavarasan et al., 2021; Abbasi et al., 2022; Ahmad et al., 2022). Pakistan is the most affected country in this region by climate change (Irfan et al., 2019,

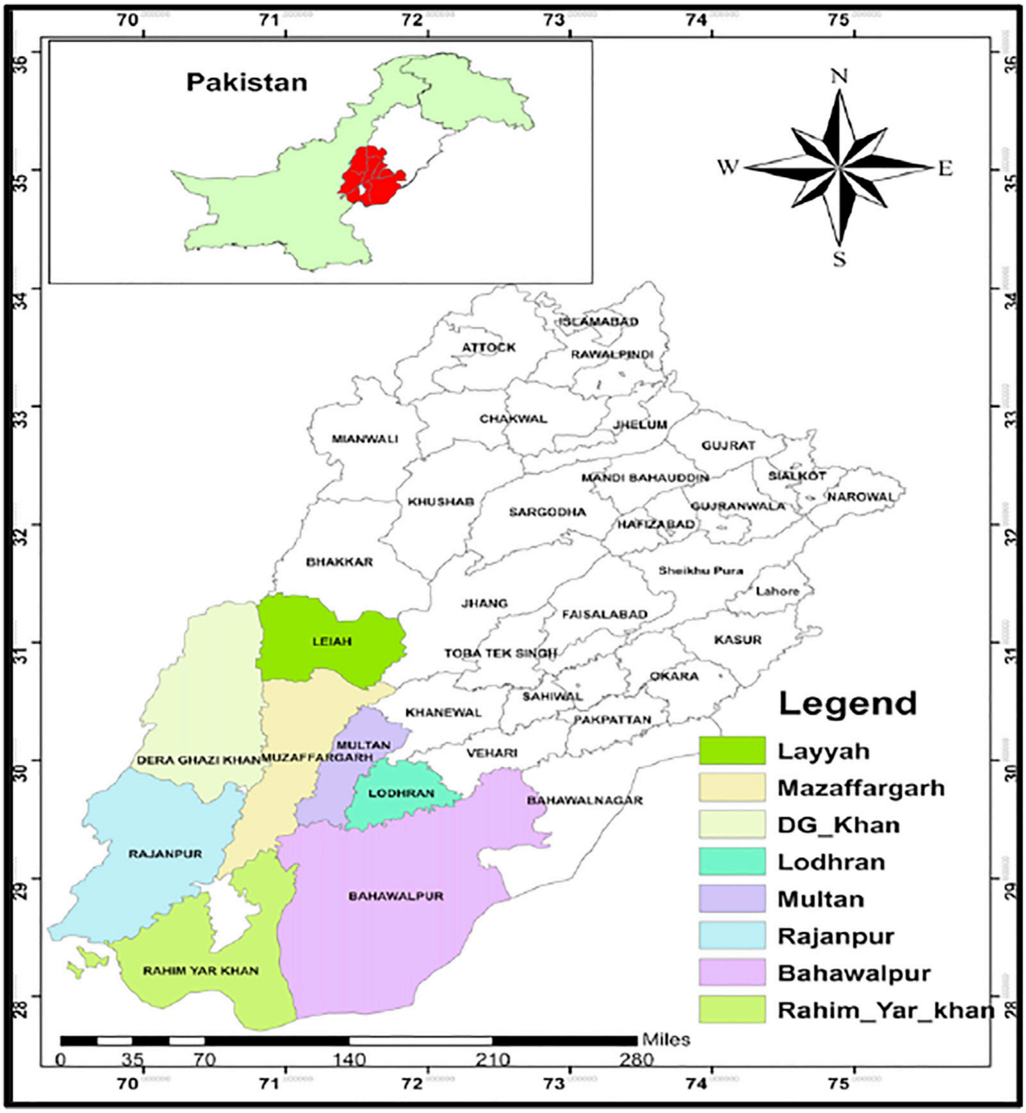

FIGURE 1 | Study area.

2020; Ali et al., 2021; Tanveer et al., 2021), and high temperatures can have negative effects on agriculture (Ali et al., 2021; Chandio et al., 2021; Irfan et al., 2021). Pakistan's contribution toward global warming is very low, but the impact of climate change has grown day by day (Fahad et al., 2018). Floods, droughts, and storms are all too common in Pakistan these days as a result of the high temperature, which is linked to climate change (Mueller et al., 2014; Khan et al., 2020). Many scholars acknowledged that farmers use various ways to adapt climate change vulnerability (Bryant et al., 2000; Bryan et al., 2009) and stated that climate change vulnerability and risk perception adaptability at the household level are critical to minimize climate change impacts on agriculture (Abid et al., 2016; Srivastava, 2020). Pakistan is a developing country, and the situation in terms of adaptation and vulnerability is unsatisfactory (Hussain and Mudasser, 2007; Sohail et al., 2014; Sohail et al., 2019a). Adger and Kelly (1999) claim that good adaptation can mitigate the harmful effects of climate change (Sohail et al., 2021a). Climate change has been shown in numerous studies to have a significant impact on people living in rural areas connected to the farming sector (O'Brien and Leichenko, 2000). Because there is a significant link between climate change and agriculture, those who work in agriculture are more likely to be affected by the effects of climate change (Field et al., 2012). Climate change is a serious threat to many countries' agricultural sectors, and implementing adaptation strategies is thus vital to protect future agricultural production and farmers' livelihoods (Chandra et al., 2017; Amir et al., 2020). Pakistan is mainly an agricultural country (Sohail et al., 2015; Fiaz et al., 2016), and agriculture depends on irrigation (Lee et al., 2020). It is very common in many countries to use wastewater for agriculture purposes, and it is a good way of disposing wastewater with advantages such as a lot of nutrients, which make the crop yields rise without using fertilizer, but apart from some positive impacts,

TABLE 1 | Survey participants.

Province	District	No. of interviewed farmers
Punjab	Layyah	130
	Muzaffargarh	140
	DG Khan	145
	Lodhran	160
	Multan	140
	Rajanpur	155
	Bahawalpur	150
	Rahim_Yar_Khan	180
	Total	1,200

it contains organic compounds, heavy metals, and a wide spectrum of enteric pathogens which can harm human health, the environment, and agricultural productivity (Sohail et al., 2019b; Mahfooz et al., 2019; Sohail et al., 2020). Usually, farmers depend on canal water and wastewater for agriculture purposes, and wastewater is considered to have a positive impact on crops (Yamin et al., 2015). Sometimes wastewater cannot be fit for agriculture and can have negative impact on crops, soils, vegetables, environments, and human health (Holt, 2000; Hassan et al., 2013; Ullah et al., 2013; Mustafa et al., 2022). Furthermore, sometimes some farmers do not have access to canal water or suffer from shortage of allocated canal water due to lack of canal water supply. Therefore, if they have easy access to wastewater pumping stations, they will use wastewater as an alternate source of irrigation (Anwar et al., 2010). It is estimated that about 200 million farmers irrigate 20 million hectares of land with wastewater globally (Raschid-Sally and Jayakody, 2009). All these have severe impact on the production of different crops in Pakistan (Lobell and Gourdji, 2012). But still, there are missing comprehensive policies to deal with such natural disasters (Shah et al., 2020; Yen et al., 2021; Liu et al., 2022). The sustainable livelihoods approach (SLA) was used in this research, to check how livelihood assets help to achieve farmers' well-being. In this research, we build SLA by mixing household adoption techniques and costly adaptation strategies, along with consequences for livelihood outcomes (Shinbrot et al., 2019). The objectives of this study were: 1) farmers' awareness of climate change and adaption of different techniques to deal with climate change. 2) Farmer's awareness about the impact of reuse of wastewater on crops. 3) Farmer's livelihood assets and life status in South Punjab, Pakistan. This study will aid policymakers in assisting farmers in their daily lives and farming operations. Without the intervention of the government, it is impossible to provide assistance and support to vulnerable farmers for the adaptation and implementation of good practices (Udmale et al., 2014).

MATERIALS AND METHODS

Study Area

Punjab is the most populous and second-largest province of Pakistan. It encompasses 25.8% of Pakistan's total land area. The weather in Punjab province varies throughout the year. By mid-February, the temperature starts to rise, and the spring weather lasts until mid-April when the summer heat hits, and June and July are the hottest months of the year. Temperatures in the Punjab region range from 2 to 45°C but can reach 50°C (122°F) in the summer. Punjab has three distinct seasons in terms of climate. Punjab has a total land area of 20.63 million hectares, with 59 percent of that area under cultivation. The province accounts for 53% of the country's overall agricultural GDP and 74% of its cereal production (Abid et al., 2015; 34.; Ahmad and Afzal, 2020). Due to the importance of this agricultural area, Farmers' perceptions toward climate change and adaptation measures were studied in this study (**Figure 1**).

Data Sources and Data Preparation

This study was based on farmers' experience with climate change, the use of wastewater for irrigation, and their adaption techniques toward climate change (Fahad and Wang, 2018; Sohail et al., 2021c). A semi-structured questionnaire was adopted from the existing literature and modified as per the study area requirement to collect data from eight districts of South Punjab, Pakistan (Layyah, Muzaffargarh, DG Khan, Lodhran, Multan, Rajanpur, Bahawalpur, and Rahim_Yar_Khan) (Fahad and Wang, 2018; Fahad et al., 2020). Basic research ethics were considered while defining the objectives of the research and collecting data from farmers, and the objective of the research was clearly explained to farmers (Bogner et al., 2009; Rasool et al., 2017), and it was informed to farmers that these data will be used only for research purposes and there is no compulsion for them to answer these questions (McCusker and Gunaydin, 2015). A survey team consisting of five researchers (Ph.D., Master, and Postdoc) was sent to collect data from farmers of South Punjab, Pakistan. Farmers were informed about the purpose of the research; the first portion was about demographic information of participants, and the rest of the questionnaire was about the use of wastewater for irrigation purposes (Mojid et al., 2010), farmer's livelihood assets, determining factor of climate change, and adaption measures. In this study, 1,200 completely filled questionnaires were collected from the study area, and a pre-test was carried out to check the reliability of data and to avoid any discrepancies. After data collection, data were fed into SPSS 24 for further analyses. A confidence level of 95% was used with a 7% margin error. Some other researchers also used the same margin error of 7% (Hussain and Thapa, 2012; Fahad et al., 2018, 2020). Some statistical tools (correlation and regression) were used to analyze the data.

RESULTS AND DISCUSSION

Table 1 shows the number of farmers interviewed in the present study; a total number of 1,200 farmers were interviewed from Punjab Province of Pakistan (Layyah 130, Muzaffargarh 140, DG Khan 145, Lodhran 160, Multan 140, Rajanpur 155, Bahawalpur 150, and Rahim_Yar_Khan 180) **Table 1**. There are some internal possible factors such as personal characteristics, individual circumstances, and farming practices which are additionally

TABLE 2 | Demographic information of participants.

Characteristic	Category	Districts of Punjab (%)							
		Layyah	Muzaffargarh	DG Khan	Lodhran	Multan	Rajanpur	Bahawalpur	Rahim_Yar_Khan
Gender	Male	85.4	81.4	73.8	75.0	77.1	71.6	74.0	72.2
	Female	14.6	18.6	26.2	25.0	22.9	28.4	26.0	22.8
Age (years)	18–25	17.7	13.6	13.8	15.0	19.3	23.2	22.7	20.6
	26–35	37.7	20.7	37.2	33.1	32.9	34.8	33.3	26.7
	36–45	28.5	43.6	26.2	40.6	32.1	28.4	32.7	41.1
	Above 45	16.2	22.1	22.8	11.3	15.7	13.5	11.3	11.7
Education (years)	0	31.1	23.6	25.5	45.6	52.1	49.0	39.3	30.6
	1–5	43.1	50.0	54.5	40.6	39.3	41.3	34.7	38.9
	6–10	14.6	15.7	11.0	9.4	5.0	7.7	18.7	21.1
	11-above	9.2	10.7	9.0	4.4	3.6	1.9	7.3	9.4
Family size (numbers)	1–2	16.2	25.7	18.6	11.9	19.3	21.9	16.7	11.7
	3–5	43.8	32.9	44.8	39.4	44.3	44.5	48.7	43.9
	6-above	40.0	41.4	36.6	48.8	36.4	33.5	34.7	44.4
Farming present land (years)	1–5	26.2	35.0	46.2	45.0	53.6	49.0	54.0	61.7
	6–10	50.0	32.9	28.3	31.9	20.7	36.1	28.7	28.9
	11–15	10.0	21.4	18.6	15.6	22.1	9.0	12.7	5.6
	16-above	13.8	10.7	6.9	7.5	3.6	5.8	4.7	3.9
Land preparation (use)	Tractor	76.2	55.7	73.8	76.3	53.6	78.1	73.3	63.3
	Bullocks	18.5	35.7	20.0	18.8	42.1	21.3	25.3	34.4
	Both	5.4	8.6	6.2	5.0	4.3	0.6	1.3	2.2
Plowing per year	Once	16.9	3.6	4.1	6.9	8.6	5.8	8.0	5.0
	Twice	70.0	78.6	80.7	61.3	63.6	56.8	45.3	45.0
	Three-more	31.1	17.9	15.2	31.9	27.9	37.4	46.7	50.0
Information sources	Media	25.4	30.7	24.0	18.1	18.6	16.8	14.0	7.8
	Other farmers	31.1	35.0	35.2	31.9	35.7	40.0	36.0	33.3
	Own view	29.2	29.3	29.0	40.0	31.4	32.9	44.0	50.0
	Do not know	12.3	5.0	11.7	10.0	14.3	10.3	6.0	8.9
Are you aware of climate change	Yes	78.5	87.9	82.8	83.1	87.1	74.8	79.3	85.6
	No	21.5	12.1	17.2	16.9	12.9	25.2	20.7	14.4

defined as individual farmers' response and adaption capacity (Udmale et al., 2014).

Table 2 explains the demographic information of all respondents in these eight districts of Punjab province: Layyah 85.4% male and 7% female, Muzaffargarh 81.4% male and 18.6% female, DG Khan 73.8% male and 26.2% female, Lodhran 75% male and 25% female, Multan 77.1% male and 22.9% female, Rajanpur 71.6% male and 28.4% female, Bahawalpur 74% male and 26% female, and Rahim_Yar_Khan 72.2% male and 22.8% female. In all selected districts of Punjab province, the age of most farmers was between 26 and 45 years, which showed that most of them are young, experienced, and active in farming. In most of the districts, farmers' education level was not high, most of them have primary-level education, and some of them have had more than 6 years of education level. The majority of farmers were experienced, and some of them have about five to 10 years of farming experience. Deressa et al. (2009) described that the awareness of the farmer is positively related to farming experience and education. The family size in all districts was a little high; almost all families have more than two children, while most of them have more than five as well, and they consider it labor force in farming. In all eight districts, the majority of the respondents used tractors for plowing land, and some of them used bullocks as well. The percentages of farmers plowing using tractors in all districts are Layyah 76.2%, Muzaffargarh 55.7%, DG Khan 73.8%, Lodhran 76.3%, Multan 53.6%, Rajanpur 78.1%, Bahawalpur 73.3%, and Rahim_Yar_Khan 63.3%. The majority of farmers were plowing twice a year, and the number of people plowing three times a year was not less as well. It is very considerable from where farmers get information for their farming; most of the people said they got information from their co-farmers and particularly old farmers in the same area. To check the farmer's awareness, there was another question "are you aware of climate change," and the response to this question was very satisfactory with Layyah 78.5%, Muzaffargarh 87.9%, DG Khan 82.8%, Lodhran 83.1%, Multan 87.1%, Rajanpur 74.8%, Bahawalpur 79.3% and Rahim_Yar_Khan 85.6% who were well aware of climate change (**Table 2**). The existing literature informed us that farmers' perception of climate change and its impact emphasizes that awareness of climatic risks is mediated by farmland features and farmers' demographic assets (Singh et al., 2017). Knowledge, information sharing, and communication are always beneficial for farmers in decision-making, and it helps them with proper adoption measurement for climate change and associated factors (Drafor and Agyepong, 2005). It is also approved by the existing literature that climate change adaptation techniques used at their farmhouses are concerned by the significance of demographic characteristics and socioeconomics of farmers.

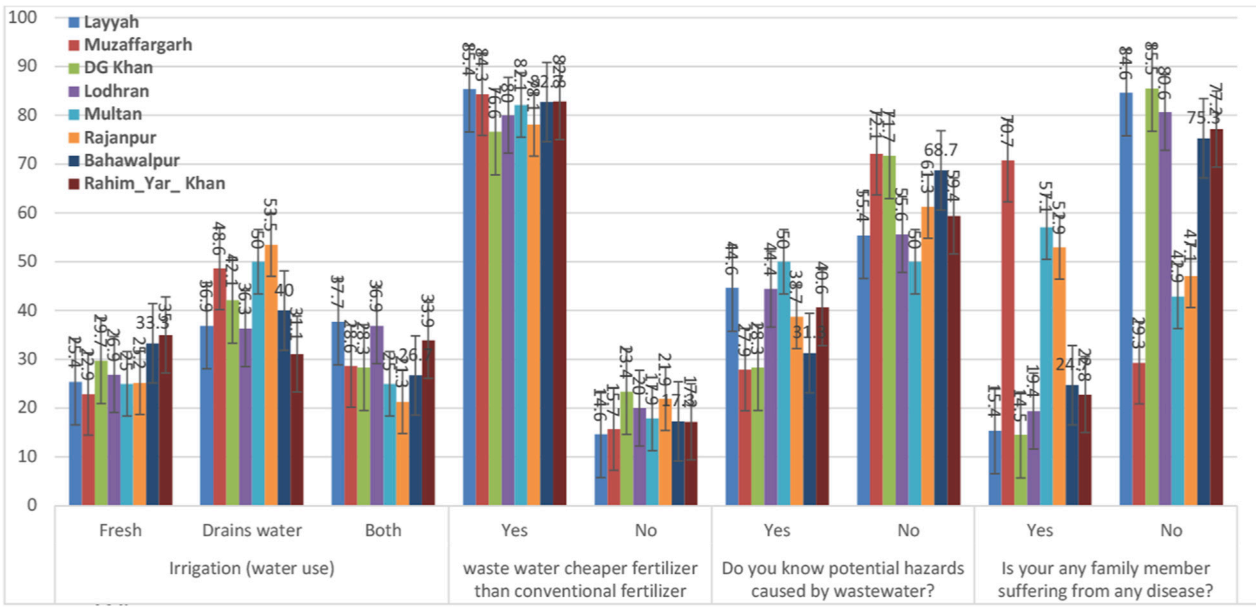

FIGURE 2 | Wastewater use for irrigation (%).

There is not a satisfactory infrastructure for wastewater collection and treatment in Pakistan at any level, especially in South Punjab, Pakistan (Kanwal et al., 2020). Major industries are throwing their wastewater directly into nearby water bodies or cultivated land (Shahid et al., 2020). The climate of Pakistan fluctuates in different parts of the country, and freshwater is very scarce, especially in Sindh and southern Punjab provinces of the country, it is scarce due to the semiarid to arid climate (Shah et al., 2019), the reason why farmers are using canal water, groundwater, and wastewater for crop irrigation. Groundwater for irrigation is expensive and unreliable in Pakistan due to energy crises (Murtaza et al., 2019). Moreover, groundwater is mostly of poor quality in these areas of Pakistan due to enhanced concentrations of soluble salts and toxic metal contents (Murtaza et al., 2019). Due to these reasons, wastewater is commonly used for irrigation in some areas, and considering the current situation, there are many chances that the application of wastewater may increase in the coming years (Shahid et al., 2020). **Figure 2** elaborates on the situation of water used for irrigation purposes. The results of this survey showed that people used drains or both drain and freshwater for irrigation purposes which was average to high in this study area. Some researchers explained that the use of low-quality water for irrigation can have an impact on soil and groundwater quality and can have a bad impact on human health (Bruvold and Crook, 1981). As the usage drains the water, for to know the reasons, there was another question, which was "wastewater is cheaper fertilizer than conventional fertilizer." Most of the responses were in favor of "yes" and accounted for Layyah 85.4%, Muzaffargarh 84.3%, DG Khan 76.6%, Lodhran 80.0%, Multan 82.1%, Rajanpur 78.1%, Bahawalpur 82.7%, and Rahim_Yar_Khan 82.8%. Most farmers added that there are some main reasons for using drain water which were: 1) lower water price, 2) lower cost of the fertilizer, and 3) increase crop production (Mojid et al., 2010). Most of the farmers were unaware of the possible hazards of using drain water which accounted for Layyah 55.4%, Muzaffargarh 72.1%, DG Khan 71.7%, Lodhran 56.6%, Multan 50.0%, Rajanpur 61.3%, Bahawalpur 68.7%, and Rahim_Yar_Khan 59.4, while some districts farmers were aware of possible hazards which accounted for Multan 50.0%, Layyah 44.6%, Lodhran 44.4%, and Rahim_Yar_Khan 40.6% (Carr et al., 2011). If wastewater is easily available for irrigations farmers, they will prefer to use it due to economic benefits; usually, they do not consider human health or environmental risks due to wastewater (Mahfooz et al., 2020; Shahid et al., 2020; Sohail et al., 2021b). Many farmers like to use wastewater due to its positive impact and existence of nutrients for crops, although nutrients level in wastewater are not explored fully (Khalid et al., 2020), and studies have outlined the possible hazards related to the toxic metal buildup in wastewater-irrigated topsoil and on human health (Kanwal et al., 2020, Shahid et al., 2020). Many farmers said that no one in their family suffered from any diseases, while some farmers said that they have some people; but, in three districts, some people were infected with minor to major diseases which accounted for Muzaffargarh 70.7%, Multan 57.1%, and Rajanpur 52.9% (Shahid et al., 2020) (**Figure 2**).

Table 3 describes farmers' lifestyles and assets, for example, motorbikes, tractors/plow, bicycles, spraying device, children going to school, tube well, electric generator, air conditioners, gas generator, car, and pets (Jezeer et al., 2019). In these eight districts of South Punjab province, Pakistan, the majority of farmers have all the aforementioned assets related to their farming and daily life. Some farmers owned tractors for land preparation, but many of them used bullocks, and sometimes rented a tractor for their land preparation.

TABLE 3 | Farmer's livelihood assets.

Characteristic		Punjab (districts)							
		Layyah	Muzaffargarh	DG khan	Lodhran	Multan	Rajanpur	Bahawalpur	Rahim_Yar_Khan
Motorbike	No	48.5	22.1	24.8	30.6	27.9	30.3	36.0	36.7
	Yes	51.5	77.9	75.2	69.4	72.1	69.7	64.0	63.3
Bicycle	No	65.4	77.1	72.4	75.6	68.6	65.2	66.0	60.0
	Yes	34.6	22.9	27.6	24.4	31.4	34.8	34.0	40.0
Tractor/plow	No	41.5	52.0	47.6	25.5	75.7	67.7	68.0	68.3
	Yes	58.5	47.9	52.4	47.5	24.3	32.3	32.0	31.7
Spraying device	No	80.0	78.6	69.7	74.4	76.4	72.9	74.0	63.3
	Yes	20.0	21.4	30.3	25.6	23.6	27.1	26.0	36.7
Tube well	No	47.7	84.3	79.6	80.0	53.6	78.1	82.7	82.8
	Yes	52.3	15.1	24.4	20.0	46.4	21.9	17.3	17.2
Children going to school	No	29.2	26.4	56.6	28.7	35.0	33.5	26.0	20.0
	Yes	70.8	73.6	43.4	71.3	65.0	66.5	74.0	80.0
Electric generator	No	85.4	84.3	75.5	73.8	87.1	78.1	82.7	81.7
	Yes	14.6	15.7	25.5	26.3	12.9	21.9	17.3	18.3
Gas generator	No	79.2	83.6	71.0	70.6	79.3	73.5	77.3	78.3
	Yes	20.8	16.4	29.0	29.4	20.7	26.5	22.7	21.7
Air conditioner	No	71.5	71.4	64.8	65.0	66.4	62.6	72.7	72.8
	Yes	28.5	28.6	35.2	35.0	33.6	37.4	27.3	27.2
Car	No	85.4	82.9	69.0	78.1	77.9	74.2	76.0	77.2
	Yes	14.6	17.1	31.0	21.9	22.1	25.8	24.0	22.8
Pets (dog and horse, etc.)	No	61.5	62.9	45.5	60.6	70.7	58.7	65.3	59.4
	Yes	38.5	37.1	54.5	39.4	29.3	41.3	34.7	40.6

TABLE 4 | Correlation of selected variables.

	Gender	Age group	Education level	Cultivated land	Source of information	Wastewater use (WWU)	Farmers' assets (FA)	Determinants of climate change (DCC)	Adaption measures (AM)
Gender	1								
Age group	0.022	1							
Education level	0.165**	0.052	1						
Cultivated land	**0.202****	0.035	0.047	1					
Source of information	0.011	**0.340****	-0.033	-0.030	1				
Wastewater use (WWU)	**0.419****	0.155**	0.154**	0.118**	0.133**	1			
Farmers' assets (FA)	**0.766****	0.014	0.174**	0.180**	0.021	**0.435****	1		
Determinants of climate change (DCC)	**0.381****	0.034	0.128**	0.072*	0.034	**0.239****	**0.440****	1	
Adaption measures (AM)	**0.449****	0.030	0.128**	0.126**	0.038	**0.284****	**0.466****	**0.269****	1

***Correlation is significant at the 0.01 level (two-tailed).*
**Correlation is significant at the 0.05 level (two-tailed).*

Many other secondary kinds of luxuries, for example, cars, air conditioners, generators, and tube wells in the study area were not available to all farmers, which approved their less luxurious life, showing the compulsions of climate change (Ullah et al., 2013). They are supposed to access the latest technology for farming, and agricultural assets stimulate progress in agriculture and help to lessen poverty (Fahad, et al., 2018). Some researchers indicated that the farmers who were eager to reduce the risk associated with indeterminate climate change had enough resources and had more capacity to adapt (Deressa et al., 2009). The farmers with enough resources and assets regarded themselves as safer and have enough capacity to bear the negative impacts of climate change; additionally, small farmers are always at risk due to natural disasters such as heavy precipitation, droughts, and floods (Qasim et al., 2015; Zhao et al., 2019).

Table 4 and **Figures 3A,B** elaborate on the perception of farmers toward climate change in South Punjab, Pakistan. No doubt impacts of climatic change have become gradually apparent over the past few decades (Patt and Schröter, 2008). The main indicators which were encompassed to check perception were flood, irrigation, droughts, agriculture, drinking water in agriculture areas, soil issues, communication, transportation to the agricultural land, animal diseases, and crop pests. As per response from farmers, the flood rate in Muzaffargarh is 48.6%, DG Khan is 75.9%, and Rajanpur is 70.3% which is high while the rest of the tehsils put it at more moderate or lower rate than that of the study area, but till they were under severe pressure of floods. It means food can be the main threat to the farmers in those areas due to the Indus River. The literature provided sufficient evidence of the impact of high

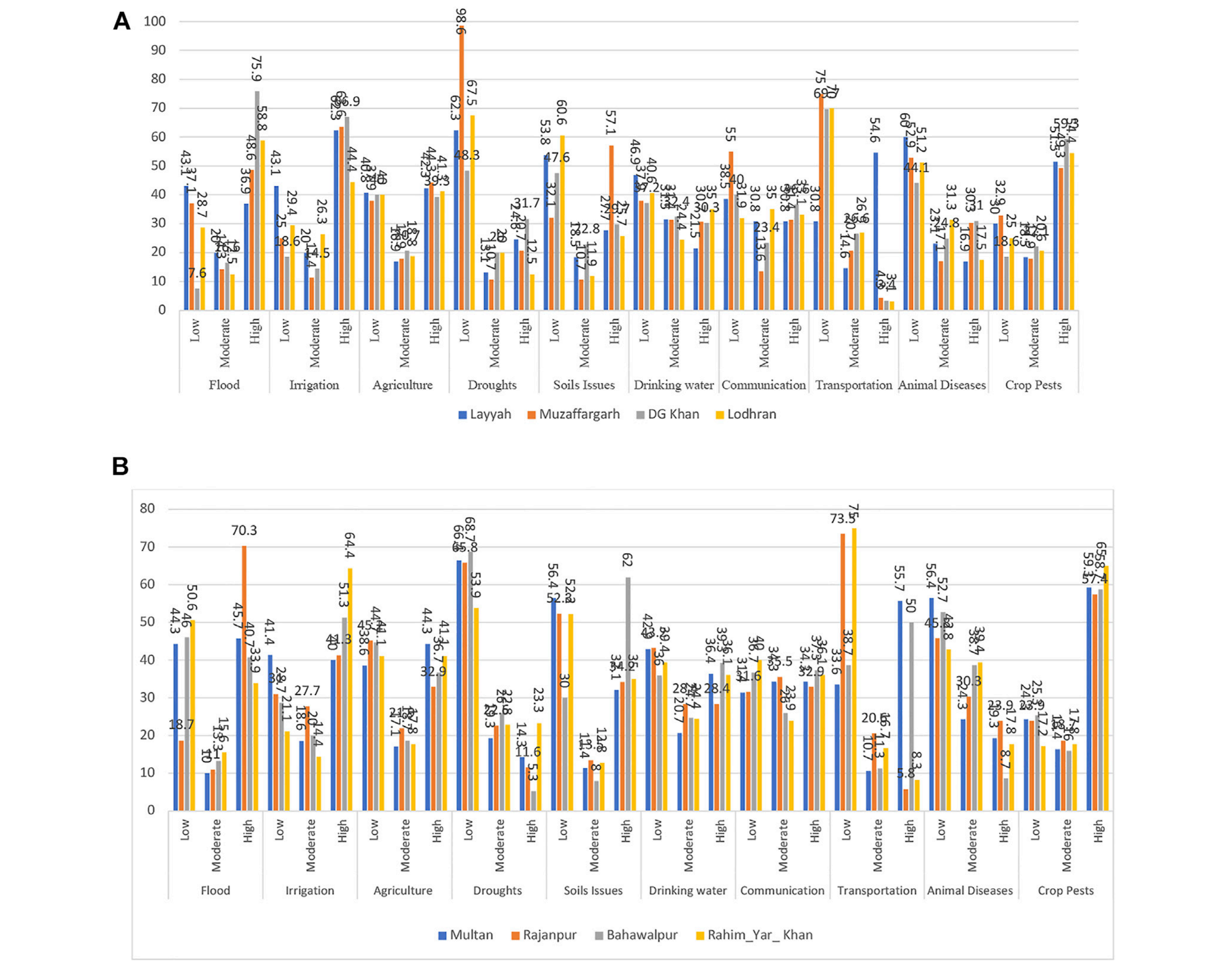

FIGURE 3 | Determining factors of Climate Change (%) in South Punjab Pakistan.

temperatures and floods on farmers' life (Maheen and Hoban, 2017). Pakistan is a developing country and trying to make progress in many sectors, but still like many other developing countries major portion of the population is living under unsatisfactory conditions, particularly farmers who are living in rural disaster areas (Fahad, et al., 2018). There have been many destructive floods in the history of Pakistan in different areas (Hoanh et al., 2006) such as 2010, 2011, and 2014 which caused forestry, damage to livestock, fisheries, infrastructure, fertilizers, animal sheds, and loss of approximately 250,000 farm households, and one million cultivated lands were devastated (NDMA, 2014). Such disasters can be reasons for crop failure, poor yields, and livestock mortality (Harvey. 2014). Soil issues are another main issue for many farmers in South Punjab, Pakistan (Maqbool et al., 2021). As per responses from farmers, soil issues in this study area were low to moderate, but still, some farmers face soil issues which accounted for Layyah 27.7%, Muzaffargarh 57.1%, DG Khan 29.7%, Lodhran 25.7%, Multan 32.1%, Rajanpur 34.2%, Bahawalpur 60.0%, and Rahim_Yar_Khan 35.0% (Javed et al., 2020). Animals are always an important asset for farmers in the whole world, and animal diseases can be another challenge for them (Musungu, 2020). As per the response from farmers, there are some farmers who were facing animal disease problem in South Punjab, Pakistan. Crop pets are going to be severe in South Punjab for some years (Khan et al., 2020). The responses from farmers about crop pets in this study area were high, which accounted for Layyah 51.5%, Muzaffargarh 49.3%, DG Khan 59.3%, Lodhran 54.4%, Multan 59.3%, Rajanpur 57.4%, Bahawalpur 58.7%, and Rahim_Yar_Khan 65.0%.

The present study also included adaption techniques against climate change (**Figure 4**). It is very common among many farmers to choose crop variety, fertilizer adjustment, water, agrotechnical support, and agricultural finance and to deal with livelihood risks (Kuang et al., 2020). It is reported that similar kinds of adaptation measures such as changing planting dates, crop types, changing varieties, and changing input mix are adopted by farmers in Pakistan (Gorst et al., 2015). Sometimes farmers faced problem-

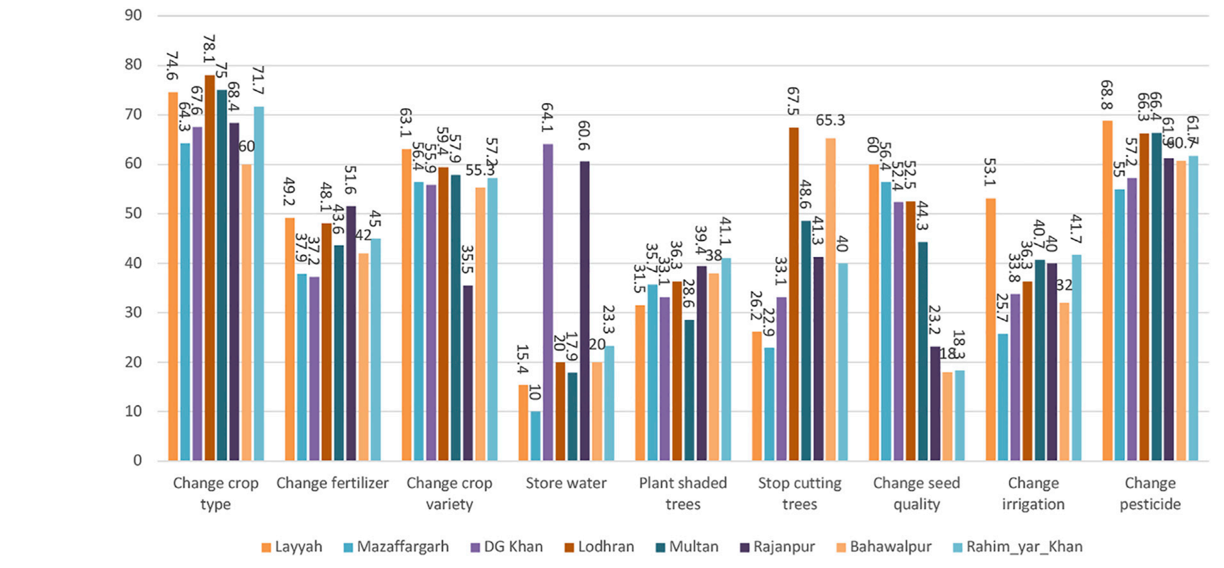

FIGURE 4 | Adaption strategies/measures (%) by farmers in South Punjab, Pakistan.

TABLE 5 | Linear regression table of selected variables.

Variable	Coefficient			t	Sig
	Unstandardized coefficient		Standardized coefficient		
	B	Std. error	Beta		
Animal diseases	0.021	0.008	0.073	2.695	0.007***
Soil issues	0.021	0.006	0.087	3.206	0.001***
Droughts	0.050	0.008	0.176	6.552	0.000***
Flood	0.015	0.007	0.063	2.303	0.021**
Crop pests	0.005	0.007	0.018	0.659	0.510
Store water	0.086	0.013	0.178	6.574	0.000***
Transportation to agriculture land	0.036	0.007	0.134	4.948	0.000***
Drinking water in agriculture areas	0.015	0.007	0.058	2.172	0.030**
Possible potential hazards caused by wastewater	0.070	0.012	0.154	5.662	0.000***

[a]*Dependent variable: adaption measures (AM); significance levels: *= P ≤ 0.10; **= P ≤ 0.05 and; ***= P ≤ 0.01.*

related attacks of pests on crops which is comparatively high in South Punjab for many years, and it may affect production so in different time zones, and they use different techniques to reduce risk (Ishtiaq et al., 2020). It is also stated that in recent times crop production reduction can be due to different plant diseases, climate change, poverty, or irrigation issues (Fahad et al., 2018). The literature showed that small farmers were relatively more vulnerable to adopting climate changes than big farmers (Jamshidi et al., 2019), and the impact of climatic risks on farmer's income, family food, and security was significantly hypothetically stronger by low-resource-endowed being farmers (Shukla et al., 2019), and as per another study in Africa, they indicated it as the first step to the adoption process toward climate change (Trinh et al., 2018). The existing literature described the impact of climate changes on crop production (Hay and Mamura, 2010). Pakistan is an agricultural country, and a major portion of its GDP comes from agriculture, but unfortunately Pakistan recently is dropping its crop production due to climate issues (Tingju et al., 2014). Farmers must learn about climate risks and adoption measures, which can help them to reduce risk rates and can help to increase crop production (Fahad et al., 2018). Meanwhile, physical assets and natural and social assets have positive effects on farmers' adaptation strategies (Kuang et al., 2020).

Table 4 shows the results of descriptive statistics and correlation coefficient of these selected variables (gender, age, education, farming experience, source of information, wastewater use (WWU), farmer's assets (FA), determination of climate change (DCC), and adaption measures (AM)). Correlation is a tool to check the relation between two or more variables. The values of correlation are between +1.00 and -1.00. The strength of the correlation is determined by the magnitude of the number with one being the maximum. In the current study, correlation values of selected variables are significant among all variables, and there is a medium to strong correlation among different variables. Farmers' assets

(FA) with determinants of climate change (DCC) and adaption measures (AM) are highly significant with the correlation values 0.440 and 0.466, respectively, and DCC with AM (0.269). The correlation values for other variables are: gender with cultivated land 0.202, waste water use (WWU) 0.419, farmers' assets (FA) 0.766, determinants of climate change (DCC) 0.381, and adaption measures (AM) 0.449. All variables were found significant with a week to moderate correlation among all selected variables (**Table 4**).

Table 5 shows the results of linear regression among selected variables of the present study. Among explanatory determinants, animal diseases showed significance (p-value of 0.01 and coefficient of 0.073). For instance, as the farmers adopt sufficient measures, they can control diseases among animals, and animals are always basic assets of farmers (Musungu, 2020). In other words, farmers always adopt some measures in different regions to control animal diseases, and there is a significant relationship between farmers' adoption strategies and animal diseases. The variable soil issues is highly significant (with a p-value of 0.001 and coefficient of 0.087). This means that with enough resources and measurement soil issues can be handled. Flood and drought variables have shown a significant relationship with adaption measures [(p-value 0.000 and coefficient 0.176) and (p-value 0.021 and coefficient 0.063), respectively] indicating that adoption measures can be helpful for droughts and floods. Crop pet variable has shown an insignificant relationship (p-value 0.510 and coefficient 0.018). It showed that sometimes farmers are adopting different measures to control crop pets but they are unable to do it; as from last few years, there are a huge number of pets appeared every year, especially in South Punjab, Pakistan. Stored water showed statistical significance with the dependent variable at p-value 0.000 and positive coefficient 0.178 with farm households' adoption measure strategies. The transportation to agriculture and drinking water in agriculture variables have shown a significant relationship with adoption measure at p-value 0.000 and coefficient of 0.134 and p-value 0.030 and coefficient of 0.058, respectively. The variable possible potential hazards caused by wastewater has indicated a significant relationship with the dependent variable at p-value 0.000 and coefficient 0.154; in other words, more good adoption measures and access to information related to hazards of wastewater use can help to reduce the impact of wastewater on human health.

CONCLUSION

Farmers of the study area described that drought, temperature, floods, and variation are the major risks linked with climate change, and it is adversely affecting agriculture in this study area; farmers used some techniques against climate change such as irrigation, seeds, fertilizer, and crops. Pakistan is an agricultural country, and a major portion of GDP comes from this sector, and the majority of the population belongs to farming. Most of the farmers were unaware of the possible hazards of using drain water. Many statistical tools were used to check the relationship among different variables, wastewater use, and any family member suffering from any disease, which showed a significant relation. The farmers with enough resources and assets regarded themselves as safer and have enough capacity to bear the negative impact of change in the climate. In the current study, correlation values of selected variables are significant among all variables, and there is a medium to strong correlation among different variables. This study was limited to one province of Pakistan. But, main results of this research can be implemented in other places as well where the climate change adaptations are still ineffective. The study will help to support the implementation of proper monitoring and public policies to ensure integration and sustainability, and it will aid policymakers to provide support to farmers in their daily life and farming practices.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

MTS: conceptualization, methodology, software, and writing—original draft. EBE: supervision and final draft approval. MI: data collection and analyzing. AA-D: editing and data collection. SM: visualization, and investigation. All authors contributed to the article and approved the submitted version.

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Policy Uncertainty, Financialization and Enterprise Technological Innovation: A Way Forward Towards Economic Development

Yan Zhang[1,2]*, Chengfeng Zhuo*[3] *and Feng Deng*[1]*

[1]School of Economics and Management, Xinjiang University, Xinjiang, China, [2]School of Economics and Management, Shihezi University, Shihezi, China, [3]Institute of Guangdong, Hong Kong and Macao Development Studies, Sun Yat-Sen University, Guangzhou, China

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***Correspondence:**
Feng Deng
dengfengxju@126.com

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Technological innovation is the core factor for enterprises to maintain competitiveness. This paper aims to investigate how policy uncertainty affect enterprises' innovation. On the basis of theoretical analysis, this study selects data from 2008–2017- and a share of non-financial listed companies as the research sample. Using patent data of listed companies and China's economic policy uncertainty (EPU) index, the study examines the impact of EPU on enterprise innovation. In addition, the regulatory effect of enterprise financialization has been investigated. The results show that the EPU can promote the quantity growth of enterprise innovation but inhibit the improvement of enterprise innovation quality. The impact of EPU on enterprise innovation will be affected by enterprise ownership, financing constraint level, life cycle, regional administrative level and regional economic level. Furthermore, enterprise financialization shows a negative regulatory effect in the process of EPU affecting enterprise innovation. This study provides policy enlightenment for reasonably formulating economic policies and promoting enterprise financialization, so as to effectively improve enterprise innovation ability and economic development.

Keywords: policy uncertainty, financialization, technological innovation, economic development, China

1 INTRODUCTION

The COVID-19 pandemic has changed our lives in certain ways (Yang Zhen. et al., 2021; Elavarasan et al., 2021; Ahmad et al., 2022; Huang et al., 2022; Hussain et al., 2022; Wen et al., 2022). In this regard, economic policy is not only an important means for the state to regulate the economy and market, but also an important external condition for enterprises (Yumei et al., 2021; Tang et al., 2022). The frequent adjustment of economic policies by the government can stimulate the investment vitality of enterprises in the short term, but it will also make enterprises to face the uncertainty of the policy environment when making business decisions (Shi et al., 2022; Xiang et al., 2022). According to the global Economic Uncertainty Index data developed by Baker et al. (2016) and jointly released by Stanford University and The University of Chicago, the global EPU Index increased by about 200% from January 2014 to December 2020. The index in December 2020 was much higher than that during the 2008 financial crisis, reaching a record high. China's EPU index was high during 2008–2009, 2011–2012 and 2016–2020. It is closely related to the changes of global economy, China's economic development and many intensive economic policies of Chinese government.

At present, China's economy has shifted from a stage of high-speed growth to a stage of high-quality development (Wu et al., 2021; Irfan and Ahmad 2022; Rauf et al., 2021). The Chinese government emphasizes that adhering to the core position of innovation in the overall modernization, deeply implementing the innovation driven development strategy and improving the technological innovation ability of enterprises (Hao et al., 2020; Hao et al., 2021; Abbasi et al., 2022). How to strengthen the dominant position of enterprises in scientific and technological innovation, improve the independent innovation ability of nation and enterprise, and promote high-quality economic development has become an urgent issue for China. However, finance, real estate and other industries in China have high profit margins compared with the traditional manufacturing industry. The profit seeking characteristics of capital urge enterprises to make a lot of financial investment, while lack enthusiasm for technological innovation and R&D activities. In this context, what impact does financialization have on enterprise innovation in the face of high EPU? Will this impact change with the differences of enterprise ownership, life cycle, financing constraints, regional administrative level and urban economic development? Obviously, the impact of EPU and financialization on enterprise innovation is still an issue worthy of investigation.

2 LITERATURE REVIEW

The existing research on EPU can be divided into two categories. One category of literature studies the impact of EPU on macroeconomic activities. The literatures discussed the impact of EPU on macroeconomic fluctuations, economic recovery, employment, productivity and so on (Caldara et al., 2016). Another category of literature investigates the impact of EPU on micro enterprises' operation, R&D investment and other decision-making activities. The studies have found that when EPU is enhanced, enterprises' cash holding level (Wang et al., 2014), commercial credit financing (Zhang et al., 2020), senior management change (Rao and Xu, 2017), R&D investment behavior (Li and Yang, 2015; Gulen and Ion, 2016; Bhattacharya et al., 2017), the level of financialization (Peng et al., 2018) and investment efficiency (Rao and Xu, 2017) will be affected.

For the impact of economic policy uncertainty on enterprise innovation, the existing literature has the opposite conclusion. Some literatures believe that enterprise R&D investment is positively correlated with macro EPU (Meng and Shi, 2017; Irfan et al., 2019; Irfan et al., 2020). EPU has incentive effect and selection effect on enterprise innovation. EPU can affect the enterprise R&D investment and patent application. At the same time, the relationship between EPU and innovation will be affected by the characteristics of enterprises, such as the ownership, government subsidies and financing constraints (Gu et al., 2018). Uncertain policy environment will encourage enterprises to carry out innovation investment as early as possible to obtain future growth options, thus promoting enterprise innovation activities (Liang and Xie, 2019). In addition, Yang C. et al. (2021) explored the internal mechanism between EPU and enterprise innovation from the perspective of corporate social responsibility, and found that EPU had a more significant impact on enterprise invention patent, namely substantive innovation. Yang H. C. et al. (2021) found that EPU has a positive effect on R&D input and innovation output of family business. The literature holds negative views believes that EPU will increase the bank credit risk and make the enterprise have to face strong financing constraints, thus having obvious inhibitory effect on enterprise technological innovation (Zhang and Feng, 2018). The lack of financing capacity caused by macroeconomic uncertainties will limit the improvement of enterprises' R&D and innovation (Pan and Dong, 2021). In addition, EPU will significantly reduce the product innovation, increase the proportion of service business, promote the transformation of manufacturing enterprises to services (Zhang et al., 2019). Regarding the research question whether economic policy uncertainty can promote enterprise innovation, although there are a lot of research results, there is not a relatively consistent conclusion. When facing the uncertainty of external economic policies, do enterprises with different characteristics have the strategic choice of actively seeking change? Whether there are different innovation behaviors and different innovation outcomes is also the question that this paper considers and tries to answer.

With the continuous attention to financialization in the academic world, scholars at home and abroad have begun to discuss the impact of corporate financial investment on corporate technological innovation. Scholars have not reached a consensus on the impact of financialization on enterprise innovation. Some literatures believe that increasing the investment proportion of financial assets will crowd out the funds for technological innovation, so that enterprises lack sufficient funds for R&D innovation, which will have a restraining effect on enterprise innovation (Wang et al., 2017; Duan and Zhuang, 2021). Other studies show that enterprises can increase the liquidity of assets by using idle funds for short-term financial investment, which can not only realize the maintenance and appreciation of capital, but also bring more investment income, thus alleviating the financing constraints and promoting enterprise innovation (Bonfiglioli, 2008; Yang et al., 2019). In addition, financial investment may also indirectly promote R&D innovation by improving enterprise performance.

Through reviewing the above literature, we find that the existing literature mainly investigates the impact of EPU on enterprise innovation investment, new product sales revenue or the total number of patents. However, there is a lack of analysis from the dual perspective of innovation quantity and innovation quality. Especially, less attention has been paid to the impact of EPU on enterprise innovation with different characteristics. In addition, there is no consensus on the impact of financialization on enterprise innovation.

The marginal contribution of this study lies in three aspects. Firstly, this study investigates the innovation effect of EPU from the dual perspective of innovation quality and innovation quantity, thus enriching the research scope of existing literature and deepening the understanding of EPU. Secondly, this study includes financialization into the analysis of the

innovation effect of EPU, and examines the complex relationship between financialization, EPU and enterprise innovation. It not only expands the relevant research perspective, but also provides a reference for enterprises to reasonably allocate financial assets in the face of EPU. Thirdly, this study investigates the differences in the innovation effects of EPU among different types of enterprises. It not only helps to enrich the understanding of the EPU's innovation effect, but also provides inspiration for different types of enterprises to make scientific innovation strategies in the face of EPU.

The rest of this paper is arranged as follows: The third part contains theoretical analysis and research hypothesis. The fourth part is about research design. The fifth part includes the estimation result and robustness test of the basic model. The sixth part contains further research. The last part is about the conclusion and enlightenment of this paper.

3 THEORETICAL ANALYSIS AND RESEARCH HYPOTHESIS

3.1 EPU and Enterprise Innovation

Facing the uncertainty of economic policy, enterprises cannot accurately predict whether, when and how the government will change the current economic policy (Gulen and Ion, 2016). EPU is an important part of economic uncertainty. The objective existence of economic policy uncertainty will have a profound impact on macro-economy and micro enterprise behavior. The continuous adjustment of policies and the differences in the interpretation and implementation of policies by local governments will also bring a certain degree of uncertainty to enterprise operations. Theoretically, if we only rely on the market mechanism to allocate resources, it may lead to problems such as uneven resource distribution and income gap. Therefore, the government needs to adopt corresponding economic policies to overcome or make up for the defects of resource allocation by market mechanism. However, due to the change of market environment and the objective existence of information asymmetry, the government is often unable to make accurate judgment in time. The decision-making and implementation of economic policies often lags behind the changes of the market. Then there is the distortion of resource allocation, which makes enterprises lack of effective incentive mechanism (Lin et al., 2010; Chen et al., 2011).

As a high-risk and high-yield activity, innovation has the characteristics of high R & D cost, long R&D cycle and low success probability. Enterprises are not only the main body of economic activities, but also the main body of innovation activities. They have the demand to transform technical advantages into product advantages, transform innovation achievements into commodities, and get returns through the market. The output of enterprise innovation not only has the form of goods, but also appears in the form of knowledge products such as patents and proprietary technologies. The benefits of technical knowledge and information cannot be fully occupied by individuals alone (Arrow, 1962), but show strong positive externalities through spillover effects. However, it is this spillover effect that makes other enterprises have "free riding" behavior and carry out "imitation innovation" or "follow-up innovation". This will undoubtedly reduce the motivation of enterprises to carry out independent innovation and breakthrough innovation, and make the innovation activities evolve into a waiting game (Guo, 2018).

When faced with the EPU, the business environment of enterprises will become more complex. Enterprise managers have more difficulty in predicting the changing trend of the market, thus increasing the operating risk and making it more difficult for enterprises to obtain credit resources from banks and other financial institutions. The rise of financing costs increases the uncertainty of corporate profits. Due to financing constraints and risk aversion, enterprises will reduce investment and restrain technological innovation activities (Zhang et al., 2019). However, Bloom (2007) pointed out that although uncertainty brings short-term negative impact on employment, productivity and investment, its impact on enterprise R&D innovation may be different from other economic activities. He also pointed out that the relationship between EPU and firms' R&D and innovation activities is a very important topic that needs to be further studied theoretically and empirically. Gu et al. (2018) showed that EPU had a positive impact on the enterprise R&D investment and patents. Policy uncertainty will encourage enterprises to implement innovation investment as soon as possible to obtain future growth options, thus promoting enterprises innovation.

The above analysis shows that the impact of EPU on enterprises will vary according to specific behaviors such as enterprise investment, financing behavior or technological innovation. Its impact on enterprise innovation may be different from that on enterprise general investment behavior. Although the increase of EPU inhibits enterprises' physical capital investment (Li and Yang, 2015), enterprises may transfer part of their investment to R&D input, thus promoting the quantity of enterprises' innovation output. Innovation is an effective means for enterprises to gain market share and excess profits. When enterprises are faced with market competition and external EPU, they will increase their investment in innovation to strengthen their market power. However, when enterprises face too high EPU, they will weigh the risks and benefits of innovation. Out of caution, enterprises are more willing to carry out "imitation innovation" or "follow-up innovation" and reduce investment in "breakthrough innovation" with high capital demand and high risk. This makes enterprises pay more attention to the quantity growth of innovation rather than the quality improvement of innovation. Therefore, this paper proposes H1:

H1: EPU has a positive effect on the quantity growth of innovation, and a negative effect on quality improvement of innovation.

3.2 EPU, Financial Investment and Enterprise Innovation

In the process of EPU affecting enterprise innovation, enterprise financialization plays a regulatory role. On the one hand, the

increase of EPU will make it difficult for enterprises to accurately predict future market demand, thus increasing the uncertainty of corporate cash flow. For the precautionary demand, enterprises will use idle funds for financial investment, increasing the liquidity and revenue of assets. Technological innovation is a process that requires continuous and large investment. Financial investment can create a capital "reservoir" to deal with the capital shortage in the long-term R&D activities (Yang et al., 2019). The rate of return brought by financial investment is generally high. Financial investment can significantly improve the financial performance of enterprises, alleviate the financing constraints of enterprises, and then promote enterprises to pursue the improvement of innovation quality. However, on the other hand, the rise of EPU may lead to a decline in the profits of non-financial industries. As a result, more and more non-financial enterprises choose to invest in financial products, thus crowding out the resources of enterprises for technological innovation (Wang et al., 2017). For enterprise managers, investing in financial products with higher returns can improve business performance in the short term. Therefore, managers have sufficient motivation to reduce investment in R&D activities with long cycle, high cost and high risk, which will eventually inhibit enterprise innovation.

When the uncertainty of economic policies increases, enterprises will choose to hold more financial assets to cope with the uncertainty of cash flow and reduce operational risks (Duchin et al., 2017), which will further enhance the trend of corporate financialization and affect enterprise innovation. On the one hand, the continued to decline in the real economy profit and income under the continuous rise in the overall environment of financial assets, non-financial enterprises to carry out a large number of financial asset investment behavior, will continue to use enterprise resources for technology innovation, crowding out effect on corporate r&d, make enterprises lack enough money for product research and development of innovation and equipment update, Leading to the decline of enterprise innovation output; on the other hand, when enterprises face the uncertainty of external environment and policy, in the face of increasing financial investment, enterprises will be more eager to gain more market share through technical innovation and the excess profit, enterprises under the condition of the limited research and development through compression "strategic innovation" project investment, increasing the financial input in "real innovation" project, In order to increase their core competitiveness, enhance the value of enterprises, and make the innovation quality of enterprises rise. Based on the above analysis, we propose hypothesis H2:

H2: In the process of the impact of economic policy uncertainty on firm innovation, financial investment has a negative moderating effect.

4 RESEARCH DESIGN

4.1 Sample Selection and Data Sources

This paper selects A-share listed companies from 2008 to 2017 as research samples. The data mainly come from CSMAR database, Wind database and The National Intellectual Property Office database. The product innovation data comes from the patent database of listed companies and subsidiaries provided by CSMAR and The National Intellectual Property Office database. The data used to measure the EPU comes from the *Uncertainty Index of China's Economic Policy* developed by Baker et al. (2016). Considering the availability, validity and quality of data, this paper eliminated the samples as follows: 1) ST and *ST enterprises were eliminated; 2) Exclude financial and insurance enterprises; 3) Eliminate enterprises with missing core variables. In order to reduce the influence of extreme values on regression results, the continuous variables at the enterprise level were treated with 1% bilateral tail shrinking.

4.2 Definition of Variables

4.2.1 Explained Variable: Enterprise Innovation

Existing literature often adopts R&D input, innovation output and innovation efficiency to measure enterprise innovation. Innovation output can be measured by patent output or sales revenue of new products. In this study, patent output is used to measure the enterprise innovation. Patent types include invention patent, utility model patent and design patent. Among them, invention patents have the highest technical content and innovation level. It needs substantive examination. The technical content of utility model patents and design patents is relatively low, and only need to pass the formal examination. Their application authorization rate is close to 100%. The patent data used in this paper comes from the patent database of listed companies and subsidiaries provided by CSMAR. The patent query system of the China National Intellectual Property Database is used to check and verify the patent data of listed companies and subsidiaries. This paper uses the logarithm of "total number of patent applications +1″ to measure the quantity of enterprise innovation (*Innovnum*), and uses the proportion of invention patent applications in total patent applications to measure the quality of enterprise innovation (*Innovqua*).

4.2.2 Explanatory Variable: Economic Policy Uncertainty (EPU)

The *Economic Policy Uncertainty Index* developed by Baker et al. (2016) and published regularly by Stanford University and the University of Chicago covers major economies around the world. The index uses the media's attention to the uncertainty of economic policy to infer the EPU faced by microeconomic subjects. Baker et al. (2016) used text retrieval and filtering methods to measure China's EPU index with the Hong Kong South China Morning Post as the retrieval platform for news reports. Referring to Meng and Shi, 2017 and Zhang et al. (2019), this paper uses the geometric mean of monthly EPU index as the annual EPU. In addition, this paper uses the arithmetic mean of monthly EPU index as the explanatory variable in the robustness test.

4.2.3 Moderating Variable: Financialized Investment

At present, there is no unified view on how to measure the level of enterprise financialization. Most of the existing literatures

TABLE 1 | Variable definitions and descriptive statistical results.

Variables	Definition	obs	Mean	Std	Max	Min
Innovnum Innovqua	Take the log of the total number of patent applications plus 1	12,400	2.062	1.899	6.967	0
EPU	Number of invention patent/total number of patent	12,400	1.480	1.649	1	0
Fin	EPU index level of financialization	12,400	196.811	92.875	364.83	98.89
Soe	Nature of property right	12,400	0.204	0.147	1	0
Cf	Financing constraints (SA index)	12,400	0.587	0.492	1	0
Size	Enterprise scale	12,400	-3.234	2.891	9.688	−14.65
Roa	Enterprise age	12,400	22.234	1.411	26.135	18.874
Lev	Return on total assets	12,400	204.725	61.602	354	60
Fixs	Asset-liability ratio	12,400	0.038	0.061	0.245	−0.191
Inco	Fixed assets ratio	12,400	0.375	0.288	0.964	0
Cen	Main business income	12,400	0.252	0.189	0.765	0.001
Eco	Equity concentration	12,400	21.575	1.623	25.616	16.547
Gov	Level of urban economic development	12,400	0.360	0.155	0.761	0.084
Inv	Proportion of financial expenditure	12,400	11.107	0.584	12.129	9.418
—	—	12,400	0.156	0.065	0.464	0.066

Data source: Author calculates and collates according to Stata software.

measure it from the perspective of asset allocation and investment return. This paper aims to explore the regulatory effect of financialization on enterprise innovation under the influence of EPU. Therefore, this paper defines the enterprise financialization from the perspective of financial asset allocation. Based on Wang et al. (2017) and Duan and Zhuang, 2021, this paper uses the proportion of enterprise financial assets in total assets to measure enterprise financialization. Enterprise financial assets mainly include monetary capital, trading financial assets, available for sale financial assets, investment real estate, held to maturity investment, dividends receivable and dividends receivable.

4.2.4 Control Variables

The selection of control variables in this paper mainly refers to the research of Gu et al. (2018) and Zhang et al. (2019). The size, age, return on assets, leverage ratio, fixed assets ratio, main business income and ownership concentration of enterprises are selected as control variables at the enterprise level. The level of economic development, proportion of financial support and proportion of fixed asset investment were used as control variables at the regional level. Where, enterprise *Size* is measured by the natural logarithm of the company's total assets. The *Age* of the enterprise is calculated from the year when the enterprise is established. Return on total assets (*ROA*) is related to corporate profitability and asset utilization efficiency, and is expressed by net profit/total assets. The leverage ratio (*Lev*) is related to corporate financial risk, the higher the leverage ratio is, the greater the financial risk is. Fixed assets ratio (*Fixs*) adopts fixed assets to total assets ratio. Main business income (*Inco*) is expressed logarithmically. Equity concentration (*Cen*) is the sum of the previous three shareholders' shareholding ratio. The level of economic development (*Eco*) is logarithmic with per capita GDP. Fiscal expenditure ratio (*Gov*) adopts the ratio of local government fiscal expenditure to GDP. Fixed asset investment ratio (*Inv*) adopts the ratio of total fixed asset investment to GDP. **Table 1** reports the definitions and descriptive statistical results of all variables. It can be seen from **Table 1** that the logarithmic mean of total patent applications from 2008 to 2017 is 2.062, the logarithmic mean of invention patents is 1.480 and the logarithmic mean of non-invention patents is 1.623. It shows that there is no obvious quantitative difference between invention patents and non-invention patents among the listed companies in China. The maximum value of the EPU index is 364.83, and the minimum value is 92.875, indicating that the EPU index of China changes greatly from 2008 to 2017, and the degree of uncertainty is relatively obvious.

4.3 Model Construction

In order to test the impact of EPU on enterprise innovation, this paper refers to Zhang et al. (2019) and establishes the following basic regression model:

$$Innovnum_{it} \Big/ Innovqua_{it} = \alpha_0 + \alpha_1 \, EPU_{it} + \sum controls_{it} + FirmFE + YearFE + \varepsilon_{it} \tag{1}$$

Among them, *Innovnum* represents the quantity of enterprise innovation and *Innovqua* represents the quality of enterprise innovation. *EPU* represents the uncertainty index of economic policy. ε_{it} is the error term. $\sum$ *Controls* are a series of enterprise and regional control variables, including: *Size*, *Age*, *Roa*, *Lev*, *Fixs*, *Cen*, *Inco*, *Eco*, *Gov* and *Inv*. *FirmFE* and *YearFE* represent individual fixed effect and time fixed effect, respectively. We mainly focus on the coefficient α_1, which reflects the impact of EPU on the quantity and quality of enterprise innovation.

5 EMPIRICAL RESULTS ANALYSIS

5.1 Benchmark Regression Results

Table 2 reports the regression results of EPU on enterprise innovation. Columns 1) and 2) do not add control variables. Columns 3) and 4) add enterprise-level control variables. Columns 5) and 6) add all control variables. The regression results show that EPU has a significant positive effect on the quantity of enterprises' innovation and a significant negative effect on the quality of enterprises' innovation. The regression

TABLE 2 | Regression results of EPU and firm innovation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Innovnum	Innovqua	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.291***	−0.019***	0.001	−0.008***	0.021*	−0.007**
—	(32.83)	(−8.15)	(0.08)	(−2.69)	(1.86)	(−2.07)
Scale	—	—	0.322***	0.027***	0.320***	0.027***
—	—	—	(12.53)	(3.82)	(12.47)	(3.78)
Age	—	—	0.008***	0.001***	0.007***	0.001***
—	—	—	(21.30)	(6.71)	(13.63)	(4.62)
Lev	—	—	0.054	−0.054**	0.052	−0.053**
—	—	—	(0.62)	(−2.21)	(0.59)	(−2.20)
Roa	—	—	0.399**	0.014	0.418**	0.015
—	—	—	(2.37)	(0.30)	(2.48)	(0.32)
Fixs	—	—	−0.053	−0.068**	−0.067	−0.069**
—	—	—	(−0.55)	(−2.51)	(−0.69)	(−2.55)
Inco	—	—	0.046**	0.004	0.047**	0.005
—	—	—	(2.21)	(0.77)	(2.26)	(0.80)
Cen	—	—	−0.912***	−0.071**	−0.927***	-0.071**
—	—	—	(−7.43)	(−2.06)	(−7.56)	(−2.09)
Eco	—	—	—	—	0.101**	0.003
—	—	—	—	—	(2.38)	(0.28)
Gov	—	—	—	—	−0.771**	−0.069
—	—	—	—	—	(−2.11)	(−0.68)
Inv	—	—	—	—	0.242***	0.025
—	—	—	—	—	(4.15)	(1.53)
FirmFE	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,400	12,400	12,400	12,400	12,400	12,400
R^2	0.088	0.066	0.242	0.271	0.247	0.282

*Note: The numbers in brackets are robust standard errors of clustering to enterprises, ***means* $p < 0.01$*, **means* $p < 0.05$*, *represents* $p < 0.1$*. The following tables are the same. Data source: Author calculates and collates according to Stata software.*

result verifies H1. As mentioned above, when facing the EPU, enterprises are more willing to enhance their core competitiveness, improve market share and obtain more profits by increasing R&D investment and strengthening the innovation ability of products and technologies. Therefore, the quantity of enterprise innovation will increase. At the same time, with the increase of EPU, the risk and uncertainty of enterprises carrying out innovation activities increase. Motivated by prudence, enterprises are more willing to carry out "follow-up innovation" than breakthrough innovation with high risk, long cycle and high investment, which reduces the innovation quality of enterprises. The coefficients of control variables indicate that the larger the scale of the enterprise, the greater its innovation output. The reason lies in that large companies have resource advantages and stronger technological innovation ability. In addition, the results show that the older the firm, the more innovative it is. The higher the main business income and the higher the rate of return on total assets, the greater the number of innovation output. The more concentrated the equity, the smaller the quantity and quality of innovation. Moreover, regional economic development has positive impact on the quantity of enterprise innovation.

5.2 Robustness Test

In order to ensure the reliability of the benchmark regression results, a series of robustness tests were conducted in this paper.

5.2.1 Replace the Explained Variables

In the benchmark regression, we use the patent applications to calculate the quantity and quality of innovation. In the robustness test, we replace the patent applications with patent authorization, and use the same calculation method to calculate the quantity and quality of enterprise innovation. The regression results are shown in columns 1) and 2) of Table 3a.

5.2.2 Replace Core Explanatory Variables

Referring to Meng and Shi, 2017, the arithmetic mean of monthly EPU index is used as the new explanatory variable in the robustness test. The regression results are shown in columns 3) and 4) of Table 3a.

5.2.3 Further Reduce the Impact of Extreme Values

The core variables were treated with bilateral tail shrinking on the 5% quantile to further reduce the impact of extreme values on the estimated results. The regression results are shown in columns 5) and 6) of Table 3a.

5.2.4 Add Control Variables

Referring to Li and Yang, 2015, this paper further added the regional research support (*Scisup*) and regional financial development (*Finc*) into the regression model. The regression results are shown in columns 1) and 2) of Table 3b.

TABLE 3 | Robustness tests.

Table 3a

Variables	Quantity of patents granted		Arithmetic mean of EPU		Shrink 5%	
	(1)	(2)	(3)	(4)	(5)	(6)
	Innovnum	Innovqua	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.021*	−0.055***	0.016	−0.006*	0.022*	−0.007**
—	(1.89)	(−18.42)	(1.41)	(−1.95)	(1.94)	(−2.13)
Control	Yes	Yes	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,400	12,400	12,400	12,400	12,400	12,400
R^2	0.276	0.291	0.247	0.228	0.236	0.218

Table 3b

Variables	Add control variables		Manufacturing samples		Tobit regression	
	(1)	(2)	(3)	(4)	(5)	(6)
	Innovnum	Innovqua	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.010	−0.008**	−0.022	−0.015***	0.692***	−0.106***
—	(0.93)	(−2.46)	(−1.47)	(−3.32)	(11.29)	(−6.66)
Control	Yes	Yes	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,400	12,400	6,730	6,730	12,400	12,400
R^2	0.236	0.227	0.317	0.233	0.191	0.210

5.2.5 Use Manufacturing Samples

The non-manufacturing enterprises were further removed from the whole samples, and 6,730 manufacturing sample enterprises were retained for robustness test. The regression results are shown in Columns 3) and 4) of Table 3b.

5.2.6 Change Estimation Method

Since the quantity of enterprise patents is non-negative and there is a large number of zero values, this paper chooses Tobit model for robustness test. The regression results are shown in columns 5) and 6) of **Table 3**.

The results of Table 3a and 3b show that after a series of robustness tests, the regression results of core explanatory variables are consistent with the results of benchmark test. It shows that our benchmark test is reliable. EPU can improve the quantity of enterprise innovation, but it does not improve the quality of enterprise innovation.

5.2.7 Discussion on Endogeneity

For enterprises, EPU is an exogenous variable. Therefore, a single enterprise cannot affect EPU in reverse. Nevertheless, in order to be robust, this paper refers to Zhang et al. (2019) and selects India's EPU as the instrumental variable of China's EPU for analysis. The reason is that India and China have similarities in economic development and policy environment. At the same time, there are close trade ties between China and India. This makes the two countries have similarities in the formulation and implementation of economic policies. We use the two-stage least square method (IV-2SLS) to estimate the parameters. The results are shown in **Table 4**. It can be seen that the coefficient of EPU has not changed significantly, which also shows that the benchmark conclusion of this paper is still valid after dealing with the endogenous problem.

TABLE 4 | Discussion on endogeneity.

Variables	(1)	(2)
	Innovnum	Innovqua
EPU	1.782***	−0.154***
—	(1.230)	(−2.125)
Control	Yes	Yes
FirmFE	Yes	Yes
YearFE	Yes	Yes
Observations	12,400	12,400
Anderson canon. corr. LM	0.000	0.000
Cragg-Donald Wald F	752.38	500.37

Note: Anderson canon. corr. LM, represents the p *value corresponding to this statistic. Cragg-Donald Wald F represents the value of the statistic.*

6 FURTHER ANALYSIS

6.1 Heterogeneity Analysis

The impact of EPU on enterprise innovation would be heterogeneous due to the differences of enterprises' characteristics (Zhang et al., 2019). This paper holds that the innovation effect of EPU will be affected not only by the characteristics of the enterprise, but also by the characteristics of the region where the enterprise is located. The following is to study the heterogeneous innovation effect of EPU from the perspective of enterprise characteristics such as ownership, financing constraints and life cycle, as well as regional

TABLE 5 | Heterogeneity of firm ownership.

Variables	State-owned enterprises		Private enterprises	
	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.027*	−0.004	0.017	−0.010*
—	(1.85)	(−0.93)	(0.94)	(−1.93)
Control	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
Observations	7,280	7,280	5,120	5,120
R^2	0.271	0.226	0.225	0.234

characteristics such as the regional administrative level and the regional economic development.

6.1.1 From the Perspective of Enterprise Characteristics

1) Heterogeneity of enterprise ownership. The results of **Table 5** show that the EPU has a significant positive effect on the quantity of innovation of State-Owned enterprises, and doesn't have significant effect on the quality of State-Owned enterprises. when it comes to private enterprises, the impact of EPU on the quantity of innovation is not significant, while the impact on the quality of innovation is significantly negative. The reason for this result is that compared with private enterprises, state-owned enterprises have convenient policy information channels in resource allocation and can obtain the government's policy guidance in time. At the same time, most of the executives of state-owned enterprises are directly appointed by the government, which makes them think more about being responsible to the government than to the long-term development of enterprises. Therefore, state-owned enterprises are often unwilling to bear the uncertainty and risk of R&D activities (Li and Yu, 2012), and prefer to pursue utility patents and design patents with relatively low risk. When private enterprises are faced with high EPU, they will reduce the capital investment of invention patents due to capital constraints and consideration of financial security. Therefore, the innovation quality of enterprises has declined. The difference of ownership will influence the resource allocation of enterprises, and then lead to different responses to the EPU. China's private enterprises often face serious "credit discrimination" in the process of financing. Bank credit, government subsidies, land supply and other resources will be allocated more to state-owned enterprises, significantly increasing the R&D input of state-owned enterprises. However, the private enterprises are difficult to obtain the bank credit (Zhang et al., 2012).
2) Heterogeneity of financing constraint. Enterprise's internal research and development, technology innovation activities can produce a large number of capital requirements, sustainable, when the enterprise funds nervous, facing serious financing constraints, the enterprise will be limited number of priority funds for daily operation activities and short-term profitability good projects, reduce spending on research and development makes the enterprise technology innovation levels drop. Based on the method of Hadlock & Pierce (2009) [31], this paper uses SA index to measure the degree of financing constraints faced by enterprises. *SA* index can be calculated as follows: $SA = 0.737\, Size + 0.043\, Size^2 - 0.04\, Age$. In this formula, *Size* is the enterprise scale, and *Age* is the age of the enterprise. The smaller the *SA* index is, the smaller the financing constraint is. We use *SA* index to measure the financing constraint of enterprises.

According to the median of financing constraints, enterprises are divided into strong financing constraint enterprises and weak financing constraint enterprises. The estimated results are shown in **Table 6**. The results show that, for enterprises with weak financing constraints, EPU has a significant positive impact on the quantity of enterprise innovation and a significant negative impact on the quality of enterprise innovation. For enterprises with strong financing constraints, EPU has a significant positive impact on the quantity of innovation, but not on the quality of innovation. The reason for this result is that when financing constraints are weak, enterprises have cash flow that can be used for R&D investment. However, in the face of higher EPU, enterprises may choose to carry out R&D activities with lower risk and reduce the investment in invention patents. This makes the quantity of enterprise innovation increase, while the quality of innovation decreases. Zhang et al. (2012) found that financing constraints have a negative effect on enterprises' R&D investment. Pan and Dong (2021) believe that insufficient financing capacity caused by macroeconomic uncertainties would limit the improvement of enterprises' innovation level. Yu et al. (2019) found that when the degree of macro policy uncertainty is high, enterprises will increase their cash holdings. Therefore, with the rise of EPU, the business risk of enterprises increases and enterprises prefer to invest in financial assets with higher returns. When the financing constraints faced by enterprises are small, enterprises have more funds for financial asset investment. Therefore, enterprises' investment in financial assets is actually an occupation of innovation resources (Duan and Zhuang, 2021). In addition, the government should focus on overcoming the financing constraints for private enterprises (Ren et al., 2021).

3) Heterogeneity of life cycle. Life cycle theory points out that the scale, investment, financing strategy, profitability, growth and R&D willingness of enterprises will be significantly different at different development stages. There are many methods to define enterprise life cycle in existing literature (Anthony and Ramesh, 1992; Dickinson, 2011). Referring to Dickinson's method, this paper divides samples into three types: growth stage enterprises, mature stage enterprises and decline stage enterprises. The Dickinson's method measures the life cycle of enterprise through the combination of the net cash flow of operation, investment and financing activities. It can not only avoid the interference of industry differences, but also avoid the subjective assumption of enterprise life cycle distribution. It has strong objectivity. We conduct grouping regression for enterprises with different life cycles. The results are shown in **Table 7**. It shows that EPU has a heterogeneous impact on the

TABLE 6 | Heterogeneity of firm financing constraints.

Variables	Weak financing constraint		Strong financing constraint	
	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.051***	−0.010**	0.027*	−0.004
—	(2.97)	(−2.03)	(1.76)	(−0.88)
Control	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
Observations	6,274	6,274	6,126	6,126
R^2	0.295	0.227	0.190	0.228

innovation of enterprises with different life cycles. EPU has no significant impact on the innovation quantity of growth enterprises, but has a significant negative impact on the innovation quality. EPU has no significant impact on the innovation of mature and decline enterprises. The reason may be that compared with the enterprises in the mature and decline periods, the growth enterprises need to make more investment in production and operation, thus crowding out the investment of R&D activities and making the proportion of invention patents relatively low. Enterprises in different development stage have differences in their ability to acquire resources for innovation (Xie and Fang, 2011).

6.1.2 Regional Characteristics Perspective

1) Heterogeneity of regional administrative levels. China's regional administrative level reflects the structure of state power allocation. The essence of many regional development imbalances is the imbalance of resource allocation among regions. Many provinces in China have successively implemented the strategy of developing central cities, which promotes the allocation and agglomeration of resources to the provincial capital and central cities, and then forms a strong squeeze effect and siphon effect on other cities in the province.

Referring to the national standards of administrative divisions, we define the municipalities directly under the central government, provincial capital cities, sub-provincial cities as high-level cities. The rest of the city is defined as a low-level city. At the same time, according to the administrative level of the city where the enterprise is located, the sample enterprises are further divided into high-level enterprises and low-level enterprises. The estimated results are shown in **Table 8**. As can be seen, EPU has significant positive impact on the innovation quantity of high-level enterprises, and has negative but insignificant impact on the innovation quality. In addition, EPU has no significant impact on the quantity and quality of innovation of low-level enterprises. It means that the impact of EPU on the innovation of enterprise in cities with different administrative levels is heterogeneous. Jiang et al. (2018) found that compared with lower-level cities, enterprises in high-level cities have more government subsidies, greater talent advantages, more financing facilities and smaller local tax burden.

2) Heterogeneity of regional economic development. Since the Reform and Opening up, China's economy has been growing at a high speed, but it has also shown a significant regional imbalance. The level of economic development and innovation in the Yangtze River Delta, the Pearl River Delta and the Bohai Rim are significantly higher than those in the central and western regions. This paper refers to Huang et al. (2021), uses the per capita GDP of cities to measure the level of regional economic development. According to the median of per capita GDP of cities, the sample is divided into enterprises with high economic development level and enterprises with low economic development level. Through comparison, it is found that the average of patent applications of enterprises with high economic development level is 128.38, which is significantly higher than 68.98 patents of enterprises with low economic development level. The results of **Table 9** show that EPU has no significant impact on the quantity of enterprise innovation, but has a significant negative impact on the quality of innovation. Kou and Liu (2020) shows that there is an obvious regional imbalance in the innovation of Chinese enterprises. The level of industrial agglomeration and innovation in the eastern regions is significantly higher than that in the central and western regions. The eastern regions have three-quarters of the quantity of patent applications in China. Cities with low economic development level have insufficient innovation capacity. Therefore, when facing EPU, these regions are more inclined to carry out innovation activities for accelerating technological progress and promoting economic development.

TABLE 7 | Heterogeneity of enterprise lifecycle.

Variables	Growth period		Mature period		Decline period	
	Innovnum	Innovqua	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.027	−0.015***	0.003	−0.005	0.046	−0.003
—	(1.44)	(−2.83)	(0.13)	(−0.80)	(1.52)	(−0.34)
Control	Yes	Yes	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5,434	5,434	4,275	4,275	2,691	2,691
R^2	0.302	0.229	0.240	0.230	0.133	0.114

TABLE 8 | Heterogeneity of administrative levels.

Variables	High-level enterprises		Low-level enterprises	
	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.024*	−0.006	0.004	−0.009
—	(1.74)	(−1.61)	(0.21)	(−1.45)
Control	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
Observations	8,410	8,410	3,990	3,990
R^2	0.230	0.222	0.290	0.242

6.2 The Moderating Effect of Financialization

The R&D activities of enterprises need a lot of continuous funds. When an enterprise invests funds in various financial assets, on the one hand, it will make the enterprise's funds tight and financing limited. The enterprise will reduce the funds for R&D, thus reducing the innovation output of the enterprise. On the other hand, the high return of investing in financial assets can significantly improve the financial performance, alleviate the financing constraints of enterprises, and then promote the innovation of enterprises. Refer to Wu et al. (2020) and Ren et al. (2021), we establish the following regression equation to test whether the financialization shows a moderating effect during the EPU affects enterprise innovation:

$$Innovnum_{it} \Big/ Innovqua_{it} = \alpha_0 + \alpha_1\, EPU + \alpha_2 Fin_{it} + \alpha_3 Fin_{it} \times EPU + \sum controls + FirmFE + YearFE + \varepsilon_{it} \quad (2)$$

In the above formula, Fin represents the financialization of enterprise. The larger Fin is, the higher the enterprise's financialization level is. The definition of other variables is the same as model **(Eq. 1)**. We mainly focus on the coefficient α_3, which reflects the moderating effect of financialization in the process of EPU affecting enterprise innovation.

The results are shown in **Table 10**. Columns 1) and 2) only control time and individual fixed effect. Columns 3) and 4) further include enterprise and regional control variables. As can be seen, the coefficients of *Fin × EPU* in Columns 3) and 4) are −0.243 (significant at 1% level) and 0.028 (significant at 10% level) respectively. This means that in the process of EPU affecting enterprise innovation, enterprise financialization has a negative regulatory effect. In the face of EPU, the innovation quantity of enterprises with high degree of financialization is declining, but the innovation quality is rising. Although non-financial enterprises' investment in financial assets will crowd out resources for R&D activities, thus making enterprises lack sufficient funds for product innovation and equipment upgrading, and resulting in a decline in the quantity of enterprise innovations. However, when facing EPU, enterprises will be more eager to obtain excess profits through innovation. Therefore, on the premise of limited R&D resources, enterprises will focus more on the research of cutting-edge technologies, so as to improve the core competitiveness. This finally makes the innovation quality of enterprises rise. This conclusion also verifies hypothesis 3.

7 CONCLUSION AND IMPLICATIONS

On the basis of theoretical analysis, this paper establishes the relationship between macroeconomic policy and micro enterprise innovation. Taking Chinese A-share listed companies from 2008 to 2017 as research samples, this paper examines the impact of EPU on enterprise innovation by using patent data of listed companies and the Uncertainty index of China's economic policy constructed by Baker et al. (2016). Meanwhile, the moderating effect of financialization is tested. The results show that the EPU will increase the quantity of enterprise innovation, but inhibit the improvement of enterprise innovation quality. In the process of EPU affecting enterprise innovation, financialization has a negative moderating effect. The impact of EPU on innovation will be affected by enterprise ownership, financing constraint level, life cycle, regional administrative level and regional economic level.

The conclusion of this paper has some policy implications. Firstly, the results of this study show that EPU positively promotes the growth of firm innovation quantity, but inhibits the improvement of firm innovation quality. The increased uncertainty of economic policy will also bring a lot of negative impacts to enterprises. For example, it may cause the rise of enterprise operating costs, inhibit enterprise investment, and lead to the decline of investment efficiency. At the same time, the EPU will also bring negative impacts to the macro economy, such as increasing the volatility of macroeconomic variables and financial assets, affecting employment and output, and hindering economic recovery. Therefore, when relevant government departments frequently adjust economic policies to

TABLE 9 | Heterogeneity of the economic development level.

Variables	High economic development level		Low economic development level development	
	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.019	−0.007*	0.028	−0.010*
—	(1.23)	(−1.72)	(1.62)	(−1.91)
Control	Yes	Yes	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
Observations	6,194	6,194	6,206	6,206
R^2	0.186	0.121	0.244	0.131

TABLE 10 | Regression results of the moderating effect of financialization.

Variables	(1)	(2)	(3)	(4)
	Innovnum	Innovqua	Innovnum	Innovqua
EPU	0.333***	0.011***	0.074***	−0.013***
—	(20.69)	(2.74)	(4.43)	(−2.72)
Fin	−0.179	−0.084**	−0.060	−0.098**
—	(−1.17)	(−2.14)	(−0.42)	(−2.44)
Fin × *EPU*	−0.181***	0.034**	−0.243***	0.028*
—	(−2.87)	(2.12)	(−4.23)	(1.75)
Control	No	No	Yes	Yes
FirmFE	Yes	Yes	Yes	Yes
YearFE	Yes	Yes	Yes	Yes
Observations	12,400	12,400	12,400	12,400
R^2	0.092	0.086	0.251	0.228

smooth economic fluctuations, promote economic growth and improve national innovation ability, they should weigh the impact of EPU on different regions, different economic subjects and different economic activities. Secondly, the results of this paper have some inspiration for the adjustment of government innovation policy. Relevant departments should consider the heterogeneous impact of EPU on the innovation of enterprises with different characteristics. We will strive to build a transparent, fair and stable policy environment, promote policy implementation and help enterprises give better play to their innovation vitality. Thirdly, as a big country of patent application, China is not a strong country of patent quality. Patent is an important part of innovation output. The creation of high-quality invention patent and the technology spillover effect of patent itself are the key to promoting technological progress and economic growth. In the face of policy uncertainty and the increasing proportion of financial investment, enterprises should make use of the excess returns brought by financial investment to alleviate the financing constraints, obtain more market shares and excess profits through technological innovation, so as to increase their core competitiveness, enhance corporate value, and improve the quality of innovation. Fourth, in order to further stimulate and protect innovation and promote high-quality development of patents, the State Intellectual Property Office of China (SIPO) has adjusted the funding policy for patent applications. The funding for patent application phase will be completely cancelled by the end of June 2021, and the funding for patent licensing phase will be completely cancelled by 2025. In the face of an application for a patent for aid policy changes, the enterprise should pay attention to regulate the behavior of patent application, improving the quality of patent applications, from a number of one-sided pursuit of innovation to improve the quality of innovation, constantly enhance their innovation through technology innovation level, promote independent innovation ability, promote our country imported from intellectual property powers to create power. Finally, we should recognize that the uncertainty of economic policy has both the causes of policy-making and policy implementation. Local governments should scientifically implement enterprise-related policies and gradually promote the transparent, fair, stable and continuous implementation of various policies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YZ: Conceptualization, Writing—original draft, and methodology. CZ: supervision. FD: Formal analysis. All authors have read and agreed to the published version of the manuscript.

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Role of Financial Development, Green Technology Innovation, and Macroeconomic Dynamics Toward Carbon Emissions in China: Analysis Based on Bootstrap ARDL Approach

Jiayu Yang[1], Yunpeng Sun[2]*, Huaping Sun[3]*, Chi Keung Marco Lau[4]*, Nicholas Apergis[5] and Kun Zhang[2]*

[1]School of Finance, Nankai University, Tianjin, China, [2]School of Economics, Tianjin University of Commerce, Tianjin, China, [3]School of Finance and Economics, Jiangsu University, Jiangsu, China, [4]Department of Economics and Finance, Hang Seng University of Hong Kong, Hong Kong, Hong Kong SAR, China, [5]Department of Banking and Financial Management, University of Piraeus, Piraeus, Greece

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Iqra University, Pakistan

***Correspondence:**
Jiayu Yang
yangjiayu@nankai.edu.cn
Yunpeng Sun
tjwade3@126.com
Huaping Sun
shp797@163.com
Chi Keung Marco Lau
marcolau@hsu.edu.hk

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This study focuses on determining the relationship between carbon emissions, financial development, population, green technology innovation, energy Consumption, and employment rate from 1980 to 2019 in China. The study applies the unit root test, bootstrapped ARDL cointegration, and the Granger causality to examine the data properties and association between the variables of interest. Empirical findings indicate that green technology innovations and financial development play a major role in environmental protection, specifically in the long run. In contrast, energy consumption and employment rate are more vulnerable to protecting the natural environment in China. On the other side, the findings under short-run estimation do not support the role of green technology innovation in reducing environmental degradation. Based on the empirical findings, it is suggested that a strong financial system would help to achieve long-run sustainability and the emissions mitigating effects can be further strengthen by implementing green technologies across industries. In doing so, strict environmental regulations can regulate the financial and traditional industrial sector in adoption of energy efficient technologies.

Keywords: fd, ER, CO2 emissions, pop, GdpP, bootstrapped ARDL cointegration method, granger causality test

1 INTRODUCTION

For the sustainable development of human society, changing climate is a significant threat and leads to a range of ecological consequences (Ahmad et al., 2021; Yuaningsih et al, 2021; Irfan et al., 2022). These issues are melting snow and ice, extreme weather conditions, and increasing temperature levels (Yang et al., 2021a; Iqbal et al., 2021; Ahmad et al., 2022; Wen et al., 2022). Such climate changes are largely caused by a range of human activities like burning coal and oil (Nawaz et al., 2021b; Chien et al., 2021; Irfan et al., 2022a). However, such changing climate threats could be reduced by avoiding greenhouse gas emissions in the natural environment (Ali et al., 2021; Chandio et al., 2021; Abbasi et al., 2022). Turning toward the Chinese economy, it has become the world's largest carbon emitter during 2006, whereas the largest energy consumer in 2009 (Hao et al., 2021; Rauf et al., 2021; Nuvvula et al., 2022). Furthermore, the carbon

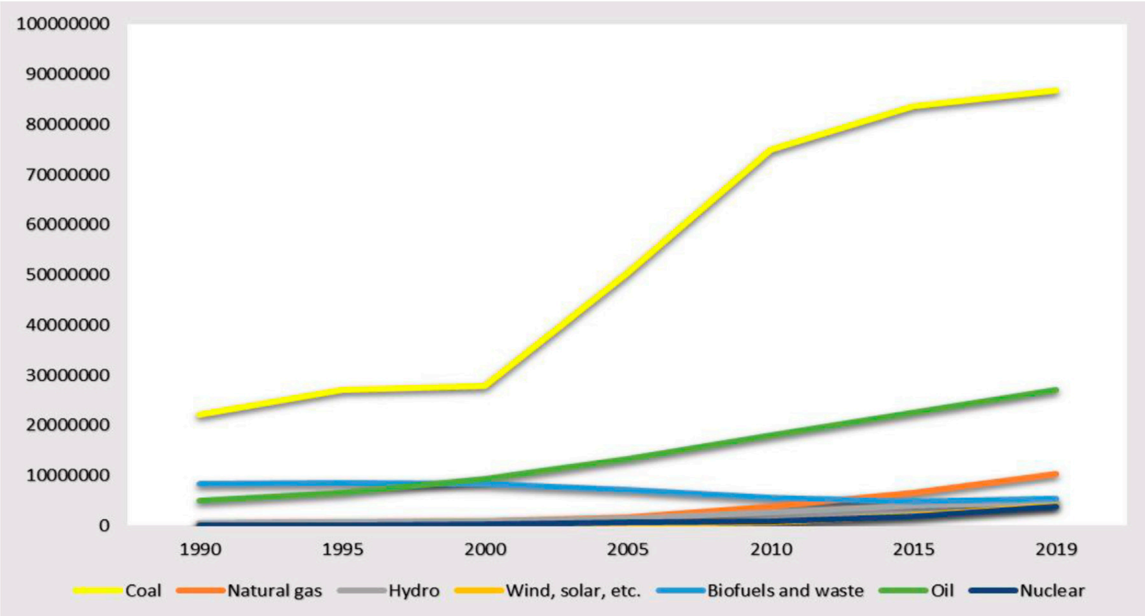

FIGURE 1 | Total energy supply (TES) by source, People's Republic of China 1990–2019 Source: International Energy Agency (2022).

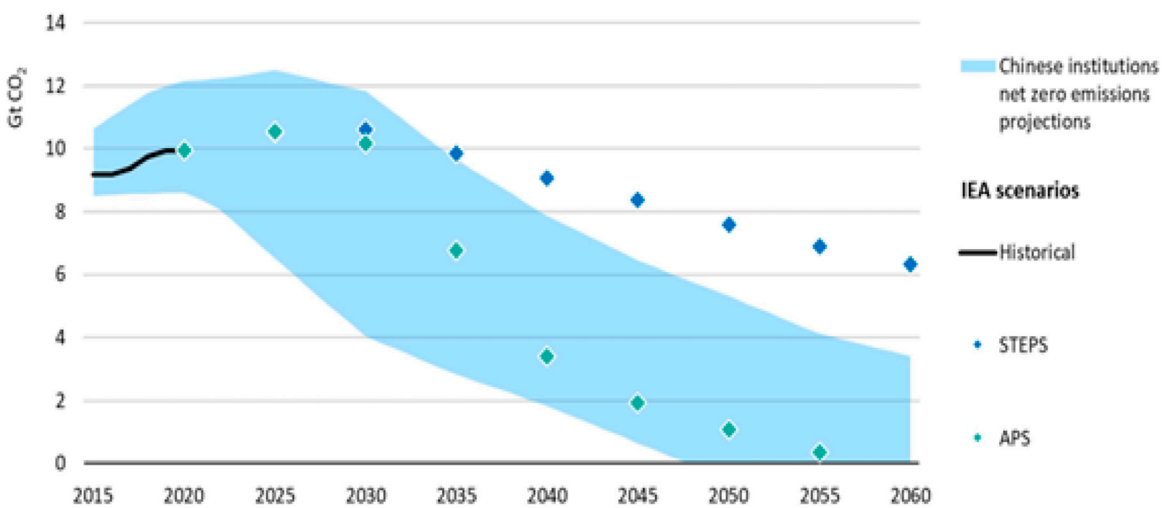

FIGURE 2 | CO2 emissions from the existing energy-related infrastructure in China Source: (IEA, 2021).

emission in China was reached 9.15 billion during 2015, which accounts for 27.3% of the world's emissions (Zhang et al., 2017; Irfan and Ahmad 2022).

Meanwhile, in recent years, China's emissions will probably increase by 500 Mt in CO_2 due to increasing demand for energy during 2020, whereas in 2021 it was almost 600 Mt CO_2 (IEA, 2021). Although the contribution of fossil fuels is higher in CO_2 emission in China, coal is expected to be dominant while contributing almost 70% (IEA, 2021). This higher level of coal is mainly in the power sector. Contrary to higher carbon emission, there is a growing trend for energy from renewable sources (Irfan et al., 2022b), which is almost 7% during 2019–2021. **Figure 1** provides the outlook for the total energy supply through different sources. Coal is at the highest rank, followed by natural gas; hydro, wind, and solar; biofuel and waste; and oil and nuclear, respectively.

In addition, as per the findings of the International Energy Agency (2021), there is a significant gap in the energy sector's carbon emission between the Stated Policies Scenario (STEPS) and Announced Pledges Scenario (APS), which are specifically

opened up after 2030. These challenges are achieving carbon neutrality while accelerating clean and green energy technologies. More specifically, after the recent pandemic of COVID-19 and its economic impacts, there is an upward trajectory in the emissions after a decline in the growth rate during 2020. It is expected that emissions will reach 6 Gt in 2060, which is to be considered as more than 35% below their level during 2020. However, in APS, emissions are expected to follow a similar path to 2030 but fall much more rapidly and reach net zero in 2060 (IEA, 2021). Besides, carbon emission from fossil fuel combustion will be around 450 Mt by 2060. **Figure 2** provides a better outlook for the energy-related CO2 emissions in China by scenario during 2015–2060.

There is much interest in carbon neutrality, the most important factor in developing green technologies (GTIs) (Tanveer et al., 2021; Shi et al., 2022; Xiang et al., 2022). The reason is that GTI is dynamic in the long run while minimizing environmental pollution compared to traditional techniques (Razzaq et al., 2021a; Fang et al., 2022). At the same time, financial development in any economy plays a major role in dealing with environmental concerns while utilizing more energy-efficient technologies (Tamazian and Rao, 2010; Tang et al., 2022). According to the OECD (2019), the performance of the GTIs can be viewed in a context that they help protect natural resources and preserve their value. However, the notion related to population growth is normally accepted as a major cause of environmental challenges (Cramer, 2000; Sun et al., 2020). However, there is a significant difference across the countries regarding the world's population, GDP growth and CO_2 emissions, financial development, and energy consumption (An et al., 2021; Razzaq, et al., 2021b; Sun et al., 2022; Yu et al., 2021). According to Walz (2011), production techniques and technology greatly influence the economy's structure. This research paper focuses on determining the relationship between CO_2 emissions, FD, PoP, GTI, ENC, and ER using a dataset from 1980 to 2019 in China. The study applies the unit root while using the ADF and ZA tests and BARDL estimation. In this regard, various studies have been found while applying the stated techniques. For example, considered the autoregressive distributive lag (ARDL) model. By applying a bootstrap autoregressive-distributed lag (BARDL) test proposed by McNown et al. (2018). The bootstrapping ARDL bound testing technique was applied to evaluate the cointegration among key factors.

The motivation for conducting this research highlights several important points. First, to the best of our knowledge, the literature supporting examining the role of financial development, green technology innovation, energy consumption, population, and employment rate under the shadow of environmental Kuznets curve and STIRPAT show some mixed findings. For this reason, our study incorporates all of these stated variables to provide some meaningful policy implications specifically from the context of China. Second, our study provides both long-run and short-run estimations for examining the relationship between the variables of interest. A sustainable perspective regarding carbon neutrality would be easily developed. Third, the Chinese economy has achieved outstanding economic and social development by transforming the planned socialist system to a more open and market-based economy. Its GDP has been growing 30 times larger than in the 1980s. This remarkable growth rate has also created some serious challenges in terms of environmental sustainability, for which this research has provided some meaningful empirical evidence and practical solutions. The following sections have been included to finish the paper: **Section 2** focuses on the literature review, section three covers the research methodology, data collection, and research design. **Section 4** covers the results and discussion, whereas the last section mainly considers the conclusion and policy implications.

2 LITERATURE REVIEW

2.1 Influence of FD, GTI, and GDP on Environmental Pollution

A study conducted by Zaidi et al. (2019) demonstrated that FD affects natural quality, whereas Chen et al. (2020) demonstrate that political globalization reduced environmental pollution. Salahuddin et al. (2018) used the VECM Granger causality test and shows that GDP, FDI, and FD are linked with environmental concerns. Ertugrul et al. (2016) explored that economic growth plays an important role in the growth of CO_2 emissions. Akalpler and Hove, 2019) determined a strong correlation between economic output, capital expenditures, energy consumption, and environmental concerns. Jiang et al. (2019) revealed that FD directly affects environmental pollution. According to GDP and FDI contributed to natural collapse by increasing CO_2 emissions. Meanwhile, Dzator and Acheampong (2020) discovered that GTI has a favorable impact on CO_2 emissions. Usman and Hammer (2020) revealed that the FD and GTI protect environmental quality over the long run. As GTI getting improves, there is a reduction in environmental pollution. (Abdouli and Hammami, 2017).

In addition, Razzaq et al. (2021) stated that uncertainty exists in economic patterns because of time-varying factors. For this reason, it is quite imperative to examine the nexus between environmental and economics. Their study mainly focuses on the Chinese economy to explore long-run and short-run non-linear associations between financial development, carbon emission, globalization, and natural resources for 1980–2017. In doing so, they applied a non-linear autoregressive distributed lag (NARDL) framework and observed that financial development and globalization are positively linked with carbon emissions. However, negative shocks in natural resources also positively determine China's environmental pollution. Khan et al. (2020) observed the panel heterogeneity among 192 economies for carbon emission, financial development, and energy consumption. The study results confirm that through panel quantile regression estimation, financial development has its increasing influence, whereas clean energy consumption reflects a negative influence on carbon emission. Acheampong et al. (2020) conducted a comparative analysis of CO2 emission intensity and financial market development while considering developed and emerging

economies. The empirical findings infer that the development of financial markets increases the intensity of carbon emission among frontier financial economies.

In contrast, there is no linear relationship between financial market development and carbon emission intensity in standalone financial economies (Khan et al., 2022). Shan et al. (2021) examined the impact of green technology innovation, and renewable energy on carbon emission in the Turkish economy through bootstrapping ARDL. The authors confirmed that green technology innovation and renewable energy help in reducing carbon emission, whereas non-renewable energy boosts carbon emission (Sun and Razzaq, 2022a). Furthermore, both population and personal income have their determinantal effect on carbon emissions. Shan et al. (2021) analyzed the effects of GDP, energy sources, and carbon emission in the OECD and BRICS economies in the long and short run through panel data estimation. It has been finalized that there is a negative correlation between GDP and carbon emission, whereas a negative association exists between non-renewable energy and carbon emission, respectively.

2.2 Population Growth Impact on CO_2 Emissions

According to Haseeb et al. (2016), urbanization harms environmental sustainability, whereas discovered a strong relationship between GDP, energy consumption, FDI, exchange transparency, and CO_2 neutrality. Vélez-Henao (2020) found that population development in cities is a major cause of natural debasement. Amin et al. (2020) discovered that energy usage reduces the natural quality, but trade openness and population improve environmental pollution in the long term. Sadorsky (2014) described that population growth shows its influence on CO_2 emissions. However, the size of the population is a very important factor that directly affects CO_2 emissions (Dagar et al., 2021; Atchike et al., 2022; Cui et al., 2019; Xiang et al., 2022). Dong et al. (2018) observed the trends in CO_2 emission through economic growth, population, and renewable energy sources across different regions. Considering the cross-sectional dependence and slope heterogeneity during 1990–2014, their study mainly observes that at both regional and global levels, and population and economic growth have their significant and direct role toward a higher level of carbon emission. However, energy from renewable sources is causing a decline in CO_2 emissions. Furthermore, it also confirms that panel causality exists along with the variables of interest. Khan et al., 2021 examined renewable and non-renewable energy sources, natural resources, population growth toward CO_2 emission, and ecological footprints. The study findings confirm that population growth and non-renewable energy sources degrade environmental quality. Weber and Sciubba (2019) stated a long-lasting dispute regarding the extent to which population growth is playing its role toward environmental degradation. However, it is stated that regional level analysis may provide some robust output while isolating the effect of population on the carbon dioxide emission during 1990–2006. Their findings provide some considerable outcomes for the regional population growth on the carbon emission. Sulaiman and Abdul-Rahim (2018) explained in its theoretical context that population growth is to be considered as playing its role toward greenhouse gas emission, specifically in the form of CO2 due to a range of human activities. For 1971–2010, their study mainly considers the autoregressive distributed lag model. However, the study findings confirm that population is not a determinant factor toward carbon dioxide emissions. In contrast, economic growth has its long-term determinantal effect on the carbon emission during the study period.

3 RESEARCH METHODOLOGY

3.1 Data Collection Sources

To carry out the statistical analysis, data were collected from 1980 to 2019. Data for the financial development were collected from the official website of the International Monetary Fund (IMF). In contrast, data for the population, employment rate, carbon dioxide emissions, and energy consumption were collected from the official data portal of the World Development Indicator during the study period. Furthermore, the data for green technology innovations have been collected from the official data portal of OECD statistics.

3.2 Theoretical Framework

The IPAT is an equation format that integrates sustainability outputs to three major causal factors: population, affluence, and technology. The equation of IPAT was initially proposed during the 1970s to deeply understand the change in population, affluence, and technology toward their environmental impact (I) (Ehrlich and Holdren, 1972). More specifically, in the IPAT application, the term T mainly determines the environmental impact per unit for the economic activity. Such activities are normally determined through economic growth in the form of gross domestic product with the help of I/GDP ratio. Furthermore, technical efficiency is observed as a key factor to reduce the cause of the environmental outcomes caused by anthropogenic activities.

Meanwhile, among IPAT applications, climate change is very popular, specifically among those studies that are energy-emission based (Wang et al., 2017; Zaman and Abd-el Moemen, 2017; Ozcan and Ulucak, 2021). The preceding (Raskin, 1995) discoveries have provided evidence for using the IPAT model to figure out what causes carbon dioxide emissions to occur (Paramati et al., 2020). The IPAT model is extended into a stochastic variation called Stochastic Effects of Relapse on Popular and Technology (STIRPAT) (Dietz, 1997). Although the implication of the IPAT model was reasonable enough, there was a range of limitations linked with it. To overcome this issue, Rosa and Dietz (1998) have proposed the STIRPAT model. A major advantage of the STIRPAT model comes from its ability to test hypotheses empirically and the conditions that will be present during the experiment,

$$CO_{2it} = f\left(FD_{it}, PoP_{it,it,}ENC_{it}, GTI_{it}, ER_{it}\right). \quad (1)$$

TABLE 1 | Conversation valuation reports.

Variables	Mean	Mini	Maxi	Stan. Devi	Jarq-Bera	Probability
CO_2	1.157	1.138	1.19	0.014	1.538	0.461
FD	1.86	1.534	1.823	0.06	4.175	0.101
PoP	1.961	1.908	1.239	0.039	1.935	0.384
GTI	4.866	4.818	4.744	0.016	1.957	0.423
ENC	1.042	1.083	1.096	0.007	1.476	0.141
ER	2.093	5.761	4.758	0.023	1.609	0.489

Note: CO2, carbon dioxide emission; FD, financial development; PoP, population; GTI, green technology innovations; ENC, energy consumption; ER, employment rate.

The above-expressed model was taken on from the exploration commitments (Paramati et al., 2017). In the above condition (**Eq. 1**), CO_2 consists of the components of the population, financial development, energy consumption, green technology innovation, and employment rate, respectively.

3.3 Research Design

This research applies the bootstrapping autoregressive distributed lagged (BARDL) bound testing technique as it is unique for two major reasons. First, this model is not complex toward the integration properties of the study variables. Second, this approach is also suitable for dynamic time-series data. However, compared to conventional ARDL models, the BARDL addresses the issues like inconclusive cases, as expressed by McNown et al. (2018). It also helps in reducing indecision cases because critical values are generated. Furthermore, this method is moderate and dynamic with multiple explanatory variables. Goh et al. (2017) have expressed their view that the BARDL approach in its traditional concept can be specified with the help of the following equation:

$$y_t = \sum_{i=1}^{p} \alpha_i y_{t-i} + \sum_{j=0}^{q} \beta_j x_{t-j} + \sum_{k=0}^{r} \gamma_k z_{t-k} + \sum_{i=1}^{s} \tau_t D_{t,l} + \mu_t, \tag{2}$$

wherein in **Eq. 2**, the small letters i, j, k, and l show the lags. Meanwhile, the term t shows the time duration, and yt indicates the main dependent variable: carbon dioxide emission. Furthermore, xt and zt show the key predictors or explanatory variables. Additionally, Dt, i reflects the dummy variable in structural breaks (Kim and Perron, 2009). β *and* γ demonstrate the coefficients for the dummy variables, whereas μ_t is the error correction terms that can be specified with the help of the following equation:

$$\triangle y_t = \phi y_{t-1} + \gamma x_{t-1} + \psi z_{t-1} + \sum_{i=1}^{p-1} \lambda_i y_{t-1} + \sum_{j=1}^{q-1} \delta_j x_{t-j} + \sum_{i=1}^{r-1} \pi_k z_{t-k} + \sum_{i=1}^{s} \omega_i D_{t,l} + \mu_t. \tag{3}$$

Here, the terms $\lambda_i, \delta_j, \pi_k,$ *and* ω_i cover the connected functions. However, the transformation of the above equation into error-correction form, an AR vector in the level, and the equation can be presented in the following format:

$$\triangle y_t = \tilde{c} + \tilde{\phi} y_{t-1} + \tilde{\gamma} x_{t-1} + \tilde{\psi} z_{t-1} + \sum_{i=1}^{p-1} \tilde{\lambda}_i y_{t-i} + \sum_{j=1}^{q-1} \tilde{\delta}_i x_{t-j} + \sum_{i=1}^{p-1} \tilde{\pi}_t z_{t-k} + \sum_{i=1}^{p-1} \tilde{\omega}_i D_{t,l} + \tilde{\mu}_t. \tag{4}$$

TABLE 2 | Correlation analysis's best-guess estimates.

	CO_2	FD	PoP	GTI	ENC	ER
CO_2	1					
FD	0.775***	1				
PoP	0.675***	0.583	1			
GTI	0.679***	0.207	0.201	1		
ENC	0.477***	0.594*	0.383**	0.675***	1	
ER	0.515**	0.774**	0.405**	0.499**	0.511	1
			VIF			1/VIF
FD			1.434			0.697
PoP			1.273			0.699
GTI			1.537			0.709
ENC			1.475			0.837
ER			1.505			0.73
Mean VIF			1.576			-

Note: CO2, carbon dioxide emissions; FD, financial development; PoP, population; GTT, green technology innovations; ENC, energy consumption; ER, employment rate. ***p < 1%, **p < 5%, and, *p < 10%.

Meanwhile, the above equation indicates the significance of the three null hypotheses to explain the cointegration among the variables.

I) All relevant error-correction terms are tested by the F1 test ($H0$: $\phi = \gamma = \psi = 0$ whereas H1: At least one (ϕ, γ, ψ) are not zero.
II) All of the explanatory variable terms are tested by F2 ($H0$: $\phi = \gamma = 0$ against H1: At least one (ϕ, γ). are not zero
III) Lagged dependent variables are tested by ($H0$: $\phi = 0$ against H1: ϕ is other than zero).

In addition, the traditional ARDL estimation helps generate the critical values test for the F1 and T tests, respectively. Meanwhile, BARDL helps in generating some critical values.

4 RESULTS AND FINDINGS

Descriptive results are reported in **Table 1**, where both central tendency and dispersion measures are provided. It shows that Green technology innovations report a higher mean score, followed by employment rate, population growth, and financial development. However, the lowest mean trend is reported from energy consumption which is 1.02. On the other side, all the study variables show a standard deviation below 1, which is a good sign for the low risk in the dataset. Additionally, for the Jarque–Bera test, the following null and alternative hypotheses are tested.

H0: The distribution of the study data is normal.
H1: The distribution of the study data is not normally distributed.

TABLE 3 | Preliminary estimates on the number of unit root tests.

Variables	ADF (level)	ADF(Δ)	ZA (Level)	Break year	ZA (Δ)	Break year
CO_2	0.576	−7.847***	−2.271	2000 (Q-1)	−5.075***	2001 (Q-4)
FD	−0.254	−3.057***	−0.356	2005 (Q-2)	−8.003***	2019 (Q-1)
PoP	−1.008	−5.069***	0.471	2019 (Q-1)	−6.528***	2005 (Q-1)
GTI	−0.267	−5.372***	−0.236	2001 (Q-4)	−5.097***	2014 (Q-2)
ENC	−0.847	−4.281***	−2.024	2010 (Q-1)	−3.809***	2007 (Q-1)
ER	−0.472	−2.669**	−0.338	2019 (Q-2)	−5.654***	2019 (Q-2)

Note: CO2, carbon dioxide emission; FD, financial development; PoP, population; GTI, green technology innovations; ENC, energy consumption; ER, employment rate. The ADF and ZA test statistics are defined by the estimated values shown in the table above. However, p < ****1%,* p < ***5% points, and* p < **10%.*

The findings for the Jarque–Bera test through probability values reflect that all the variables are found to be statistically insignificant. Therefore, H0 is not rejected; hence, data for the study variables are normally distributed. Therefore, we can move on toward further empirical investigation in both the long and short run, respectively.

4.1 Correlation Analysis Estimates

Table 2 covers the pairwise correlation matrix for the study variables. A positive and significant correlation exists between CO_2 emissions, FD, GTI, and energy consumption, respectively. More specifically, a highly positive and significant correlation exists between carbon emission and financial development during the study period. On the other hand, energy consumption, green technology innovation, GTI, and employment rate are also positively and significantly correlated. Furthermore, this research examines the VIF scores along with the tolerance level (1/VIF) to justify whether the correlation is problematic or not. As shown in **Table 2**, all the variables of interest reflect a VIF score of less than 5, and similar is the case with Mean VIF. Accordingly, the tolerance level is also above 0.10; hence, it is inferred that the correlation between the variables of interest is acceptable.

4.2 Preliminary Unit Root Tests

The study employs an ADF unit root test, which is very useful in detecting the unit root for each study variable (Tissue et al., 2009). Meanwhile, as stated under **Table 3**, through different years and relative quantiles, multiple structural breaks have been presented and tested accordingly. Furthermore, the level of integration between the variables also plays an important role in the justification of the relevant technique's hereafter. Meanwhile, the ADF unit root test has greater explanatory power than some traditional unit root tests, providing some accurate findings. The study findings in **Table 3** report that under ADF (level), all the variables have reported unit root problems. For this reason, with the first difference, the variables are found to be statistically significant. Furthermore, the findings under the ZA test confirm that at ZA (Δ), the study variables are statistically significant with the different structural breaks. This would justify the argument that variables have distinctive order of integration; therefore, our study applies cointegration techniques to examine the presence of cointegration.

4.3 BARDL Co-Integration Estimation

After analyzing the structural breaks in the data, our study considers the BARDL cointegration analysis through estimated models, lag length, break year, F score, T score, and the rest of the results under **Table 4**. The findings under **Table 4** through F and T values confirm a long-run equilibrium cointegration association between the study variables such as population, energy consumption, economic growth, employment rate, financial development, and carbon emission, respectively. The results of bootstrapped ARDL cointegration test disclosures from the F test and T test, CO_2 emissions are accounted for all of the identifying factors, which has a value of R^2 which accounts for 80.6% variation in the model. Finally, the results of the JB test show that the variables of interest are normally distributed during the study period. T_{DV} served as the t-value for the dependent variable, whereas T_{IV} was the t-value of the major explanatory variables of the study.

4.4 Analysis of BARDL Co-Integration (Long Run)

To examine the long-run cointegrated association between the outcome and explanatory and outcome variables, findings are presented in **Table 5**. It confirms that financial development in Chinese economy reduces the carbon emission in a significant manner (i.e., beta = −0.231, t-value = −2.003, *p*-value = 0.001). It justifies that more development of financial markets and related institutions in the Chinese economy is a productive indication of environmental degradation; hence, such financial development reflects its sustainable outlook. The existing literature has found supporting and contrary evidence for the nexus between financial development and carbon emissions. In this regard, Amin et al. (2020) explored different proxies of financialization toward carbon emission among top emitters with the help of quantile estimation. It is confirmed that financial development increases carbon emission at low quantiles, negatively affecting pollution over higher quantiles when examined through nine different proxies. However, some other studies have contrary findings. For example, Shahzad et al. (2017) showed that financial development increases the carbon emission by 16.5% under long-run estimation, whereas this impact is observed as 8.7% under short-run, respectively. Zhang (2011) also exerted that financial development is an important driver of carbon emission in the past.

TABLE 4 | BARDL cointegration analysis results.

Estimated models	Lag length	Break year	F_{PSS}	T_{DV}	T_{IV}
Model	1,2,2,0,1,2,1	2010 Q1	2.0823***	–8.003***	–5.0827**
R^2	**Q-stat**	**LM(2)**	**JB**		
0.806	5.0782	2.0839	0.872		

*Note: The ideal lag time was found using the Akaike Information Criterion (AIC). The bootstrap method creates asymptotic critical bounds for the F-statistic FPSS, ***p< 1%, **p< 5%, and *p< 10%.*

TABLE 5 | Results of BARDL (long run) cointegration analysis.

Dependent variable = CO_{1t}

Variables	Co-efficient	t-value	*p*-value
Constant	0.236***	3.676	0.000
FD_t	–0.231***	–2.003	0.001
PoP_t	–0.319***	–4.109	0.000
GTI_t	–0.471***	–5.966	0.000
ENC_t	0.341***	4.014	0.000
ER_t	0.208**	2.96	0.000
D^2	0.196**	3.205	0.000
R^2	0.943		
$Adj–R^2$	0.939		
Durbin Watson	1.937		
Stability Test		**F-Statistics**	***p*-Value**
X^2 Normal		0.257	0.153
X^2 Serial		0.348	0.301
X^2 ARCH		0.361	0.256
X^2 Hetero		0.38	0.424
X^2 RESET		0.753	0.147
CUSUM		Stable	
CUSUMsq		Stable	

*Note: *** = p< 1%, **p< 5%, and *p< 23%.*

TABLE 6 | BARDL cointegration analysis estimations (short-run).

Dependent variable = CO_{2t}

Variable	Co-efficient	t-value	*p*-value
Constant	0.053	0.516	0.6130
FD_t	–0.172***	–2.721	0.0000
PoP_t	–0.101***	–2.521	0.001
GTI_t	0.253***	3.652	0.000
ENC_t	0.105***	5.462	0.000
ER_t	0.161***	5.721	0.001
D_{1006}	0.051	1.213	0.1630
ECM_{t-1} R^2	–0.216***	–2.362	0.0001
$Adj–R^2$	0.365		
Durbin Watson	1.973		
Stability Analysis			
Test		**F-value**	***p*-value**
χ2 Normal		0.363	0.261
χ2 Serial		0.166	0.605
χ2 Arch		0.361	0.103
χ2Hetero		0.165	0.673
χ2Reset		0.101	0.723
CUSUM		Even	
CUSUMsq		Even	

*Note: GTI, GTI, CO_2, carbon dioxide emissions, ENC, energy consumption, GDPPC, GDP per capita; POP, population, whereas *** = p< 1%, **p< 5%, and, *p< 10%.*

Furthermore, the effect of population toward carbon emission is also negatively significant at 1% as shown in **Table 6**. This means that increasing population is not a problematic sign of environmental pollution. One of the several reasons for this negative nexus between population and carbon emission might be shifting energy sources from non-renewable to renewable ones. Khan et al. (2021) confirmed that population growth and carbon emissions are related. However, Sulaiman and Abdul-Rahim (2018) claimed that population, among other macroeconomic variables, has a direct role toward more emission and vice versa. Qi and Li (2020) focused on estimating the transfer in carbon through population migration and energy use in China. They highlight that migration flows in China are causing differential outcomes in residential carbon emissions. However, China's population migration has increased the national total carbon emission.

The findings also report that energy consumption and green technology innovations show their positive/negative role toward carbon emission in the Chinese economy as observed through long-run estimation. More specifically, it shows that a 1% change in GTI and ENC is causing an upward/downward shift of 47.1 and 34.1% in the carbon emission in China. The increasing utilization of energy is among the major carbon emission sources, as highlighted in recent and past studies. Zaman and Moemen (2017) focused on various environmental hypotheses to explore the nexus between energy consumption, carbon emission, and economic growth. The study findings confirm that more energy consumption induces carbon emission. Nawaz et al. (2021a) confirmed the empirical association between energy consumption from non-renewable sources and carbon emission, whereas a long-run positive correlation between energy consumption and carbon emission also exists. The literature also supports mixed evidence about the nexus between green technology innovation and carbon emission. For instance, Du and Li (2019) investigated the trends in carbon dioxide emission through green technology innovation for 71 panel economies. Their results show that ecological innovations do not significantly reduce carbon emissions, specifically among economies below a threshold income level. However, contrary to our findings, Du and Li (2019) stated that it is difficult to find significant evidence for the positive effect of green technology innovation toward carbon productivity, specifically among less developed economies.

Furthermore, we observe that the employment rate among the macroeconomic indicators is directly causing environmental pollution. The coefficient of ER is 0.208, with a t-value of 2.96. This would reflect a significant and positive nexus between the employment rate and carbon emission in China. Yu and Li (2021) examined the association between carbon emission and enterprises' labour demands. It is stated

TABLE 7 | Results of the Granger causality test estimations.

H_0	F-value	Probability
CO_2 does not result in GTI as a result of the Granger syndrome	18.362***	0.0001
CO_2 does not affect Granger's ER	38.573***	0.0001
CO_2 the Granger Effect does not cause ENC	39.796***	0.00001
CO_2 Doesn't cause Granger Effect PoP	6.038**	0.0180
CO_2 Granger Cause does not cause FD	4.968*	0.058
GTI Granger Cause does not produce CO_2	27.473***	0.0002
CO_2 from Granger Cause is not induced by ER	22.593***	0.0001
Granger Effect CO_2 is not induced by ENC	48.483***	0.002
Granger Cause CO_2 is not induced by POP	20.583***	0.0002
The Granger Cause does not produce CO2 when using FD	10.542***	0.0001

*Note: *** = p< 1%, **p< 5%, and, *p< 10%, Source: results determined by Authors Estimations.*

that approximately 11.5% total employment effect of carbon emission trading policy is found in China.

Likewise, the findings under short-run estimation through the BARDL method show that financial development and population are causing a reduction in carbon emission. In contrast, green technology innovation, energy consumption, and employment rate are causing environmental degradation. The findings under short-run estimations are quite identical to long-run estimation except for the change in the coefficient for the green technology innovation. Furthermore, it is observed that the adjusted value of the R^2 is found to be 36.5% under short-run estimation, reflecting a reasonable variation in the main dependent variable entitled carbon dioxide emission. Using Durbin Watson's statistics, the autocorrelation is identified and determined to be non-existent in the empirical findings. Besides, stability analysis has provided satisfactory empirical findings both in the long and short run, respectively.

4.5 6I Granger Causality Test Estimations

Finally, our study considers the Granger Causality test estimation for the variables of interest. The findings are presented under **Table 7** and observe that study variables are Granger cause with each other at 1% level of significance, except for the CO2-FD, which is significant at 10%.

5 CONCLUSION AND POLICY IMPLICATIONS

The research paper focuses on determining the relationship between CO_2 emissions, financial development, energy consumption, population, employment rate, green technology innovation, and carbon emissions in China from 1980 to 2019. The study applies unit root testing to examine the structural breaks and unit root properties. The bootstrapped ARDL cointegration (short- and long-run) analysis is also under consideration, whereas the Granger causality test was applied to find the causal relationships between all variables. The study findings through descriptive scores confirm the normal distribution of the data. In contrast, the correlational matrix also determines that interdependency is not problematic as VIF scores for all the variables are below the threshold level. In addition, the findings through long-run estimation confirm that financial development in the Chinese economy is playing a significant role in reducing environmental pollution like CO2. In contrast, the population also shows a negative trend toward carbon emission. Meanwhile, the long-run estimation confirms that the energy consumption and employment rate directly contributes to more pollution and environmental degradation during the study period. At the same time, our study analysis confirms a significant and constructive role of financial development in China under short-run estimation in treating climate issues. Besides, green technology innovations are among the core sources in reducing environmental issues in China, but only for the long run. Besides, the model's explanatory power under short-run estimation is lower than the long-run estimation.

Based on the empirical findings, it is suggested that a better and strong financial system in the form of financial markets and efficiency would provide some outstanding long-run outcomes in the form of low carbon emission. Therefore, financial development should be among the key priorities in the Chinese region. However, contrary to financial development, green technology innovations should also be coupled with government policy. In short-run estimations, more promotion is required to achieve sustainable outcomes in lower carbon dioxide emissions. For this reason, it is suggested that environmental regulations may be considered a promotional tool for different industries in utilizing those technologies having their sustainable results. Besides, this study is limited in regional implications and non-consideration of different proxies of financial development (i.e., financial markets and financial institutions), green growth, and energy transition. Future studies are highly suggested to add these factors in analyzing the trends in carbon emission in different economies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

JY: conceptualization, data, methodology, formal analysis, and visualization; YS: conceptualization, writing—original draft,

writing; HS: data, methodology, formal analysis, and visualization; CL: conceptualization, writing—original draft, and writing—review and editing; NA: writing—review and editing; and KZ: writing—review and editing.

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Can Low-Carbon Technological Innovation Reduce Haze Pollution? —Based on Spatial Econometric Analysis

Shunlin Jin[1]*, *Weidong Wang*[1]*, *Sikandar Ali Qalati*[1]*, *Caijing Zhang*[2], *Na Lu*[1], *Guyu Zhu*[3] *and Jiahui Wu*[4]

[1]School of Economics and Finance, Jiangsu University, Zhenjiang, China, [2]School of Public Administration, Nanjing Agricultural University, Nanjing, China, [3]Institute of Blue and Green Development, Shandong University, Weihai, China, [4]Faculty of Business Administration, University of Macau, Zhuhai, Macau SAR, China

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Edited by:
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Mohsin Shahzad,
Dalian University of Technology, China

***Correspondence:**
Shunlin Jin
shunlinjin2000@163.com
Weidong Wang
wangwd@ujs.edu.cn
Sikandar Ali Qalati
qalati@ujs.edu.cnmailto

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Exploring the co-benefits of low-carbon tech-innovation in response to climate change on haze pollution is an important foundation for China's ecological construction, and also a key path to the common goal of carbon and haze reduction. Based on the STIRPAT model and EKC hypothesis, the dynamic spatial Durbin model (SDM) is constructed to empirically analyze the co-benefits and the mechanism of low-carbon tech-innovation on haze pollution in 30 Chinese provinces from 2006 to 2018. The results show that 1) haze pollution in different regions of China shows significant temporal and spatial correlation. 2) China's low-carbon tech-innovation brings the co-benefits of haze pollution suppression and long-term positive externalities between regions. 3) Environmental policy and industrial structure play a moderating and mediating role, respectively, the former produces the "innovation offset" effect. 4) Both types of low-carbon tech-innovation can suppress haze pollution, but gray tech-innovation shows better haze control ability and cross-regional diffusion ability. Therefore, a long-term mechanism for haze control and joint prevention and control should be established to prevent the rebound and agglomeration of haze, and balance the development of different types of low-carbon technologies to achieve coordinated control of carbon emissions and haze.

Keywords: low-carbon tech-innovation, haze pollution, technological heterogeneity, spatial spillover effect, dynamic spatial Durbin model

1 INTRODUCTION

Since China's reform and opening up, the rapid industrialization process and the rise of the manufacturing industry have promoted the rapid development of China's economy, which has attracted global attention. However, becoming the world's second-largest economy has come at the cost of severe haze pollution and a sharp decline in air quality across the country. Haze is generally an aerosol system composed of $PM_{2.5}$, NO_2, and other pollutants (Peng et al., 2013). According to the *2020 China Ecological Environment Bulletin* released by the Ministry of Ecology and Environment of China[1], 135 out of 337 prefecture-level cities in China exceeded ambient air quality standards,

[1]https://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/202105/P020210526572756184785.pdf.

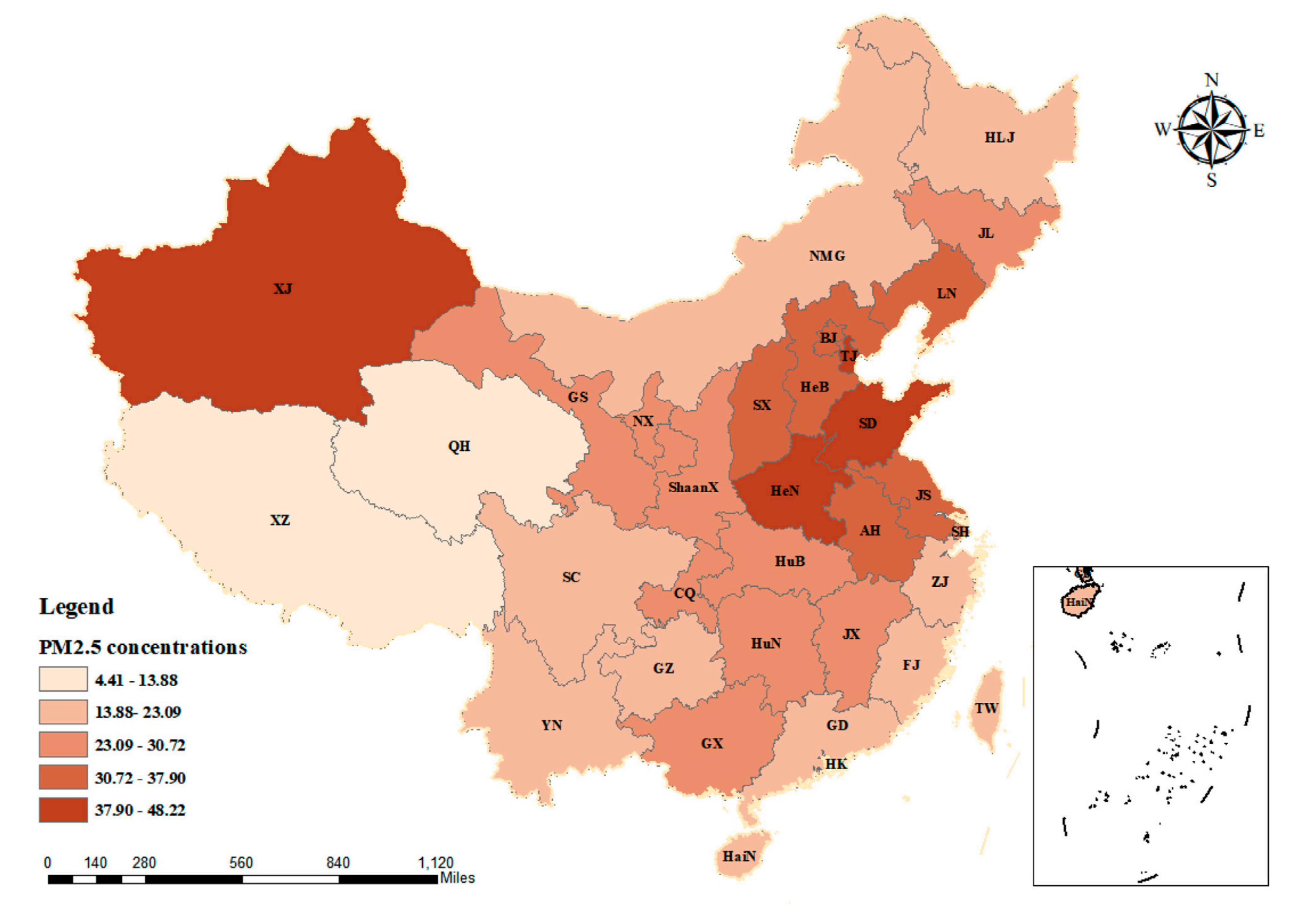

FIGURE 1 | $PM_{2.5}$ concentration in China in 2018.

accounting for 40.1%. In total, 337 cities suffered from severe pollution for 345 days, with $PM_{2.5}$, O_3, PM_{10}, NO_2, and SO_2 as the primary pollutant, and $PM_{2.5}$ (fine particulate matter with an aerodynamic diameter less than or equal to 2.5 μm) being the largest. The number of days exceeding the standard with it as the primary pollutant accounted for 51% of the total number of days, exceeding the standard. According to World Health Organization data[2], around the world, seven million people die from air pollution every year. A large amount of haze pollution will cause serious damage to the ecological environment, climate change, air pollution, and human health (Cai et al., 2018; Yang et al., 2021; Usman et al., 2022a; Wang et al., 2022). At present, severe haze pollution has brought a series of impacts on China's ecological environment and economic development (Gan et al., 2021; Yan and Cao, 2021). Moreover, these adverse effects are not only limited to one region but also affect all regions of the world as the atmosphere flows (Usman et al., 2022b). Therefore, how to effectively suppress haze pollution and reduce regional $PM_{2.5}$ concentration to improve air quality has been paid close attention by various countries around the world. The Chinese government has also issued relevant policies aimed at severe air quality, including the *Three-year Action Plan to Win the Battle Against Blue Sky* in2018[3]. However, the haze pollution problem in China is still severe. As far as the $PM_{2.5}$ concentration of each province in 2018 is concerned (see **Figure 1**), more than half of the provinces still failed to meet the World Health Organization's $PM_{2.5}$ concentration standards for the first and second transitional phases (35 μg/m3 and 25 μg/m3). Overall, China still has a long way to go to reduce haze pollution.

Compared with haze pollution, carbon emissions, which exacerbate climate change, seem to be more important in China and the world. In the face of the threat of global climate change, the EU issued the *EU Adaptation to Climate Change Strategy* in 2021, mainly to achieve carbon neutrality through technological innovation and fiscal policies, and entered the fourth stage of the carbon emissions trading system in 2021 (Anke et al., 2020). The United States has reached the peak of carbon emissions in 2007 and actively develops and utilizes new

[2]https://www.who.int/zh/health-topics/air-pollution#tab=tab_1.

[3]http://www.gov.cn/fuwu/2019-12/10/content_5459931.htm.

carbon reduction technologies to achieve carbon neutrality (Sergey et al., 2021). In 2015, China signed a commitment under the *Paris Agreement* to reduce energy intensity by 60–65% by 2030 compared with 2005, and to peak CO_2 emissions around 2030 or even earlier. In 2020, China announced new targets for its nationally determined contributions, including peak carbon emissions and carbon neutrality, which were included in the *14th Five-Year Plan* (2021–2025), and a large number of relevant policies were introduced. This shows that carbon reduction has become a top priority for China at present and in the coming decades.

A major obstacle to carbon reduction is the difficulty of reconciling the global, long-term benefits of climate change with the short-term local costs. However, relevant studies have suggested that carbon emission reduction can also reduce other emissions of air pollution, such as SO_2, NO_x, and $PM_{2.5}$, which can bring short-term and local health benefits and relieve the short-term cost pressure of emission reduction (Gehrsitz, 2017; Zhang et al., 2017; Cai et al., 2018; Wang T. et al., 2020a). Two air pollutant treatment methods, process management, and source control are closely related to the realization of emission reduction targets (Qian et al., 2021). Most of these studies focused on the assessment of air quality and health benefits of carbon mitigation policies such as carbon trading, carbon prices, and carbon tax (Shindell et al., 2018; Chang et al., 2020; Wang W. et al., 2020b), focus on assessing the benefits of individual technologies such as biofuels and carbon sequestration (CCS) for tackling climate change (Ou et al., 2018; Wang T. et al., 2020a), balance carbon reduction and haze reduction and the resulting high cost, and endogenous technological progress is often given high expectations (Acemoglu et al., 2012; Yi et al., 2020; João et al., 2022). From the perspective of enterprises, to cope with the government's increasingly strict environmental policies, it will carry out technological innovation to relieve the cost pressure (Ouyang et al., 2020; Zhu et al., 2021; Cui et al., 2022; Ding and Shahzad, 2022), which is consistent with Porter's hypothesis. According to the endogenous growth theory, knowledge accumulation or innovation is the result of enterprises' "conscious" R&D investment (Romer, 1986). Such "consciousness" at this time is reflected in alleviating the pressure of environmental cost, which is also consistent with the R&D model. The formation of industrial clusters creates favorable conditions for knowledge flow, which helps to accelerate knowledge spillover among enterprises within clusters (Chyi et al., 2012) and stimulate the generation of "MAR externalities," thus improving regional innovation capability, and such knowledge spillover itself plays an important role in improving energy efficiency (Sun et al., 2021). Since the 21st century, China's crazy technological catch-up and even technological transcendence in some fields indicate that the China's innovation level has been significantly improved (Mu and Lee. 2005; Lyu et al., 2019; Jin et al., 2022). In terms of low-carbon technologies, the number of patent applications increased by more than 10 times during the 12 years from 2006 to 2018 (see **Figure 2**), and the technological innovation level of all provinces has been significantly improved[4] (see **Figure 3**). Such vigorous low-carbon tech-innovation activities will certainly have a positive effect on carbon reduction, which has been studied in detail (Lin and Ma, 2022a; Lin and Ma, 2022b), but whether the increasingly large low-carbon technological innovation is also conducive to reducing haze reduction, to play the dual role and co-benefits of carbon reduction and haze reduction has not been systematically discussed.

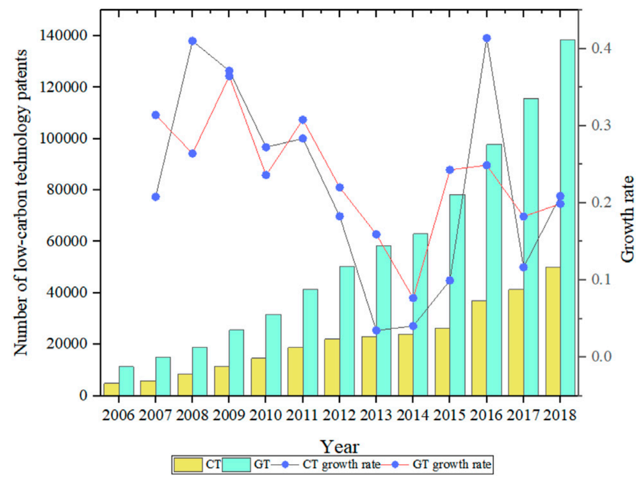

FIGURE 2 | Patent applications and the growth rate of clean and gray technologies in China from 2006 to 2018.

Accordingly, in the context of a growing body of research focusing on the co-benefits of mitigating global climate change and curbing air pollution, this article took China as an example and used an empirical model to analyze the effect of low-carbon tech-innovation committed to climate change on the suppression of haze pollution. In addition, low-carbon tech-innovation is divided into clean and gray technology to study the heterogeneity of haze pollution prevention effects of different technologies. On this basis, the mechanism of suppressing haze pollution by low-carbon technological innovation is further analyzed. To improve the rationality and reliability of the research, we integrated the STIRPAT model and classical EKC hypothesis to construct a spatial econometric model, including the spatial spillover effect and used Y02 low-carbon patent data to measure low-carbon technological innovation activities more objectively.

This study filled the gaps in the current research on the co-benefits and positive externalities of air quality brought about by low-carbon technological innovation and produced three research contributions 1) we systematically studied the co-benefits of haze reduction brought by endogenous low-carbon tech-innovation as a whole, and expanded the research on "externalities" of low-carbon tech-innovation; 2) heterogeneity analysis of low-carbon technology was conducted to distinguish the difference between clean and gray technology in the process of haze pollution suppression; 3) in the

[4]Guangdong, Jiangsu, and Shandong have the highest number of low-carbon patent applications.

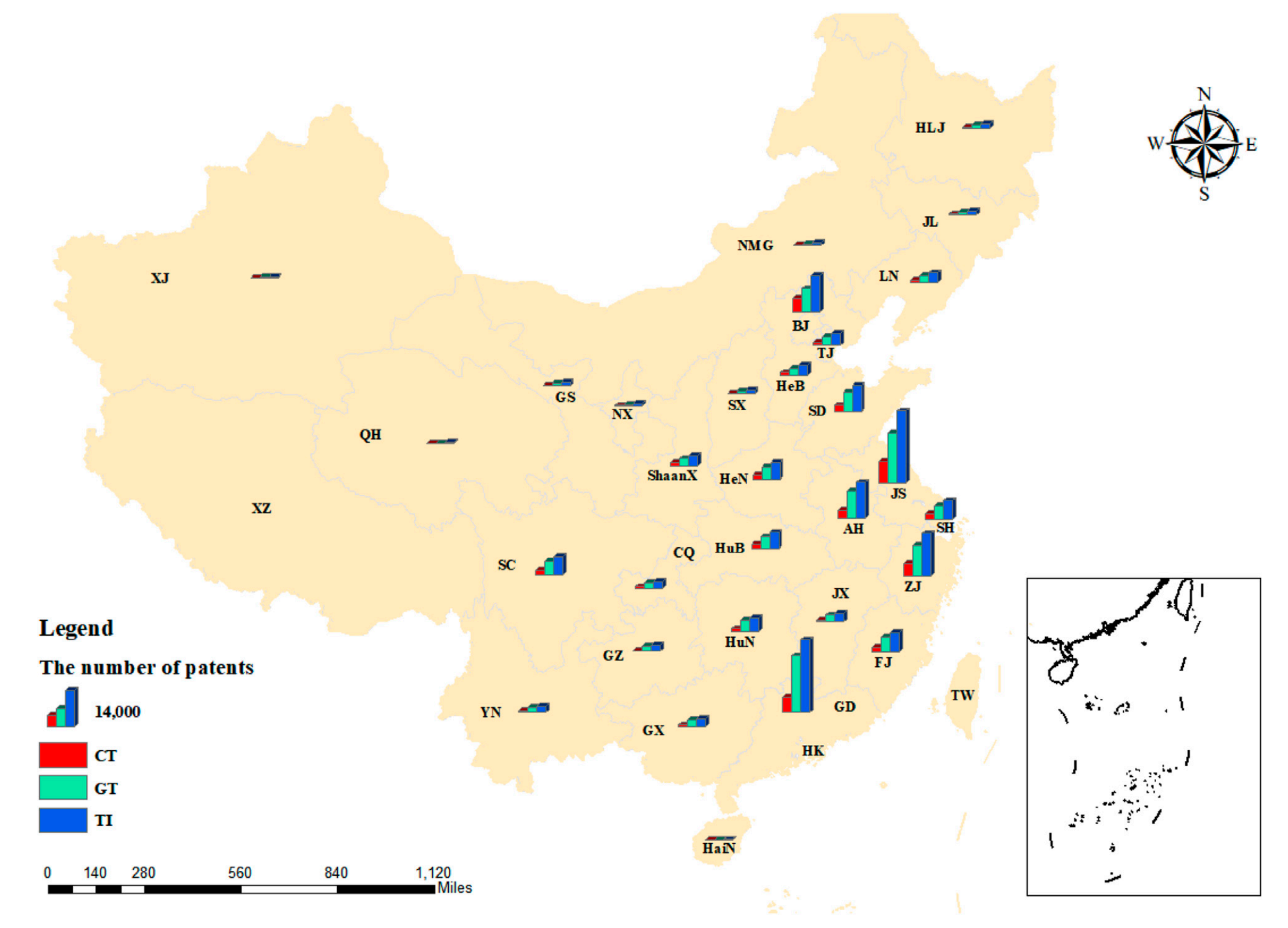

FIGURE 3 | Number of patent applications for low-carbon technologies by provinces in China in 2018.

study of co-benefits, the spatial nature was included, and the mechanism analysis was carried out from two aspects of environmental policy and industrial structure. The findings of these efforts will help China achieve its dual goals of carbon neutrality and air quality improvement as soon as possible through the development of low-carbon tech-innovation. The remaining of this article is structured as follows: **section 2** provides the literature review and mechanism analysis. **Section 3** introduces the methods and data. The empirical results and discussions are presented in **section 4**. Finally, **section 5** puts forward the conclusions, policy implications, and future research direction. To show the author's research ideas, we drew the following flow chart (**Figure 4**).

2 LITERATURE REVIEW AND MECHANISM ANALYSIS

2.1 Co-benefits of Air Quality and Climate Change

Climate change and haze pollution have the same root and origin, creating great potential for joint control (Thambiran and Diab, 2011; Vandyck et al., 2018). Studies on the co-control or co-benefits of carbon reduction and haze reduction focus on the reduction of local air pollutant emissions through measures aimed at reducing greenhouse gas emissions, or the reduction of greenhouse gas emissions through measures aimed at reducing air pollutants in response to global climate change (Rypdal et al., 2007; Tollefsen et al., 2009; Yeora. 2010). For the former scenario, simulation is often used. For example, Li et al. (2019) combined the China-TIMES model with the GAINS-China model to simulate the synergistic effect of different carbon mitigation strategies on air quality improvement and found that different low-carbon development methods could further improve China's air quality. In the long term, it can also reduce the cost of air pollutant control. Wei et al. (2017) used the WRF-Chem model to investigate the air quality benefits brought by carbon emission reduction strategies in four sectors in China, and found that such benefits were particularly evident in the industrial sector, emphasizing the importance of carbon mitigation in the industrial sector to achieve the dual goals of carbon reduction and haze reduction (Wei et al., 2017). In addition to air quality, the co-benefits generated by carbon mitigation are also reflected in the health. These benefits come from energy system

transformation, fuel and tech-innovation in some industries, and carbon mitigation policies (Thompson et al., 2014; West et al., 2013; Driscoll et al., 2015; Garcia-Menendez et al., 2015; Brian et al., 2020; Peng et al., 2021). As an important externality of climate change, air pollution and human health will be improved in the implementation of climate policies, including the transformation and upgrading of industrial sectors, and these improvements are expected to cover the cost of policy implementation (Shindell et al., 2016; Li et al., 2018; Vandyck et al., 2018). Markandya et al. (2018) found that the health synergies greatly exceed the costs of achieving the Paris agreement targets (2°and 1.5°C) for coordinated control of greenhouse gases and air pollutants in all cases, and China is expected to gain a net benefit of using 0.27–2.31 trillion in the process of achieving this goal, becoming the biggest winner. Yang et al. (2013) calculated the co-benefits of energy-saving technologies in the China's cement industry. Cai et al. (2018) estimated that 18–62% of the implementation cost of renewable power generation in the power generation industry can be covered by health benefits by 2030, and health benefits will increase significantly to 3–9 times the cost by 2050. However, based on the previously mentioned literature, we find that most of the studies on co-benefits focus on carbon emission trading, carbon tax, and other environmental policies, or focus on some industrial sectors (such as the power sector, transportation sector, automobile industry, and cement industry) and some specific renewable energy or negative emission technologies (such as CCUS, PV, and biomass energy) (Ou et al., 2018; Yang et al., 2018; Wang T. et al., 2020a), the co-benefits of low-carbon tech-innovation on air quality is neglected.

2.2 Haze Pollution and Technological Innovation

As a global problem, how to effectively alleviate air pollution has received urgent attention from almost all countries. Existing studies mostly discuss how to effectively suppress haze pollution from two aspects. The first is national environmental policies. Zhou et al. (2021) found that appropriate environmental regulations can help promote the upgrading of industrial structure and energy structure to suppress haze pollution, and there is a nonlinear relationship between the two. Zhang M. et al. (2019) also emphasized this point, arguing that environmental regulation changes the direction of influence of industrial structure on haze pollution. Liu et al. (2021) clarified that China's emissions trading scheme (ETS) reduced $PM_{2.5}$ in China, and analyzed the social, health, and economic benefits brought by this process. The second is the influence of economic structure change on suppressing haze pollution. Both positive and negative externalities may be caused by industrial agglomeration, which is highlighted by the "scale effect" and "crowding effect." The latter will undoubtedly aggravate haze pollution, and there is still no conclusion on what effect industrial agglomeration plays (Li et al., 2021). From the perspective of urbanization, Feng and Wang, (2019) found the relationship between urban sprawl and haze pollution by using the dynamic spatial Durbin model (u-shaped curve in large cities and inverted U-shaped curve in small- and medium-sized cities). Similarly, Wang et al. (2022) also used the dynamic spatial Durbin model to analyze the impact of economic agglomeration in 74 cities in the Yellow River basin of China on haze pollution, and found an N-shaped relationship between economic agglomeration and haze pollution, emphasizing the improvement of economic agglomeration to improve the mechanism of haze prevention and control.

However, technological innovation plays an important role in both environmental regulation and economic structure change (Jahanger et al., 2022). On the one hand, according to the endogenous growth theory, the technology progress is endogenous, which is determined to maintain a sustained economic growth factor (Romer, 1986), Technological innovation can be consciously used by enterprise to improve their production efficiency, and promote the technological level between clusters or regions through uncontrollable knowledge spillover, thus promoting the upgradation of the industrial structure and energy structure, and realizing the goal of optimizing the national economic structure (Chyi et al., 2012; Shi and Lai, 2013). On the other hand, according to the Porter's hypothesis, green technological innovation, as an effective response to government environmental regulations, can be used by enterprises to reduce production costs and thus obtain the power of sustainable development (Feng et al., 2021). Therefore, technological innovation or technological progress can be expected to achieve co-development of the economy and environment. Acemoglu et al. (2016) pointed out that increasing R&D investment is conducive to improving environmental quality and curbing haze pollution to achieve the goal of energy conservation and emission reduction. Meanwhile, the spatial spillover effect of technological innovation in this process has also been emphasized (Liu, 2018). Yet for all these advantages, there is still a lot of ambiguity. For example, Jaffe et al. (2002) found that the role of technological innovation in suppressing haze pollution is not clear, and the process of action will be largely influenced by the level of supervision, and environmental policies including the level of technological diffusion. At the same time, Popp et al. (2009) also believed that the existing technological development could not solve the environmental problem, and to solve this problem, a huge price must be paid, this is in line with Jaffe's view, and is different from Porter and other "win–win" theorists. A large number of technological innovations will inevitably bring high-cost input, which may promote innovation and development and cause greater environmental pollution. However, low-carbon tech innovation has always been faced with "dual externality" constraints, leading to the embarrassing situation that innovation input is difficult to recover monopoly benefits and environmental benefits (Horbach et al., 2012). In addition, technological innovation is not only an independent variable but also influenced by energy price (Popp, 2002), environmental policy (Jaffe et al., 2002; Feng et al., 2021), income effect (Yi et al., 2020), energy rebound effect (Horace and Robin, 2006; Yi et al., 2020), *etc*. For example, Yi et al. (2020) found that due to the energy rebound effect, energy-saving technological progress cannot effectively reduce haze pollution, but at the same time, they also emphasize the importance of

classifying technological innovations to explore their role in haze pollution, while technological innovations invested without considering emission reduction are considered to be ineffective in curbing haze pollution (Shao et al., 2016).

To sum up, the aforementioned literature has also faced the following problems: 1) these studies only involve environmental policies, changes in economic structure, or the role of specific technologies in suppressing haze pollution, and there are few articles on technological innovation. In particular, there are very few studies on the effect of low-carbon technologies on haze pollution from the overall perspective of technology. The overall changes and effects of endogenous low-carbon tech-innovation are ignored, and the double benefits of carbon reduction and haze reduction have not been paid attention to by the research on the "externalities" of low-carbon technologies. 2) There is insufficient research on the difference about common benefits of important categories of low-carbon technologies as a whole. Low-carbon technologies may vary in cost, reliability, and environmental impact (Shi et al., 2017). Therefore, it is very important to categorize low-carbon technologies as a whole. At present, the classification of clean and gray technology[5] has been emphasized (West, 2004; Acemoglu et al., 2016; Aghion et al., 2016). Therefore, it is necessary to use this classification method to explore the heterogeneity of the impacts of low-carbon technologies on co-benefits. 3) The spatial effect has not been emphasized in the study of co-benefits. Although haze has the characteristics of local and short-term, as an air pollutant, it must have certain spatial spillover, especially in China, a geographically connected country, so it is more necessary to emphasize spatial spillover in the study of the mechanism of low-carbon technological innovation affecting haze.

2.3 Mechanism Analysis

Considering the complexity of low-carbon tech-innovation, the implementation of environmental policy and the change of economic structure are likely to influence its effect on inhibition of smog pollution of size. Therefore, it is extremely important to combine the two and explore the mechanism of low-carbon tech-innovation to suppress haze pollution. Unfortunately, there is no systematic research discussion at present. We include environmental regulation and industrial structure, two variables that scholars generally attach importance to, in the study to analyze the mechanism of low-carbon tech-innovation to suppress haze pollution. There are three main types of environmental regulation ("command–control environmental regulation," "voluntary environmental regulation," and "market–incentive environmental regulation"). On the one hand, the Porter's hypothesis holds that environmental regulation can promote enterprise technological innovation to improve environmental quality and bring the innovation compensation effect, which has also been widely confirmed in China (Zhu et al., 2021), but on the other hand, in the eyes of the new classical economists, powerful environmental regulation may bring the highest processing costs to offset the benefits of technology innovation (Barbera and McConnell, 1990). In addition, heterogeneous environmental regulations themselves have internal uncertainties. Therefore, it is extremely important to explore the combination of environmental policies and low-carbon tech-innovation to suppress haze pollution. It remains to be considered whether environmental regulations magnify or inhibit the effect of low-carbon tech-innovation. Therefore, we focus on the role of "command–control environmental regulation" in this process because this kind of environmental regulation has the most obvious "compensation effect" or "offset effect" on technological innovation (Tang et al., 2020). Meanwhile, low-carbon tech-innovation will inevitably affect a country's industrial structure, and the upgrading of industrial structure will help to the environmental quality of ascension (Shi and Lai, 2013). Therefore, it is necessary to discuss in detail whether China's current low-carbon tech-innovation can promote the upgradation of industrial structures to cope with haze pollution.

Therefore, this article takes haze pollution as the explained variable, and the total number of low-carbon tech-innovation and its subcategories as the core explanatory variables, the STIRPAT model and the classical EKC hypothesis were combined to construct a dynamic spatial econometric model, which mainly analyzes three aspects spatial spillover effect of haze pollution; the effect and mechanism of low-carbon tech-innovation on haze pollution; and heterogeneity of impacts of clean and gray technologies. The innovation and improvement of the research include the following: first, it analyzed the role and mechanism of overall low-carbon tech-innovation and major categories of low-carbon technological innovation on haze pollution, expanded the research in the field of air quality benefits of current measures to cope with climate change, and expands the scope of "externalities" of low-carbon tech-innovation; second, the spatial spillover of haze is included to reveal the impact of low-carbon tech-innovation on haze pollution more accurately and completely; and third, empirical methods based on historical data are used to study the co-benefits of carbon mitigation measures, which is different from the previous simulation methods based on scenario settings.

3 MODELS AND DATA

3.1 Construction of the Spatial Econometric Model

3.1.1 Selection of the Spatial Weight Matrix

To improve the robustness of the spatial econometric model, scientific and reasonable spatial weight matrix design is indispensable. This article mainly constructs the following two common spatial weight matrices:

(1) The geographical distance spatial weight matrix (w_1): although the traditional adjacency matrix considers the spatial relationship between geographically adjacent regions; it ignores the interaction between two regions that

[5]Clean technology refers to low-carbon technologies related to zero-carbon production or consumption, while gray technology is not absolutely carbon-free, but has the potential to save energy or mitigate climate change.

are not adjacent but close to each other[6]. Therefore, the spatial weight matrix of geographical distance is set as follows:

$$w_1 = w_{ij} = \begin{cases} \frac{1}{d_{ij}}, i \neq j \\ 0, i = j \end{cases},$$

where w_{ij} is the matrix element of row i and column j, and d_{ij} is the straight-line distance between province i and province j. $\frac{1}{d_{ij}}$ is the reciprocal of the linear distance between the two regions, and the greater the distance between the two provinces, the smaller w_{ij} is. We use ArcGIS to calculate the weights according to the center coordinates of each province and carry out standardized processing.

(2) The economic distance spatial weight matrix (w_2): there are certain limitations in setting the matrix only considering the interaction between geographically adjacent regions or considering the influence between two regions only from the geographical distance[7]. Therefore, we establish the spatial weight matrix based on the characteristics of economic and geographical distance to describe the asymmetry of the spatial effect more accurately. The matrix form of economic distance space is set as follows:

$$w_2 = w_1 diag\left(\overline{Y_1}\Big/\overline{Y}, \overline{Y_2}\Big/\overline{Y}, \ldots, \overline{Y_n}\Big/\overline{Y},\right),$$

where w_1 is the spatial weight matrix of geographical distance, $\bar{Y}_i = \frac{1}{t_1 - t_0 + 1}\sum_{t=t_0}^{t_1} Y_{it}$ is the average per capita GDP of province i during the investigation period, $\bar{Y} = \frac{1}{n(t_1 - t_0 + 1)}\sum_{i=1}^{n}\sum_{t=t_0}^{t_1} Y_{it}$ is the average per capita GDP of all provinces during the inspection period, and w_2 is obtained after standardization. Through the formula, it can be found that the greater the proportion of the mean per capita GDP of a region to the mean per capita GDP of all regions, the greater the impact it will have on the surrounding regions.

3.1.2 The Spatial Correlation Model

For the analysis of flow factors, the spatial spillover effect is indispensable. Endogenous low-carbon tech-innovation will inevitably form a spillover effect, and according to new economic geography and new trade theory, regional proximity is highly correlated with the technology spillover level (Krugman, 1991), and more similar the regional innovation level and the economic development level is, the stronger the knowledge or technology spillover will be. This similarity can help reduce transaction costs or give play to "MAR externalities" (Sun et al., 2021). At the same time, haze also has trans-regional mobility, and its spatial spillover effect needs to be further discussed. Therefore, only analyzing the impact of innovation activities and environmental pollution in the same region will lead to the problem of model setting bias, and a more reasonable spatial econometric model is needed. Before building the model, global Moran's I and local Moran's I were first selected to test the spatial correlation between haze pollution (*PM*) and low-carbon tech-innovation (*TI*). Global Moran's I used for the global space autocorrelation test is a common indicator, and the formula is as follows:

$$Global{\bullet}I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{s^2\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}},$$

where $s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}$ represents the sample variance, w_{ij} is the weight value between region i and region j in the spatial weight matrix, and $\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$ is the sum of the spatial weight value between all regions. According to the formula, the value of I is between −1 and 1[8].

The local Moran's I scatter plot is adopted for the local spatial correlation test, and its calculation formula is as follows[9]:

$$Local{\bullet}I_i = \frac{(x_i - \bar{x})}{s^2}\sum_{j=1}^{n} w_{ij}(x_j - \bar{x}).$$

3.1.3 Model Specification

Considering that the basic research framework of influencing factors of environmental pollution is mainly carried out around the STIRPAT model and the EKC hypothesis[10], this article discusses the role of low-carbon tech-innovation in reducing haze pollution by combining the two. The STIRPAT model based on panel data is in the form of $I_{it} = aP_{it}^{b}A_{it}^{c}T_{it}^{d}e$, where I represents environmental impact, P represents population size, A represents per capita wealth, T represents the technological level, and e represents error term. The natural logarithm of both sides of the model can be written as follows:

$$LnI_{it} = \alpha + bLnP_{it} + cLnA_{it} + dLnT_{it} + e_{it}. \quad (1)$$

Considering that a major advantage of the STIRPAT model is that it can not only estimate the parameters of the model but also appropriately improve the influencing factors of the

[6]For example, in addition to the influence of Beijing on Tianjin and Hebei, which are geographically close to each other, we cannot ignore the influence of Beijing on other regions, which are geographically close to each other.

[7]In real economic life, in addition to being affected by geographical proximity, a higher level of economic development in a region will also bring a certain radiation pull effect on the relatively low level of economic development in the region.

[8]When *Moran's I > 0*, it indicates that the overall existence space is positively autocorrelated. When *Moran's I < 0*, it means that there is negative spatial autocorrelation. If *Moran's I* is close to 0, it indicates that there is no spatial correlation between regions.

[9]When Moran's I > 0, it indicates that there is positive spatial autocorrelation on the whole, that is, areas with high haze pollution gather together (High–High), and areas with low haze pollution gather together (Low–Low). When Moran's I < 0, it indicates that there is negative spatial autocorrelation, that is, low-value regions usually gather around high-value regions (Low–High), or high-value regions usually gather around low-value regions (High–Low). If Moran's I is close to 0, it indicates that there is no obvious aggregation between regions.

[10]According to EKC hypothesis, there is an inverted U-shaped relationship between economic development and environmental pollution. In the early stages of development, economic growth without regard to environmental protection will exacerbate environmental pollution. When a certain level is reached, the economic structure will be adjusted and environmental quality will become the focus again (Usman and Jahanger, 2021).

environment. This article will follow the classical EKC hypothesis to make appropriate improvements to the model[11], and get **Eq. 2**:

$$LnI_{i,t} = \alpha + bLnP_{i,t} + cLnT_{i,t} + d_1LnA_{i,t} + d_2\left(LnA_{i,t}\right)^2 + e_{i,t}. \quad (2)$$

In the process of building the spatial panel model, Elhorst, (2012) found that the spatial interrelationship between variables was not only reflected among regions in the current period but also influenced by the behaviors of regions in the previous period. In addition, the influence relationship of spatial dependence between regional variables is not only reflected in the region of the current period but also is affected by the key influence of the previous period due to the temporal inertia characteristics of the variables. Therefore, the modeling of the regional haze formation mechanism needs to further consider the dynamic spatial dependence in time. In addition, the spatial Durbin model (SDM) is a general form of spatial error (SEM) and the spatial lag model (SAR) and can be well used to study the dynamic spatial dependence relationship between regions. Therefore, this article will choose the dynamic spatial Durbin model (SDM) to study the effect of technological innovation in addressing climate change on haze reduction. Based on **Eqs. 1**, **2**, the model is further improved in **Eq. 3**:

$$\begin{aligned} LnPM_{i,t} &= \alpha + \varphi LnPM_{i,t-1} + \lambda\left(WLnPM_{i,t}\right) + \theta\left(WLnPM_{i,t-1}\right) \\ &+\rho_1 LnTI_{i,t} + \rho_2\left(WLnTI_{i,t}\right) + \delta_1 X_{i,t} + \delta_2 WX_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}, \end{aligned} \quad (3)$$

where i represents province, t represents time, PM represents haze pollution, TI represents low-carbon technological innovation, X represents control variables[12], ρ_1 represents the estimated coefficient of the core explanatory variable, δ represents the estimated coefficient of the control variable, and μ_i and ν_t, respectively, represent individual effects and time effects. ε_{it} is the residual term, ϕ, λ, and θ, respectively, represent the previous estimate coefficient of the haze pollution, spatial lag estimating coefficient, and time–space lag estimation coefficient on the issue of haze pollution levels influence on the current pollution level, regional haze pollution levels influence on adjacent regional haze pollution, and the influence of haze emission in the previous period on haze pollution in neighboring areas and ρ_2 is the spatial lag estimation coefficient of low-carbon tech-innovation[13].

In order to further test the mechanism of low-carbon tech-innovation on haze pollution, two variables, environmental policy and industrial structure, are introduced to construct the moderating effect model and the mediating effect model, respectively. The first is the moderating effect model **Eq. 4**:

$$\begin{aligned} LnPM_{i,t} &= \alpha + \varphi LnPM_{i,t-1} + \lambda\left(WLnPM_{i,t}\right) + \theta\left(WLnPM_{i,t-1}\right) + \rho_1 LnTI_{i,t} \\ &+\gamma_1 LnTI_{i,t} \times LnEP_{i,t} + \rho_2\left(WLnTI_{i,t}\right) + \gamma_2 WLnTI_{i,t} \times LnEP_{i,t} \\ &+\delta_1 X_{i,t} + \delta_2 WX_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}. \end{aligned} \quad (4)$$

We multiply the core explanatory variable TI and the moderating variable EP, and analyze their spatial effects simultaneously and the mediating effect model is **Eqs 5–7**:

$$LnPM_{i,t} = \zeta + \zeta_1 LnTI_{i,t} + \zeta_2 X_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}, \quad (5)$$

$$IS_{i,t} = \psi + \psi_1 LnTI_{i,t} + \psi_2 X_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}, \quad (6)$$

$$LnPM_{i,t} = \tau + \tau_1 LnTI_{i,t} + \tau_2 IS_{i,t} + \tau_3 X_{i,t} + \mu_i + \nu_t + \varepsilon_{i,t}. \quad (7)$$

The Causal steps approach proposed by Baron and Kenny (1986) is generally adopted for the setting of the mediation effect model. **Equation 5** is first regression and if ζ_1 is significant, it indicates that low-carbon tech-innovation significantly affects haze pollution; **Eq. 6** is then regression if ψ_1 is significant. Then, it indicates that low-carbon tech-innovation can affect the industrial structure. Finally, regression is performed on **Eq. 7**. If τ_1 and τ_2 are significant at the same time, it indicates that the industrial structure plays a partial mediating role; if τ_1 is not significant, but τ_2 is significant, it indicates that the industrial structure plays a complete mediating role.

3.2 Data and Variables

3.2.1. Explained Variable

Haze pollution (*PM*): haze pollution is mainly caused by particulate matter (*PM*), which is often measured by its finer particles, $PM_{2.5}$. The data used in this study were raster data from the Atmospheric Composition Analysis Group of Washington University[14] based on the annual mean global $PM_{2.5}$ concentration monitored by satellites. ArcGIS software was used to analyze the annual average $PM_{2.5}$ concentration of Chinese provinces from 2006 to 2018[15].

3.2.2 Core Explanatory Variable

Low-carbon tech-innovation (TI) A is measured by Y02 category patents in the Cooperative Patent Classification System (CPC) jointly promulgated by the European Patent Office (EPO) and the United States Patent Office (USPTO) in 2013, using the number of patent applications filed by Chinese in China. CPC combines the strengths of the USPC, ECLA, and IPC to provide information on technology, functionality, and product applications. To subdivide low-carbon technologies into clean

[11]On the basis of the general model, we add the quadratic term representing the economic level. (A) If the quadratic term coefficient is negative and the primary term coefficient is positive after regression, it indicates that the EKC hypothesis is established.

[12]Including per capita GDP, openness, population density, and energy structure.

[13]It reflects the impact of low-carbon tech-innovation in this region on haze emission in the neighboring region. If the estimation result of this coefficient is significantly positive, it indicates that the technological innovation in this region has significantly aggravated the haze pollution level in the neighboring region. If the estimation result is significantly negative, it indicates that the regional technological innovation has significantly suppressed the haze pollution level in the neighboring areas. If not significant, it indicates that the relationship between the two variables is not obvious.

[14]https://sites.wustl.edu/acag/datasets/surface-pm2-5/

[15]The reason is that although the actual monitoring data collected by ground observation stations with their own advantages can more truly reflect the haze pollution situation of the stations, the distribution of the PM2.5 concentration is not limited to a single station, and there are significant spatial differences in the same area. Therefore, if the data of ground monitoring stations are used for analysis, It will only provide a rough measurement of the haze pollution situation in the region, which will bring a large error to the actual estimation results. By contrast, satellite-based data on haze pollution concentrations ($PM_{2.5}$) can be used to give a more accurate picture of a region's $PM_{2.5}$ concentration.

technologies and gray technologies, each subclass is identified based on the concepts of clean and gray low-carbon technologies in the existing literature, based on the class Y02 of the cooperative patent classification (Wang W. et al., 2020b). In this study, the whole Y02 category represents low-carbon technologies. The patents with the CPC code in **Supplementary Appendix S1** belong to clean technologies, while the rest Y02 patents belong to gray technologies.

3.2.3 Control Variable

Control variable (*X*): based on the existing studies, four variables, population density, economic growth, openness, and energy structure, were selected as control variables 1) population density (*POP*): in this article, the ratio of population to the area of administrative division is used as a proxy index of the population size. Based on relevant studies (Fan and Xu, 2020), it is found that the agglomeration effect of the population usually leads to environmental deterioration and further aggravates haze pollution, so the coefficient of this variable is expected to be positive. 2) The level of economic development (*PGDP*): in this paper, per capita GDP is used to measure the regional economic development level. Referring to existing studies, there are two main views on the relationship between economic development and environmental quality[16]. We include the primary and secondary terms of economic growth into the model respectively to test the aforementioned two views. 3) Openness (*FDI*): in this article, the actual utilization of foreign direct investment in each administrative division is used to measure openness and convert into RMB according to the current USD to the RMB exchange rate. Openness to the outside world plays an important role in China's environmental research and is an important factor that cannot be ignored. However, relevant research conclusions are not uniform, mainly manifested in two hypotheses the "Pollution Heaven" hypothesis and the "Pollution Halo" hypothesis[17]. 4) Energy structure (*ES*): in this article, the proportion of coal consumption in total energy consumption is used to measure the energy structure. China is a big coal consumer, and the massive coal-burning caused by industrialization has become an important source of haze emission in China. Therefore, the expected coefficient is positive.

3.2.4 Moderating and Mediating Variables

Environmental Policy (*EP*): we choose "command–control environmental regulation" to represent environmental policy. Since the environmental policy is generally considered to have a "compensation effect" or "offset effect" on technological innovation, therefore, incorporating it into the model to analyze the moderating effect is helpful to reveal what effect China's environmental policy plays in the process of low-carbon tech innovation affecting haze pollution—compensation or offset? According to existing studies, the composite index of the emission of various pollutants is used to measure the intensity of environmental regulations. the higher the intensity of pollution discharge, the stricter the command-and-control regulation. Detailed calculation procedures are given in **Supplementary Appendix S2**.

Industrial structure (*IS*): we measure the industrial structure by the ratio of the output of the secondary industry in each province to the GDP of the year. The secondary industry is a typical high pollution industry, which has the greatest impact on environmental pollution among the three industries. Therefore, the smaller the proportion of the output value of the secondary industry in GDP is, the more reasonable and advanced the local industrial structure is; otherwise, the local industrial structure is not reasonable, and the local haze pollution should be more serious.

3.3 Data Source

In this article, the data of 30 provinces from 2006 to 2018 are selected for research, excluding Tibet, Hong Kong, Macao, and Taiwan, where the data is seriously missing. The original data of all variables are from China Statistical Yearbook and China Energy Statistical Yearbook, and the patent data measuring low-carbon technological innovation are from the incoPat database[18]. In this article, the natural logarithm of some variables is taken to eliminate the impact of heteroscedasticity. The descriptive statistics of variables are shown in **Table 1**.

4 EMPIRICAL ANALYSIS AND DISCUSSION

4.1 Spatial Correlation Test

In this study, Stata 16.0 software was used to test the regional spatial correlation between haze pollution and low-carbon technological innovation in China from 2006 to 2018. The calculation results of Moran's I are shown in **Tables 2**, **3**.

We found that haze pollution in all provinces in China has a significant positive spatial correlation, that is, high pollution provinces are adjacent to high pollution provinces, and low-pollution provinces are adjacent to low-pollution provinces. In

[16]Some scholars believe that the economic scale effect is still the dominant factor leading to environmental pollution problems in China at the present stage, so there is a linear relationship between the two (Kearsley and Riddel, 2010). On the other hand, the regional economic development level shows the Kuznets effect in the process of affecting environmental pollution, that is, with the improvement of the economic development level, environmental quality will first deteriorate and then gradually improve in an inverted "U-shaped" nonlinear relationship (Gan et al., 2020).

[17]The former generally believes that for economic development, regions will attract foreign investment through "competition to the bottom" and export resource-consuming products, which also aggravate environmental pollution (Kamal et al., 2021). The latter believes that FDI can bring significant environmental improvement, which is highlighted in three aspects: the improvement of economic level leads to the enhancement of local environmental awareness (Opoku et al., 2021); the stricter environmental standards of foreign-funded enterprises reduce local environmental pollution (Luo et al., 2021); and the emerging technologies brought by foreign-funded enterprises also help improve local environmental quality (Wang and Luo, 2020).

[18]https://www.incopat.com/

TABLE 1 | Descriptive statistics of variables.

Variable	Symbol	Variable meaning	N	Mean	Std. Dev	Min	Max
Explained variable	*lnPM*	Haze pollution	390	3.803	0.399	2.754	4.513
Core explanatory variable	*lnTI*	Low-carbon tech-innovation	390	6.999	1.440	2.398	10.24
	lnCT	Clean technology	390	5.754	1.400	1.386	9.050
	lnGT	Gray technology	390	6.642	1.477	1.792	9.994
Control variables	*lnPGDP*	Per capita gross domestic product	390	10.44	0.630	8.463	12.25
	lnPOP	The population density	390	7.842	0.449	6.393	8.749
	lnFDI	Actual utilization of foreign direct investment	390	12.59	1.651	6.100	15.09
	ES	Ratio of coal consumption to total energy consumption	390	0.431	0.154	0.016	0.748
Moderating variable	*lnEP*	Pollutant emission intensity	390	11.84	0.981	8.178	14.16
Mediating variable	*IS*	Ratio of output value of the secondary industry to GDP	390	0.458	0.0833	0.165	0.590

TABLE 2 | Moran's I for haze pollution.

Time	I	E(I)	SD(I)	Z	*p*-value*
2006	0.344	–0.034	0.144	2.630	0.004***
2007	0.366	–0.034	0.145	2.762	0.003***
2008	0.393	–0.034	0.145	2.956	0.002***
2009	0.368	–0.034	0.145	2.776	0.003***
2010	0.315	–0.034	0.145	2.408	0.008***
2011	0.325	–0.034	0.145	2.479	0.007***
2012	0.328	–0.034	0.145	2.488	0.006***
2013	0.477	–0.034	0.144	3.557	0.000***
2014	0.522	–0.034	0.144	3.856	0.000***
2015	0.514	–0.034	0.145	3.791	0.000***
2016	0.451	–0.034	0.144	3.373	0.000***
2017	0.456	–0.034	0.145	3.397	0.000***
2018	0.418	–0.034	0.145	3.124	0.001***

TABLE 3 | Moran's I for low-carbon tech-innovation.

Time	I	E(I)	SD(I)	Z	*p*-value*
2006	0.344	–0.034	0.102	3.724	0.000***
2007	0.344	–0.034	0.102	3.720	0.000***
2008	0.355	–0.034	0.102	3.835	0.000***
2009	0.338	–0.034	0.102	3.658	0.000***
2010	0.318	–0.034	0.101	3.495	0.000***
2011	0.324	–0.034	0.100	3.571	0.000***
2012	0.329	–0.034	0.100	3.652	0.000***
2013	0.308	–0.034	0.100	3.409	0.000***
2014	0.262	–0.034	0.101	2.947	0.002***
2015	0.276	–0.034	0.102	3.048	0.001***
2016	0.259	–0.034	0.101	2.905	0.002***
2017	0.237	–0.034	0.100	2.721	0.003***
2018	0.234	–0.034	0.098	2.741	0.003***

Note : E (I) is the expected value of I, Sd (I) is the variance, and p*-value represents the significance level, *p < 0.1; **p < 0.05; and ***p < 0.01.*

addition, according to **Figure 5A,B**, the scatter plot of haze concentration distribution shows that haze pollution in most provinces is located in the first and third quadrants (positive spatial correlation area), indicating that haze pollution in China presents a significant positive spatial spillover effect and "high–high" and "low–low" agglomeration characteristics.

Meanwhile, according to **Table 3**, there is also a significant positive spatial correlation between low-carbon tech-innovation in China's provinces, according to the scatter diagram of **Figure 5C,D**, the trend line of distribution of low-carbon tech-innovation is also located in the first and third quadrants, and the "high–high" agglomeration areas except Beijing and Shanghai are mostly concentrated in the eastern coastal areas[19]. It shows that China's low-carbon tech-innovation has a strong spatial agglomeration.

4.2 Selection Test of a Spatial Econometric Model

According to the previous test, it can be confirmed that haze pollution and low-carbon tech-innovation have spatial agglomeration characteristics. Therefore, the dynamic spatial Durbin model (SDM) is constructed, and the maximum likelihood estimation method is adopted to calculate their coefficients. First, to reasonably select fixed effects and random effects, the Hausman test was used to calculate the model. The results of both spatial weight matrices showed that the null hypothesis was rejected at the significance level of 1%, indicating that the fixed effects model should be selected. Second, to further prove the rationality of choosing the spatial Durbin model, the LM test and LR test were carried out under fixed effects[20], which further proves that it is reasonable to construct the spatial econometric model. To ensure the robustness of the model, the LR test is carried out, and the results show that LR values of SAR and SEM models are 62.15 and 56.61, respectively. Both of them passed the significance level test of 1%. Therefore, the SDM model cannot be degraded to SAR and SEM models.

Meanwhile, before testing, according to **Eq. 3**, we compared the adjusted R^2 value and the log-likelihood function value of three types of a fixed effect in the spatial Durbin model (including temporal fixed effect, individual fixed effect, and spatial–temporal fixed effect), and the economic meaning of the estimated coefficient of the explanatory variable, it is found that the spatial–temporal fixed effect of the dynamic spatial Durbin model is the best. Therefore, the spatial Durbin model

[19]Shandong, Jiangsu, Shanghai, Zhejiang and Fujian.

[20]The test results showed that the values of LM-lag, Robust LM-lag, LM-error, and Robust LM-error were 180.482, 18.791, 204.195, and 23.938, respectively, *p* values reject the null hypothesis at the significance level of 1%.

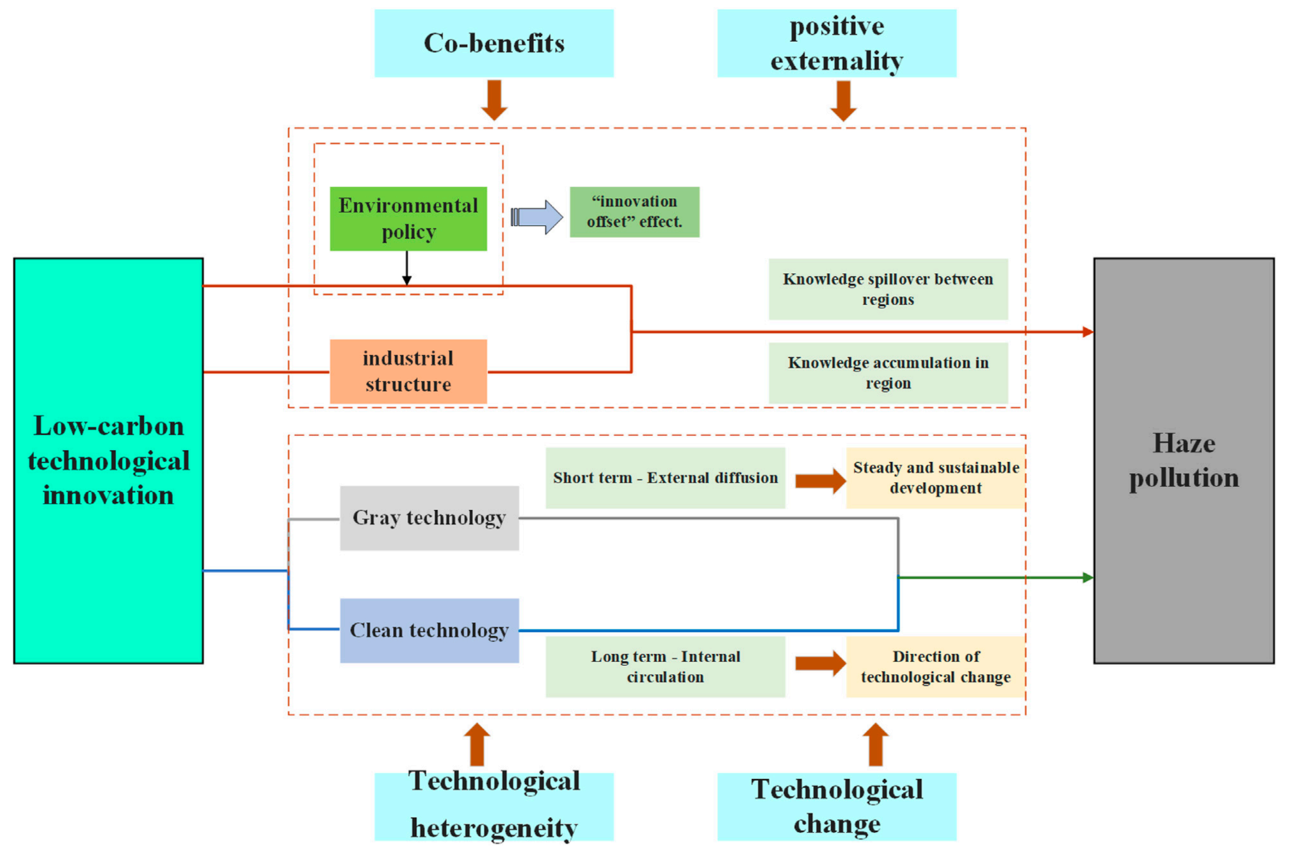

FIGURE 4 | Author's research ideas.

under the spatial–temporal fixed effect was selected for the next test.

4.3 Empirical Results of Dynamic SDM

In **Table 4**, we listed the ordinary least squares (OLS), fixed effects model (FE), the static spatial Durbin model, and the dynamic spatial Durbin model under two kinds of weighting matrices. We focus on analyzing the regression results of Models 4) and 5) because we choose a dynamic spatial Durbin model.

4.3.1 Temporal and Spatial Effects of Haze Pollution

We find that the results of model regression under the two spatial weight matrices of the geographical distance matrix and the economic distance matrix are relatively consistent, including the positive and negative coefficients and the significance level. From the perspective of the time dimension, the first-stage lag term coefficient of haze pollution φ is positive, which is 0.772 and 0.661, respectively, under the two spatial weight matrices, and both are significant at the significance level of 1%, which is consistent with the results found by Li et al. (2021) and Wang et al. (2022). It shows that haze pollution shows a certain "path dependence" and "snowball effect," that is, as the haze pollution situation in the previous period gradually deteriorates, the haze pollution level in the current period will continue to rise, indicating that the task of haze pollution control in China is still urgent and difficult[21]. From the perspective of spatial dimension, the spatial lag term of haze pollution is significantly positive at the significance level of 5%, which indicates that haze pollution has the characteristics of spatial agglomeration. Under the influence of atmospheric flow and trade of products and factors, regional haze pollution has a mutual influence. In other words, haze pollution shows an interregional correlation, which may be caused by the spatial spillover of haze pollution or a "race to the bottom" between regions. From the perspective of spatial–temporal lag, the spatial–temporal lag coefficient of haze pollution is negative and both pass the significance level of 5%, indicating that the increase in the haze pollution level in the previous period in this region will lead to the improvement of environmental quality in surrounding areas. This may be due to the "warming effect"

[21]On the one hand, the problem of environmental quality deterioration caused by haze pollution should be paid attention to immediately, and the layout and implementation of relevant control work should not be delayed. On the other hand, the treatment work should be carried out for a long time to avoid the "rebound" phenomenon of pollution after treatment.

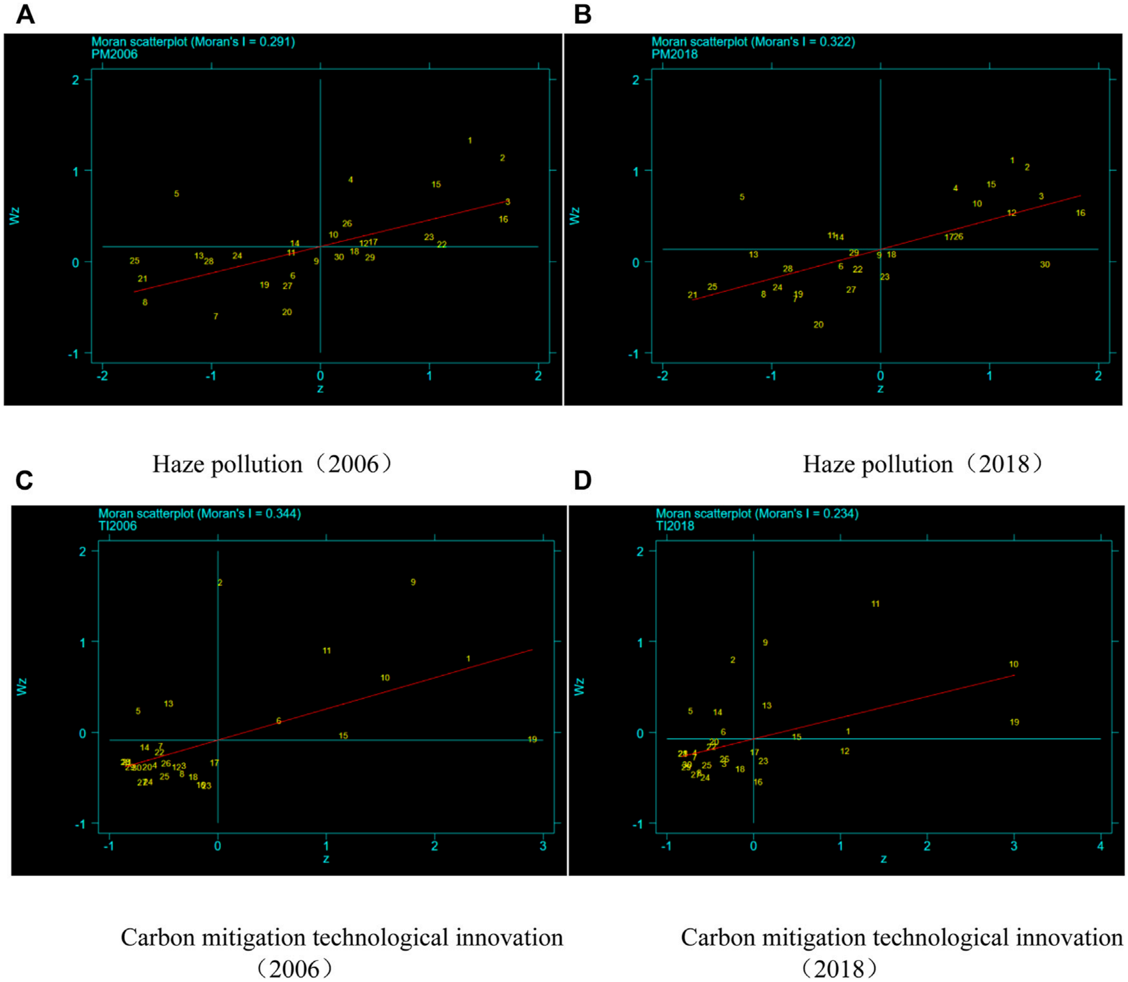

FIGURE 5 | Haze pollution and low-carbon tech-innovation local Moran's I scatter diagram. **(A)** Haze pollution (2006). **(B)** Haze pollution (2018). **(C)** Carbon mitigation technological innovation. **(D)** Carbon mitigation technological innovation.[22]

formed by media pressure and brain drain on neighboring regions or other regions with similar levels of economic development, which will take corresponding measures to protect the environment to avoid similar situations.

4.3.2 Low-Carbon Tech-Innovation and Haze Pollution

According to **Table 4**, under the two spatial weight matrices, the coefficient of low-carbon tech-innovation is significantly negative at the significance level of 1%, indicating that low-carbon tech-innovation has significantly inhibited haze pollution. While the path of technological haze control is effectively supported, it also shows that while addressing climate change, low-carbon tech-innovation has also brought significant air quality benefits, indicating that it has become a key path to tackle haze pollution, and pointing out the policy direction for addressing air pollution. Meanwhile, the spatial lag of low-carbon tech-innovation passed the significance level test of 1% and was negative, that is, when the low-carbon innovation activity in the surrounding area increased by 1%, the haze pollution level in the region would decrease by about 0.069%. On the one hand, this shows that the environmental pollution caused by haze pollution has gradually been paid attention to, and it has become the consensus of all regions to invest in the treatment of environmental quality problems through low-carbon technological innovation activities, on the other hand, the neighboring region alleviates haze pollution through input in innovation activities and has a "demonstration effect" in the region under the effect of positive externalities.

4.3.3 Control Variables

(1) Population density (*POP*): according to **Table 4**, we find that the coefficient of population density is positive, and through the

[22]Note: 1-Beijing, 2-Tianjin, 3-Hebei, 4-Shanxi, 5-Neimenggu, 6-Liaoning, 7-Jilin, 8-Heilongjiang, 9-Shanghai, 10-Jiangsu, 11-Zhejiang, 12-Anhui, 13-Fujian, 14-Jiangxi, 15-Shandong, 16-Henan, 17- Hubei, 18-Hunan, 19-Guangdong, 20-Guangxi, 21-Hainan, 22-Chongqing, 23-Sichuan, 24-Guizhou, 25-Yunnan, 26-Shaanxi, 27-Gansu, 28-Qinghai, 29-Ningxia, and 30-Xinjiang

TABLE 4 | Empirical results of low-carbon technology innovation and haze pollution.

Variable	OLS	FE	Static SDM	Dynamic SDM (W_1)	Dynamic SDM (W_2)
	(1)	(2)	(3)	(4)	(5)
$lnPM_{t-1}$	—	—	—	0.772*** (7.42)	0.661*** (5.81)
lnTI	−0.070*** (−3.21)	−0.089*** (−4.10)	−0.057* (−1.73)	−0.052*** (−5.59)	−0.054*** (−6.31)
lnPGDP	2.165*** (3.34)	0.851*** (2.83)	1.036*** (3.92)	0.893** (2.17)	0.874** (2.21)
$(lnPGDP)^2$	−0.104*** (−3.39)	−0.045*** (−2.91)	−0.051*** (−3.8)	−0.041* (−1.69)	−0.077** (−2.28)
lnPOP	0.062*** (3.14)	0.082*** (2.73)	0.065*** (2.76)	0.04** (2.36)	0.086*** (5.38)
lnFDI	0.034 (1.05)	0.015 (1.48)	0.039* (1.09)	0.022** (2.15)	0.028** (2.31)
ES	0.959*** (7.17)	0.335** (2.55)	0.199** (2.01)	0.164** (2.02)	0.308*** (6.09)
$w \times lnPM_{t-1}$	—	—	—	−0.627** (−2.28)	−0.619** (−2.19)
w×lnPM	—	—	0.591**(2.37)	0.602** (2.48)	0.631** (2.69)
w×lnTI	—	—	−0.021* (−1.72)	−0.069*** (−3.22)	−0.066*** (−3.03)
w×lnPGDP	—	—	0.721** (2.09)	0.417** (2.74)	0.579** (2.83)
$w \times (lnPGDP)^2$	—	—	−0.009 (−0.69)	−0.014* (−1.71)	−0.032* (−1.76)
w×lnPOP	—	—	0.342*** (4.99)	0.178*** (3.57)	0.221*** (3.90)
w×lnFDI	—	—	0.030* (1.89)	0.012 (0.85)	0.032 (1.52)
w×ES	—	—	0.113 (0.64)	0.167 (0.71)	0.178 (0.89)
ρ	—	—	0.746	0.975	0.869
Log-likelihood	—	—	221.271	250.094	269.723
F-test	17.28	34.33	38.43	37.29	41.81
R^2	0.721	0.643	0.475	0.498	0.519

*Note: z-statistics in parentheses, ***p < 0.01, **p < 0.05, and *p < 0.1.*

significance level of 1%, it indicates that under the fixed administrative area of each region, more the population, more the serious haze pollution. This is consistent with the study of Fan and Xu. (2020), indicating that population density mainly stimulates the generation of haze pollution through the agglomeration effect[23]. (2) Economic growth (*PGDP*): the result of the test shows that the per capita GDP of the primary and secondary items are negative, and with a significant coefficient under the 1% significance level, the inverted U-shaped relationship between regional economic growth and haze pollution has been verified, indicating that the regional haze pollution level increases first and then decreases with the continuous improvement of regional economic development level, which is consistent with the findings of Gan et al. (2020). (3) Openness (*FDI*): the results of **Table 4** show that the coefficient of openness is positive at the significance level of 5%, indicating that the amount of foreign capital directly utilized in a region will aggravate haze pollution. "Pollution Heaven," which aims at the relationship between foreign direct investment and environmental quality, is established. This proves the findings of Kamal et al. (2021), but its spatial effect is not obvious. (4) Energy structure (*ES*): coal consumption is still the source of haze pollution, and there is still a long way to go in China's energy structure transformation. Whether the energy structure improvement in one region has not affected the improvement of haze pollution in the surrounding areas, also shows that the energy structure of China's provinces is still very unreasonable and has not reached the height of joint governance.

4.3.4 Decomposition Effects of Low-Carbon Tech-Innovation on Haze Pollution

When there is a spatial spillover effect, the change of an explanatory variable will not only affect the explained variable in the local area but also the explained variable in the surrounding area, and in turn affects the local area through the feedback effect (Lichtenberg and Potterie, 1998; Elhorst, 2014). Therefore, the estimated coefficient mentioned earlier is not rigorous enough to directly reflect the marginal effect of independent variables on dependent variables and is only effective in the direction of action and the significance level. Therefore, this article further decomposed the influence of various influencing factors on haze pollution into direct and indirect effects[24]. As the dynamic spatial Durbin model is adopted in this article, in terms of the time dimension, the direct and indirect effects can be divided into short-term effect and long-term effect, respectively, reflecting the short-term immediate impact of various factors on haze emission and the long-term impact considering time lag. Under the two spatial weight matrices, the effect decomposition results of each factor are shown in **Tables 5**, **6**.

[23]Agglomeration effect refers to the haze pollution caused by the demand for housing, household appliances, and motor vehicles by people in areas with high population density, and the concentration of pollutants generated by motor vehicle fuel combustion due to the high residential density is not conducive to air circulation, thus causing haze pollution. The scale effect refers to the fact that population clustering alleviates haze pollution by improving the utilization rate of public transportation and sharing pollution control and emission reduction facilities.

[24]Direct effect refers to the influence of a factor change on haze pollution in the region, which includes the feedback effect, but its value is small and can generally be ignored. Indirect effect refers to the influence of the change of a local factor on haze pollution in other regions, namely, the spatial spillover effect of an influencing factor.

TABLE 5 | Decomposition effects of low-carbon tech-innovation on haze pollution (W_1).

Variable	Short term			Long term		
	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect
lnTI	−0.054***	−0.042**	−0.012	0.105***	−0.067***	−0.038*
	(−5.74)	(−2.03)	(−0.30)	(3.79)	(−3.47)	(−1.18)
lnPOP	1.428***	0.233***	1.195***	1.274***	0.972**	0.302**
	(6.47)	(5.96)	(6.29)	(3.97)	(2.18)	(2.52)
lnPGDP	1.719***	1.134**	0.585**	1.945***	0.901**	1.044**
	(3.97)	(2.04)	(2.36)	(4.15)	(2.11)	(2.24)
(lnPGDP)²	−0.093**	−0.066*	−0.027	−0.041*	−0.032*	−0.009
	(−2.27)	(−1.41)	(−0.75)	(−1.65)	(−1.51)	(−0.82)
lnFDI	0.107**	0.066**	0.041*	−0.039**	−0.022*	−0.017*
	(2.23)	(2.24)	(1.79)	(−1.98)	(−1.74)	(−1.96)
ES	1.563***	0.932*	0.631*	−0.670**	−0.941*	0.271**
	(3.08)	(1.55)	(2.07)	(−2.08)	(1.64)	(2.28)

*Note: z-statistics in parentheses, ***p < 0.01, **p < 0.05, and *p < 0.1.*

TABLE 6 | Decomposition effects of low-carbon tech-innovation on haze pollution (W_2).

Variable	Short term			Long term		
	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect
lnTI	−0.082***	−0.054***	−0.028	0.102***	−0.060***	−0.042**
	(−4.02)	(−3.19)	(−0.37)	(2.83)	(−4.12)	(−2.60)
lnPOP	1.253***	0.272***	0.918**	1.334***	0.537**	0.797**
	(3.19)	(3.24)	(2.37)	(3.77)	(1.98)	(2.10)
lnPGDP	1.543**	1.069**	0.474*	1.045**	0.801*	0.244
	(1.84)	(2.09)	(1.28)	(2.15)	(1.81)	(0.64)
(lnPGDP)²	−0.044**	−0.041*	−0.003	−0.065**	−0.060*	−0.005
	(−2.32)	(−1.81)	(−0.21)	(−2.03)	(−1.66)	(−0.49)
lnFDI	0.147*	0.083	0.064*	−0.110**	−0.062	−0.048*
	(1.70)	(0.80)	(1.06)	(−2.20)	(−0.27)	(−1.63)
ES	1.851***	1.226***	0.625	−0.775*	−0.904**	0.129*
	(4.08)	(6.05)	(1.07)	(−1.48)	(−2.23)	(1.72)

*Note: z-statistics in parentheses, ***p < 0.01, **p < 0.05, and *p < 0.1.*

According to **Tables 5**, **6**, it is found that there is no significant difference in model regression results under the two spatial weight matrices, and the absolute value of the influence coefficient of most long-term effects is greater than that of short-term effects, whether direct or indirect, which indicates that each factor has a more profound long-term impact on haze pollution. The low-carbon tech-innovation coefficient is negative both in the short term and the long term, indicating that low-carbon tech-innovation has successfully restrained haze pollution, that is, the haze reduction effect of low-carbon technology can continue to play a role, which is conducive to China's use of it to achieve the dual goal of reducing carbon and haze. The direct effect of low-carbon tech-innovation shows that it can significantly inhibit haze pollution in the region both in the short term and the long term. The reason may be that high-intensity low-carbon tech-innovation can bring local industrial structure optimization and reduce the use of high carbon and high pollution fuels to achieve the dual goals of reducing carbon and haze. However, the indirect effect is different. In the short term, the coefficient of low-carbon tech-innovation is negative but not significant. In the long term, the coefficient of low-carbon tech-innovation is negative and significant, indicating that in the short term, the regional low-carbon tech-innovation activities are not enough to have an impact on haze pollution in the surrounding area, and it takes a certain time for this effect to occur. The reason may be that a certain amount of technical innovation in the short term can be adopted by enterprises, thus helping to suppress the fog haze pollution in the region, but this technological innovation is not easily spread in the short term, that is, the knowledge is monopolized, therefore the innovation of air quality benefit is confined to the area, there is no pull function form of radiation. But in the long run, the diffusion of technology or spillover of knowledge leads to technological innovation by enterprises in surrounding areas, which helps improve local air quality.

4.4 Heterogeneity Analysis

Considering the importance of diversity and classification of low-carbon technologies internal (Acemoglu et al., 2016; Aghion et al., 2016), we divide low-carbon tech-innovation into two categories — clean tech-innovation and gray tech-innovation, and test the effectiveness of the two low-carbon technologies in haze pollution control. See **Table 7** for the results. According to the test results, the estimate coefficients of clean and gray tech-innovation are negative, and through a 1% significance level inspection, it shows that both clean and

TABLE 7 | Different types of low-carbon tech-innovation on haze pollution.

Variable	Dynamic SDM (W_1)	Dynamic SDM (W_2)	Dynamic SDM (W_1)	Dynamic SDM (W_2)
	(1)	(2)	(3)	(4)
$lnPM_{t-1}$	0.296*** (6.11)	0.268*** (6.08)	0.297*** (6.18)	0.278*** (6.37)
$lnCT$	−0.054*** (−3.76)	−0.055*** (−2.81)	—	—
$lnGT$	—	—	−0.069*** (−3.23)	−0.064** (−2.06)
$lnPGDP$	0.504** (2.14)	0.532** (2.47)	0.631*** (2.52)	0.657** (2.31)
$(lnPGDP)^2$	−0.022** (−2.31)	−0.018** (−2.08)	−0.034* (−1.89)	−0.029* (−1.46)
$lnPOP$	0.058* (1.72)	0.052** (2.53)	0.055* (1.66)	0.046 (1.35)
$lnFDI$	0.012* (1.86)	0.005 (0.45)	0.018* (1.51)	0.004 (0.18)
ES	0.312** (2.56)	0.305** (2.46)	0.318** (2.62)	0.304** (2.45)
$w\times lnPM_{t-1}$	−0.524** (−2.77)	−0.539** (−2.81)	−0.426*** (−2.93)	−0.510** (−2.44)
$w\times lnPM$	0.679*** (3.93)	0.651** (2.26)	0.528*** (3.42)	0.691** (2.35)
$w\times lnCT$	−0.026* (−1.72)	−0.011 (−0.98)	—	—
$w\times lnGT$	—	—	−0.069*** (−2.96)	−0.064*** (−3.92)
$w\times lnPGDP$	0.685* (1.84)	0.579** (2.83)	0.532* (1.76)	0.561** (1.96)
$w\times (lnPGDP)^2$	−0.042* (−1.68)	−0.051* (−1.83)	−0.074* (−1.73)	−0.061* (−1.68)
$w\times lnPOP$	0.227** (2.33)	0.269*** (2.96)	0.253*** (2.62)	0.310*** (3.38)
$w\times lnFDI$	0.001 (0.02)	0.006 (0.20)	0.004 (0.12)	0.004 (0.18)
$w\times ES$	0.545* (1.72)	0.453 (1.10)	0.465 (1.26)	0.454 (1.32)
ρ	0.825	0.752	0.807	0.771
Log-likelihood	286.164	308.572	320.659	339.142
F-test	31.67	33.91	37.83	39.26
R^2	0.520	0.541	0.562	0.646

*Note: z-statistics in parentheses, ***p < 0.01, **p < 0.05, and *p < 0.1.*

gray technologies play an important role in the prevention and control of local haze pollution, but the role of gray tech-innovation in the suppression of haze pollution is stronger than that of clean tech-innovation, and there may be three reasons. First, the number of gray technology patents in China is much larger than that of clean technology, indicating that the maturity of gray technology may be stronger than that of clean technology. Second, gray technology is not carbon-free but can reduce carbon emissions, with lower R&D costs and easy market promotion, especially adopted by high pollution enterprises to cope with the government's strict environmental policies. Third, China's current energy structure is still not perfect, the coal consumption is huge, the space in the use of clean energy development also hindered the development of clean technology at the same time, one can imagine that China's current low-carbon technologies are still biased toward gray technology, and with the improvement of the economic structure, the future of bias technology will change direction to clean technology.

In addition, the estimation results of the spatial lag coefficient of innovation of the two low-carbon technologies show significant differences. Gray technology is significantly negative at a 1% level, while clean technology, though negative, does not pass the significance test. This difference shows that compared with clean technology, gray technology could better cross geographical barriers, realize interregional diffusion, and greatly reduce the haze pollution of the surrounding areas through the spatial spillover effect, the reason may be that the R&D cost of gray tech-innovation is relatively low, and the monopoly benefit is less, and lead to its high degree of diffusion, However, clean technology, as a carbon-free or negative emission technology, has a high cost of research and development. Although it has good positive externalities, its overflow channels are blocked and its diffusion effect is poor, showing a little effect on reducing haze.

4.5 Mechanism Analysis

To test the two possible mechanisms proposed in **Section 2.3**, we conducted model regression according to **Eqs 4–7**, respectively[25].

According to the regression results of Model (1) in **Table 8**, although we found that the interaction coefficient between environmental policy and low-carbon tech-innovation is negative at the significance level of 5%, the coefficient decreases significantly, indicating that under the implementation of strict environmental policy, the effect of technological innovation is partially offset. This is consistent with Jaffe et al. (2002) and Popp et al. (2009), environmental policies bring about "innovation offsetting" effects, the reason may be that the current tech-innovation itself needs a lot of costs, and it takes a long time to develop, in the short term it cannot meet the requirements of environmental monitoring, so some companies may be given up technology to reduce emissions path for industrial migration or temporarily shut down high emissions department, this has weakened the low-carbon tech-innovation curb haze pollution effect. Meanwhile, according to Model (2) and Model (3), classifying the low-carbon tech-innovation and testing the regulating effect of environmental policy, we found that the "innovation offsetting" effect particularly on clean tech-innovation, shows that after strict environmental policies are implemented, enterprises will be more inclined to gray tech-

[25]The specific results are shown in **Tables 8**, **9**. Due to space limitation, we will only show the regression results under economic distance matrix (W_2).

TABLE 8 | Moderating effect of environmental policy.

Variable	Dynamic SDM (1)	Dynamic SDM (2)	Dynamic SDM (3)
$lnPM_{t-1}$	0.253*** (5.72)	0.254*** (5.76)	0.261*** (5.92)
lnEP	−0.056** (−1.85)	−0.050* (−1.95)	−0.050* (−1.79)
lnTI	−0.172*** (−3.18)	—	—
lnEP×lnTI	−0.025** (−2.26)	—	—
lnCT	—	−0.145*** (−3.23)	—
lnEP×lnCT	—	−0.011*** (−2.36)	—
lnGT	—	—	−0.172*** (−2.90)
lnEP×lnGT	—	—	−0.107** (−2.23)
lnPGDP	0.383* (1.89)	0.287* (1.66)	0.396 (1.17)
$(lnPGDP)^2$	−0.019 (−0.88)	−0.015** (−2.06)	−0.025 (−1.17)
lnPOP	0.051* (1.93)	0.052 (1.52)	0.046 (1.36)
lnFDI	0.007 (0.59)	0.006 (0.49)	0.007 (0.63)
ES	0.388*** (3.05)	0.382*** (3.01)	0.389*** (3.06)
$w \times lnPM_{t-1}$	−0.502* (−1.59)	−0.439** (−2.01)	−0.511** (−2.04)
w×lnPM	0.621** (2.33)	0.603** (2.07)	0.613** (2.12)
w×lnEP	0.128* (1.77)	0.097 (1.62)	0.128* (1.87)
w×lnTI	−0.028** (−2.57)	—	—
w×lnEP×lnTI	−0.019** (−1.98)	—	—
w×lnCT	—	−0.026** (−2.72)	—
w×lnEP×lnCT	—	−0.018* (−1.83)	—
w×lnGT	—	—	−0.034*** (−3.01)
w×lnEP×lnGT	—	—	−0.020* (−1.98)
w×lnPGDP	1.493** (2.03)	1.197* (1.69)	1.446* (1.95)
$w \times (lnPGDP)^2$	−0.066* (−1.79)	−0.054 (−1.51)	−0.063* (−1.95)
w×lnPOP	0.297*** (3.27)	0.270*** (2.97)	0.314*** (3.43)
w×lnFDI	0.012 (0.43)	0.017 (0.59)	0.010 (0.35)
w×ES	0.277 (1.27)	0.231 (0.83)	0.269 (0.92)
ρ	0.774	0.607	0.741
Log-likelihood	374.220	373.475	373.267
F-test	49.86	52.28	51.21
R^2	0.655	0.646	0.654

*Note: z-statistics in parentheses, ***p < 0.01, **p < 0.05, and *p < 0.1.*

innovation rather than clean technology. There are two main reasons. First, the cost of gray tech-innovation is low, and the effect is fast, so it can be quickly used to deal with the government's environmental regulation. Second, the enterprises most affected by the government's environmental policies are generally highly polluting enterprises. It is impossible to achieve a clean transformation in a short time, so they can only seek gray tech-innovation to reduce pollution emissions.

The spatial lag coefficients of each interaction item are all negative and significant at the significance innovation in a region that plays a joint role not only in the local area but also contributes to the alleviation of haze pollution in other surrounding regions. The possible reason is that the implementation of environmental policies in one region has a warning effect on enterprises in other regions, and local enterprises will immediately take countermeasures to avoid future changes in local environmental policies. But the spillover effect will decrease with the emergence of environmental policy, the possible reason is that the strengthening of local environmental policies increases the cost of tech-innovation of enterprises and the marginal benefit of technological monopoly, which will lead to technology spillover difficulties and blocked knowledge flow, thus affecting the innovation activity of other surrounding areas and weakening the effect of low-carbon tech-innovation in curbing haze pollution.

According to **Table 9**, we found that low-carbon tech-innovation can promote the upgrading of industrial structures to suppress haze pollution; in addition, CT and GT also help promote the development of the industrial structure upgrade, in the long run, will help control haze pollution. A large number of tech-innovations will drive the improvement of regional innovation levels. On the one hand, it will help to form an innovation cluster network, promote industrial integration, reduce the living space of high pollution enterprises, and promote the green transformation of regional industrial structure. On the other hand, the positive externalities of technological innovation contribute to the formation of knowledge spillover and technology diffusion, improve the level of technological innovation in the surrounding region, and form the trend of innovation spread. In the long term, it will contribute to the upgrading of the overall industrial structure inside and outside the region. Further analysis of the heterogeneity of low-carbon tech-innovation shows that gray tech-innovation helps reduce enterprise pollution emissions and is easy to spread, which will contribute to the positive externalities of technological innovation and help the whole industry gradually form the concept of green production, energy-saving production, and resource protection, and clean tech-innovation as no carbon or negative carbon technology, represents the future direction of low-carbon technology, a large number of clean technology innovations are conducive to the emergence and development of new sectors or industries, such as the new energy automobile industry. In the long run, this is bound to bring about the upgrading of the entire industry and fundamentally change the original traditional production forms or production technologies.

4.6 Robustness Test

In **Section 3.1**, we construct two spatial weight matrices, namely the geographical distance matrix and the economic distance matrix. To comprehensively reflect the dual characteristics of spatial geographical distance and economic attributes, we construct the spatial economic distance matrix W_3 by referring to Fingleton and Gallo (2008). The specific expression is **Eq. 11**:

$$W_3 = W_{ij} = \frac{1}{\left|PGDP_j - PGDP_i + 1\right|} \times e^{-d_i}, \tag{11}$$

where W_{ij} is the spatial economic distance matrix, $PGDP_j$ and $PGDP_i$, respectively, represent the per capita GDP of province j and province i, and d_{ij} is the geographical distance between the two provinces. Under this matrix, we re-conducted the model regression and found that the positive and negative situations and significance levels of each explanatory variable had no significant differences from those in W_1 and W_2. In addition, we replaced the explained variable $PM_{2.5}$ concentration in this study. Considering that in addition to $PM_{2.5}$, SO_2 emission from industrial production is also an important factor leading to haze pollution, we adopt the

TABLE 9 | Mediating effect of industrial structure.

Variable	lnPM	IS	lnPM	lnPM	IS	lnPM	lnPM	IS	lnPM
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
lnTI	−0.089*** (−4.10)	−0.035*** (−6.42)	−0.081*** (−3.51)	—	—	—	—	—	—
lnCT	—	—	—	−0.084*** (−4.21)	−0.024*** (−4.66)	−0.077*** (−3.74)	—	—	—
lnGT	—	—	—	—	—	—	−0.070*** (−3.46)	−0.032*** (−6.41)	−0.061*** (−2.84)
IS	—	—	0.248** (2.13)	—	—	0.305** (2.01)	—	—	0.295** (1.98)
lnPGDP	0.851*** (2.83)	−0.036 (−0.48)	0.842*** (2.80)	0.554*** (2.81)	−0.054 (−0.70)	0.570*** (2.83)	0.936*** (3.06)	0.078 (1.04)	0.913*** (2.99)
$(lnPGDP)^2$	−0.045*** (−2.91)	0.005 (1.31)	−0.044** (−2.17)	−0.030** (−2.01)	0.001 (0.18)	−0.030* (−1.89)	−0.050*** (−3.19)	0.007* (1.88)	−0.048*** (−3.04)
lnPOP	0.082*** (2.73)	0.008 (1.04)	0.084*** (2.79)	0.084*** (2.81)	0.008 (1.08)	0.087*** (2.89)	0.080*** (2.64)	0.008 (1.07)	0.082*** (2.72)
lnFDI	0.015 (1.48)	0.012*** (4.26)	0.008 (0.66)	0.005 (0.40)	0.012*** (4.09)	0.008 (0.71)	0.005 (0.44)	0.012*** (4.25)	0.009 (0.73)
ES	0.335** (2.55)	0.033** (2.01)	0.327** (2.48)	0.355*** (2.71)	0.043** (2.30)	0.342*** (2.61)	0.342*** (2.59)	0.034* (1.91)	0.332** (2.51)
N	390	390	390	390	390	390	390	390	390
R^2	0.643	0.739	0.645	0.645	0.726	0.647	0.639	0.739	0.641
F-test	34.33	54.05	32.62	34.46	50.34	32.86	33.61	54.02	32.01

industrial SO_2 emission of each province to measure the haze pollution level of each province and use the previous three spatial weight matrices to perform regression. We found that the positive and negative signs and significance levels of each core explanatory variable were the same as the previous results, indicating that the index changes of the core explained variable did not change the previous research conclusion, that is, the research results are robust.

5 CONCLUSION AND POLICY IMPLICATIONS

In this study, the STIRPAT model and the classical EKC hypothesis were combined to construct a dynamic spatial econometric model to study the spatial spillover effects of haze pollution and low-carbon technological innovation; the co-benefits and internal mechanism of low-carbon technological innovation to tackle climate change on haze pollution control; and the heterogeneity and synergy of clean technology and gray technology on haze pollution control, the following conclusions, and policy implications are obtained.

(1) Both haze pollution and low-carbon technological innovation in China show significant spatial agglomeration characteristics and spatial spillover effects. The polluted areas are mainly concentrated in the Beijing–Tianjin–Hebei region and energy-consuming provinces. From the perspective of time, haze pollution has "path dependence," showing a "snowball effect;" from the perspective of space, haze pollution shows an obvious spatial spillover effect, showing the situation of "both prosperity and loss," which is consistent with the conclusion of Wang et al. (2022). From the perspective of spatial–temporal dimensions, the haze pollution in one region in the previous period can effectively suppress the haze pollution in other surrounding areas, indicating that the good warning function of regions has been played, which supports the findings of Feng and Wang. (2019). Low-carbon tech-innovation is mainly concentrated in East China, including Beijing and Guangzhou. In addition, China's current low-carbon tech-innovation has become an important path to alleviating haze pollution, and technology spillover plays an important role in curbing haze pollution.

(2) The positive externalities of low-carbon tech-innovation in haze treatment have been expanded, and the long-term co-benefits of haze reduction have been clarified. On the one hand, low-carbon tech-innovation to address climate change also brings co-benefits to local air quality, and the path of technology to cure haze has been clarified. On the other hand, regional long-term knowledge accumulation, knowledge spillover, and diffusion of low-carbon technologies will lead to such co-benefits not only locally but also help curb haze pollution in surrounding areas and give play to the positive externalities of technological innovation. In addition, industrial structure and environmental policy play a mediating and moderating role respectively in this process, but environmental policy shows an obvious "innovation offset" effect, which weakens the role of low-carbon tech-innovation, especially in clean technology innovation. Contrary to what supporters of the Porter hypothesis believe, our findings support the views of Jaffe et al. (2002) and Popp et al. (2009).

(3) There are obvious differences between clean tech-innovation and gray tech-innovation in suppressing haze pollution. Heterogeneity analysis shows that gray tech-innovation has a stronger effect on haze pollution suppression than clean tech-innovation, and gray tech-innovation can better overcome geographical barriers to achieve cross-regional diffusion, while clean tech-innovation is more vulnerable

to environmental policies. However, both of them can promote the upgrading of China's industrial structure and thus improve air quality.

(4) Both population density and coal-based energy consumption structure are the important ways of haze pollution, the research of Fan and Xu. (2020) has been verified. Economic development and environmental pollution show an inverted U-shaped trend, that is, the haze pollution level increases first and then decreases with the improvement of the economic development level, this is consistent with Kearsley and Riddel, (2010) and Gan et al. (2020). Foreign direct investment has brought obvious haze pollution, and the "Pollution Heaven" hypothesis has been verified and is consistent with the findings of Kamal et al. (2021).

According to the aforementioned conclusions, the following policy implications can be obtained:

(1) It is necessary for policymakers to strengthen the top-level policy design and establish a long-term mechanism for haze control and joint prevention and control mechanism. As a systematic and long-term project, haze control requires an overall concept and comprehensive strategic deployment. First of all, dealing with the spatial agglomeration of haze pollution needs to focus on key provinces with haze outbreaks, namely, high–high agglomeration areas such as the Beijing–Tianjin–Hebei region. Second, the higher level government should strengthen guidance, while focusing on regional rectification, quickly establish trans-regional departments and institutions, strengthen regional cooperation, establish coordination mechanisms such as information sharing and joint law enforcement to ensure the smooth progress of joint prevention and control and coordinated governance, and take into account all factors. Additionally, in this process, it is necessary to strengthen supervision and improve relevant laws and regulations to avoid the emergence of free-riding behavior in some regions and the rebound of haze pollution.

(2) The government should make comprehensive use of environmental policy means and market means to guide enterprises to develop low-carbon technologies and give full play to the co-benefits of low-carbon tech-innovation in reducing haze. High-profile low-carbon tech-innovation as a key means to respond to climate change caused by the air quality in co-benefits must be fully effective mining. First, local governments should actively guide low-carbon innovation activities into a consensus. In addition to the implementation of relatively strict environmental regulations, relevant preferential measures should be developed to encourage enterprises to carry out low-carbon tech-innovation, reverse the "innovation offset" effect caused by environmental policies on enterprises, reduce compliance costs of enterprises, and increase the marginal benefits of technological innovation. Second, the concentration regions of haze pollution and low-carbon tech-innovation are not consistent, which shows that each region should improve the market mechanism, speed up the implementation of talent introduction strategy and create a better innovation environment, guide the optimization and integration of industrial structure to promote the rational allocation of factors, and accelerate knowledge spillover and low-carbon technology diffusion between regions, to improve the efficiency of technology in haze treatment.

(3) Short-term encouragement of gray tech-innovation and long-term support for clean tech-innovation should be combined to promote biased low-carbon technical change and green upgrading of industrial structure step by step. First, the government should comprehensively consider the heterogeneity of low-carbon technology innovation, establish a low-carbon technology development plan, and handle the relationship between gray technology and clean technology. On the one hand, effective environmental policies and market means should be adhered to promote the sustainable and stable development of gray technology innovation. On the other hand, flexible environmental policy should be focused on minimizing its impact on clean technology innovation. Second, technical cooperation and exchanges between regions should be encouraged, especially for clean technologies such as renewable energy technologies and negative emission technologies. Governments in heavily polluted areas should not only strengthen the gray technology innovation capacity within the region but also actively encourage enterprises to introduce clean technology innovation outside the region to improve the local industrial structure and reverse the long-term path dependence. Enterprises in regions with strong innovation capacity should actively fulfill their corporate social responsibility to help neighboring regions develop clean technologies and form a win–win situation of interregional cooperation. Finally, decision-makers should correctly guide the direction of technology development, change the competitive relationship between clean and gray technologies into a complementary relationship, and create a good innovation environment to increase the intensity of talent introduction and R&D investment to bring breakthrough technology innovation output, and orderly guide technology transition to the clean technology track.

(4) It is essential for the government to properly control the entry of foreign investment and improve the entry threshold of industries producing high energy consumption by strengthening the "clean" screening of foreign investment, to change the "Pollution heaven" phenomenon of foreign direct investment in haze control. In addition, the local government should optimize the urban spatial structure, pay attention to urban green design, and improve urban transportation infrastructure (such as high-speed rail and subway) to prevent the excessive concentration of population from causing more serious haze pollution. On this basis, regional coordination should be strengthened to promote win–win cooperation and cooperation mechanism for haze pollution control, prevent a "race to the bottom"

among governments, and gradually reduce the proportion of coal in energy consumption and optimize the energy structure to promote green economic growth.

According to the findings of this study, we believe that there are three directions for future research:

(1) The study of co-benefits between climate change and air pollution is one of the priorities in the field of environmental science and environmental economics. In the future, policy evaluation and technical methods for addressing climate change can be used to evaluate the co-benefits of air quality, or even to study carbon reduction and haze reduction simultaneously, that is, "shooting two hawks with one arrow."
(2) Low-carbon tech-innovation is not only a key means to alleviate global climate change but also can produce many other benefits. Therefore, the research on actively broadening the externalities of low-carbon tech-innovation will become one of the hot spots in the future. Under the theory of endogenous growth, it is necessary to analyze the environmental, health, and economic benefits of endogenous technological innovation systematically, and it is not limited to low-carbon and green technologies.
(3) Low-carbon tech-innovation can be studied from dynamic and spatial perspectives, but it is not deep enough. In the future, the analysis of the environmental, economic, and health benefits of the diffusion of carbon reduction technologies should be more potential and detailed than innovation. Moreover, technology diffusion and knowledge spillover are not limited to one country, but often take most countries in the world as the research target, which is a global network. Meanwhile, it is essential to combine technology heterogeneity analysis with biased technology change. Exploring or changing the direction of carbon mitigation or other environment-friendly technology is of great significance for improving national industrial and energy structure and promoting green economic growth.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

SJ: writing—original draft, data curation, and methodology. WW: conceptualization, project administration, writing—review and editing and supervision. SAQ: data curation and investigation. CZ: conceptualization and data curation. NL: funding acquisition and formal analysis. GZ: investigation and software. JW: investigation and data curation.

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SUPPLEMENTARY MATERIAL

The Supplementary Material, for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.893194/full#supplementary-material

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How Does Agro-Tourism Integration Influence the Rebound Effect of China's Agricultural Eco-Efficiency? An Economic Development Perspective

Guirong Jiang[1,2]*

[1]College of Economics, Southwest Minzu University, Chengdu, China, [2]College of Economics and Management, Tarim University, Alar, China

Agro-tourism integration is a breakthrough to flourish rural industries and fulfill rural revitalization. Also, agricultural eco-efficiency and agro-tourism integration are closely linked, so investigating the relationship between the two is significant for realizing high-quality agro-ecological development in China. However, existing studies have ignored the impact of agro-tourism integration on agricultural eco-efficiency. For this purpose, using a dataset of 30 provincial administrative regions in China from 2001 to 2019, this paper employs the Entropy weight approach and super efficient Slack-Based Measure (SBM) approach to measure the agro-tourism integration level and agricultural eco-efficiency, respectively. The system Generalized Method of Moments (SYS-GMM) approach is applied to investigate the effect of agro-tourism integration on agricultural eco-efficiency. The statistical results reveal that agro-tourism integration significantly contributes to agricultural eco-efficiency, which remains valid after the robustness checks are executed. There is also significant path-dependence of agro-tourism integration. Finally, agro-tourism integration significantly contributes to agricultural eco-efficiency in the eastern region, while it significantly inhibits agricultural eco-efficiency in the central-western region. Our findings suggest that policymakers not only reinforced the deep integration of agriculture and tourism to stimulate the overall rural revitalization, but also formulated agro-tourism integration policies in a differentiated and green manner to contribute to agricultural eco-efficiency growth.

Keywords: agro-tourism integration, agriculture, tourism, regional heterogeneity, agricultural ecoefficiency

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Yanshan University, China

****Correspondence:***
Guirong Jiang
Guirong_J@163.com

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1 INTRODUCTION

Agriculture is the integration of natural reproduction and economic production (Chandio et al., 2021), which is not only an essential foundation for national economic development (Jinru et al., 2021), but also material support for human survival and development (Lane and Kastenholz, 2015; Shi et al., 2022). Since 1978, agricultural development in China has made considerable contributions,

with a total agricultural grain production of nearly 669 million tons in 2020, which accounts for 24.2% of the world's total grain production (Yang and Wang, 2021)[1]. Agriculture has served as a powerful guarantee for the sustainable development of China's economy and society. However, there is also an imbalance in the supply of agricultural products with the unreasonable allocation of factors, weak competitiveness of agriculture, low-end locking of technology, and many varieties of agricultural products but not excellent. Simultaneously, to pursue high grain yield, Chinese chemical fertilizers, pesticides, and agricultural membranes have multiplied, while the excessive use of agricultural chemicals has brought about a grave problem of agricultural surface pollution (Qiu et al., 2021). The National Plan for Sustainable Agricultural Development (2015–2030) stipulates that the current utilization rate of chemical fertilizers and pesticides is less than 1/3, the recycling rate of agricultural films is less than 2/3, the effective treatment rate of livestock and poultry manure is less than half, and straw burning and marine eutrophication are severely affected (Yi et al., 2019)[2]. Just like that, agricultural pollution is a prominent problem seriously jeopardizing agricultural eco-efficiency (Irfan and Ahmad 2022). The 2015 Central Rural Work Conference specified a strategy for the sustainable and healthy development of agriculture. The Chinese government further emphasizes various initiatives to boost the green development of agriculture (Yu, 2011). Under such a background, it has emerged as an inevitable choice for the current and future development of agriculture to improve agricultural eco-efficiency, achieves resource conservation and environmental protection, and promote sustainable agricultural development.

Moreover, as China's economy has shifted from the high-speed growth stage to the stage of high-quality development (Hao et al., 2021; Rauf et al., 2021; Abbasi et al., 2022), agricultural development has also stepped into a new period from production-oriented to quality-oriented (Zhao et al., 2008). How to reverse the previous factor-driven economic development model and focus on promoting quality change, efficiency change, and power change in economic development have become an urgent issue for policymakers to tackle. To crack the industrial deficiencies, power deficiencies, competition deficiencies, and environmental degradation challenges facing the revitalization of the countryside, the Chinese government has successively proposed to prioritize the development of agriculture and rural areas and promote high-quality agricultural development, and other major guidelines and strategies (Iqbal et al., 2021; Irfan et al., 2021). Since then, the Chinese government has explicitly suggested that it is imperative to promote the revitalization of rural industries (Wang J. et al., 2021; Khan et al., 2021; Fang et al., 2022), enrich new rural industries (Wu et al., 2021a; Shao et al., 2021), expand the value chain of agricultural industries, and realize the integrated development of agriculture and adjacent industries to fulfill the comprehensive revitalization of rural areas. The integration of rural industries has broadened the boundary of agricultural production possibilities, which is a powerful grip and significant driving force for China to break through the constraints of agricultural resources and the environment and fully implement the rural revitalization strategy. Among them, the integration of agriculture and tourism (agro-tourism integration) is a significant way to integrate rural industries, which is not only beneficial to broadening farmers' income channels, promoting the transformation and upgrading of agriculture, and maintaining the prosperity and stability of rural areas but also helps to continuously enrich the tourism industry and lengthen the industrial chain. The Opinions on Accelerating the Modernization of Agriculture and Rural Areas by Comprehensively Promoting the Revitalization of the Countryside also clearly indicate that the synergistic development of agriculture and tourism is an essential element and the primary path to boost the "revitalization of the countryside" and deepen the structural reform on the supply side. Also, agro-tourism integration can develop power support for the agriculture and tourism industries, which not only significantly boosts the non-agricultural income of the rural population, but also has great practical significance for generating new rural industries and realizing ecological livability.

However, against such backgrounds as rising production costs, continuous deterioration of the ecological environment, and increasingly urgent resource constraints, the road to the development of the traditional crude agricultural tourism integration industry, relies on the original sparring resources, inputs, and ecology, which has been struggling. It is imperative to expeditiously facilitate the transformation and upgrading of agriculture, promote the coordinated development of new rural integration, and take the path of green and sustainable development of agriculture and enhancement of agricultural eco-efficiency. However, there are more researches on agricultural eco-efficiency that ignore the key factor of agro-tourism integration. Only some scholars have explored the development path of agro-tourism integration in terms of sustainable development (Tang and Yin, 2006; Rajović and Bulatović, 2015; Pan et al., 2018). For example, Rajović and Bulatović (2015) find that agritourism, as a form of selective tourism, is not only a possible way to retain residents in rural areas, but also to promote economic growth and sustainable development in rural areas. Alternatively, some scholars have only investigated the measures and influencing factors of agricultural eco-efficiency (Picazo-Tadeo et al., 2011; Deng, and Gibson, 2019; Liu et al., 2021). Agro-tourism integration is a major force to drive the development of the rural economy and realize the strategy of rural revitalization. So, what is the current status of agro-tourism integration and agricultural eco-efficiency? Can agro-tourism integration contribute to the improvement of agricultural eco-efficiency? What is the role of agro-tourism integration in influencing agricultural eco-efficiency under different regional distributions? Such questions deserve further exploration. Therefore, a fixed-effects and the system generalized method of moments (SYS-GMM) and an instrumental variables methods are employed to empirically examine the impact of agro-tourism integration on agricultural eco-efficiency on the basis of using a dataset of 30 provincial

[1]http://www.gov.cn/xinwen/2022-02/28/content_5676015.htm.

[2]http://www.moa.gov.cn/gk/tzgg_1/tz/201505/t20150527_4620018.htm.

administrative regions from 2001 to 2019. It is significant to facilitate the development of agro-tourism integration for the comprehensive revitalization of rural regions and accelerate the sustainable development of agricultural green carpets by providing decision-making references and intellectual support as well as the formulation of relevant policies.

As such, this paper aims to conduct additional research in the following three categories. This paper uses the entropy weight approach and the Slack-Based Measure (SBM) model with undesired super-efficiency to measure agro-tourism integration and agricultural eco-efficiency including agricultural carbon emissions, respectively, studying the impact of agro-tourism integration, with a view to providing evidence on whether agro-tourism integration can improve agricultural eco-efficiency and providing a reference for agricultural eco-environment improvement and industrial integration development. Furthermore, this paper identifies the impact of agro-tourism integration on agricultural eco-efficiency by categorizing the research sample into an eastern and central-western region based on regional heterogeneity, to broaden the research content of agro-tourism integration and agricultural eco-efficiency and propose deeper reference suggestions for how agro-tourism integration can differentially participate in environmental governance.

The remaining results of this paper are organized as follows. **Section 2** gives a literature review on agro-tourism integration and agricultural eco-efficiency. **Section 3** provides the variable measures, model selection, and data description. **Section 4** presents the empirical results and discusses it in detail. Finally, this paper concludes with precise policy implications and directions for future research based on the findings.

2 LITERATURE REVIEW

As the popularity of agro-tourism integration and agricultural eco-efficiency has been increasing, researchers have carried out numerous useful explorations on the relationship between agro-tourism integration and agricultural eco-efficiency from various dimensions, which also provides a rich research basis for this paper. Collectively, the research on agro-tourism integration and agro-ecological efficiency can be summarized in the following aspects.

2.1 Research on Agro-Tourism Integration

It is suggested that the research on agro-tourism integration has been conducted in the three primary dimensions as follows. First, it is the definition of agro-tourism integration and the study of cooperation mode (Koutsouris et al., 2014; Lifang, 2018; Meng, 2019). Han et al. (2020) argue that agro-tourism integration involves the development process in which agriculture and tourism interpenetrate and intersect, and eventually merge into one, gradually forming a new type of business. Li et al. (2021) identifies agro-tourism integration as an economic model that adheres to the concept of green, low-carbon, and environmental protection and integrates agriculture and tourism. Some scholars have analytically defined agro-tourism integration in terms of agro-tourism and agro-tourism (Torres, 2003; Ghadami et al., 2022). Hysa and Kruja (2022), for example, consider agro-tourism integration as the economic realization of the sharing of the agricultural and tourism sectors. Dernoi (1983) outlines the possibilities of farm tourism for the development of rural areas when agriculture and tourism are combined in Europe, which is the prototype of agro-tourism integration development. Next, some scholars have measured agro-tourism integration (Zhou et al., 2020; Uduji et al., 2021). Yi et al. (2019) used Yangjia town in Mianyang City as an example to gauge its level of agriculture-tourism integration through the AHP method and analyze the problems and solution measures in the process of its agriculture-tourism integration development. Qiu et al. (2021) explore the integration context of agriculture and tourism night from 2009 to 2018 by employing the entropy weight method and coupled coordination model in Henan Province. Yang and Wang (2021) measured the degree of agro-tourism integration based on the AHP-fuzzy integrated evaluation method considering the Enshu Gongshui grapefruit industry as an example. Finally, several scholars have undertaken profound analyses of the factors influencing agro-tourism integration (Goreta Ban, 2021). Salihoglu and Gezici (2021) first investigate the link between the tourist and agricultural sectors and analyze the impact of supplier networks and geographic economies on the integration of the agro-tourism sector. Using Tanzania as a case study, Jani and Nguni (2021) identify the nature of supply and demand, agricultural scale, tourism destination, hotel scale, and scenic area type as significant factors influencing agro-tourism integration. Fleischer and Tchetchik (2005) suggest that agro-tourism integration can stimulate agricultural development and promote the diversification of special agro-tourism products, which satisfies the diversified needs of tourists and in turn promotes the rapid development of the agricultural economy. Gruia et al. (2021) reveal that after the new crown epidemic Romania needs to guide village governance according to the spirit of rural communities is to develop new agro-tourism policies and strategies and align with Europe.

2.2 Research on Agricultural Eco-efficiency

Scholars have yielded abundant achievements on agricultural eco-efficiency, and up to now, the research on agricultural eco-efficiency is mainly covering the following aspects. First, there are the definitions and origins of agricultural eco-efficiency. Agricultural eco-efficiency was most initially originating from the broad definition of eco-efficiency. Eco-efficiency was introduced by Schaltegger and Sturm (1990), who interpreted it as the ratio of positive economic externalities to ecological load. Subsequently, the World Business Council for Sustainable Development (WBSCD) and other official bodies jointly developed a definition of eco-efficiency at different levels, and concluded that eco-efficiency is the gradual reduction of ecological impacts and resource intensity throughout the life cycle to a level acceptable to the ecological carrying capacity of the earth, while achieving the goal of environmental quality and social harmony. The concept of agricultural eco-efficiency is an extension of eco-efficiency in the

field of agriculture. Currently, there is no clear definition of agricultural eco-efficiency, but scholars have defined it in accordance with their research focus, and its connotation can be summarized as obtaining the maximum agricultural economic benefits with the minimum input of environmental and resource factors. Many scholars have transferred the applied concept of eco-efficiency to agriculture, and thus agro-ecological efficiency was introduced. However, there are many differences among the interpretations of agroecological efficiency because of the different research objectives and samples selected by scholars. However, the present study defines agroecological efficiency as the maximum agricultural economic return with the minimum agricultural resource input and the minimum undesired output. Furthermore, scholars in various research scales have tested agricultural eco-efficiency and analyzed its influencing factors. Scholars usually employ the ratio method (Park et al., 2007), the indicator system method (Lauwers, 2009; Van Caneghem et al., 2010), and the input-output method (Akbar et al., 2021; Ji et al., 2021) to determine agricultural eco-efficiency (Liu, and Cheng, 2022). For example, using factor analysis methods, Guthman (2000) estimates the scale of agricultural development and operational efficiency in California, United States.

Moradi et al. (2018) construct a DEA approach to the CCR model to assess the agricultural cycle efficiency of farms. Taking different agricultural ecological zones from Ghana in 2010, Addai et al. (2014) assess the technical efficiency of maize growers. Akbar et al. (2021) calculate the agroecological efficiency of 30 provincial administrative regions in China in terms of agroecological efficiency using an SBM that includes undesired outputs. The super-efficient SBM model has gradually emerged as a prevailing model for measuring agricultural eco-efficiency because it combines the advantages of the super-efficient DEA model and SBM model, incorporates undesired outputs into the model, and effectively eliminates the slack phenomenon of inputs and outputs and the juxtaposition of ranking (Pang et al., 2016; Coluccia et al., 2020). In terms of the influencing factors of agricultural eco-efficiency, Yang et al. (2022) utilize a differential GMM model to quantify the influence mechanism between agricultural eco-efficiency and food security and the impact of different public investments in agriculture on them. Liu et al. (2020) suggest that agricultural infrastructure conditions, agricultural industry structure, agricultural development potential, and agricultural input intensity are the determinants of agricultural eco-efficiency. Liao et al. (2021) identify energy inputs, water inputs, and carbon emissions as the core drivers of spatial heterogeneity in agricultural eco-efficiency in China. Ma and Li (2021) examine digital inclusive finance and agricultural eco-efficiency and reveal that the effect of digital inclusive finance on agricultural eco-efficiency is non-linear with significant regional heterogeneity, which is dramatically reinforced by agricultural R&D investment.

Summarizing the above literature, it can be observed that agro-tourism integration and agricultural eco-efficiency have emerged as hotspots of academic attention, scholars have made meticulous and in-depth analyses of agricultural tourism integration and agricultural eco-efficiency on the basis of different research approaches and research objects (Chemnasiri, 2012; Zhou et al., 2021). Although scholars have separately examined the influencing factors of agricultural tourism integration and the influencing factors of agricultural eco-efficiency, few scholars have investigated the impact on agricultural eco-efficiency caused by agro-tourism integration (Wang and Zhou, 2021). Additionally, despite the fact that the measurement approaches, index systems, and analysis perspectives of agro-tourism integration and agricultural eco-efficiency have their distinctive features, there are some weaknesses (Yi et al., 2019; Hysa and Kruja, 2022). Because of this, this paper introduces agricultural carbon emissions into the eco-efficiency evaluation system, and utilizes a non-radial super-efficient SBM model and the Entropy weight method model to respectively gauge 2001–2019 agricultural eco-efficiency and agro-tourism integration levels. The systematic GMM model is employed to explore the heterogeneous characteristics of agro-tourism integration on agricultural eco-efficiency, so as to promote agricultural ecological protection and high-quality agricultural development.

3 MODEL SETTING, VARIABLES DEFINITION, AND DATA DESCRIPTION

3.1 Model Setting

To alleviate the endogeneity problem, referring to Wu et al. (2020), the generalized method of moments (GMM) is applied to assess the influence of agro-tourism integration on agricultural eco-efficiency. However, compared to differential GMM, systematic GMM (SYS-GMM) has fewer bias problems and improved efficiency in estimating results with limited samples, which not only alleviates the weak instrumental variables arising from the differential GMM estimation method, but also contributes to the robustness of the model estimation. Therefore, this paper opts for a systematic GMM to estimate the impact of agro-tourism integration on agricultural eco-efficiency. The specific form of the equation is set as follows.

$$AEE_{it} = \alpha_0 + \alpha_1 AEE_{it-1} + \alpha_2 ATI_{it} + \alpha_n X_{it} + \varepsilon_{it} \tag{1}$$

where the subscripts $i(t)$ and t denote provinces (years), respectively. AEE characterizes agricultural eco-efficiency. ATI characterizes agro-tourism integration. X denotes some other factors that may affect agro-ecological efficiency, including agricultural economic level (AEL), agricultural machinery density (AMD), industrialization level (INL), agricultural employment level (AET), financial support for agriculture (FSA), human capital (HUM), information level (INF), marketization level (MAR), and R&D investment (RDI). α_0, α_1, α_2, α_n denote the coefficient to be estimated. ε denotes the random perturbation term, which is subject to the white noise process.

3.2 Variables Selection

3.2.1 Explained Variables

Agricultural eco-efficiency (AEE). Data envelopment analysis (DEA) is the method frequently employed to evaluate

agricultural eco-efficiency. DEA approach is a nonparametric statistical method based on the concept of relative efficiency and the relative effectiveness of the same type of units based on multi-indicator inputs and multi-indicator outputs (Hao et al., 2020; Yang et al., 2021a; Ren et al., 2022a). The principle of DEA lies in substituting the production function in microeconomics with an envelope and then mapping the inputs and outputs of all decision-making units (DMUs) into space. Then, the effective and ineffective points are divided by constructing a non-parametric envelope front line, with the effective points located on the frontier and the ineffective points located below the frontier (Cecchini et al., 2018; Ren et al., 2021; Su et al., 2021). However, the traditional DEA model is also classified as a radial model by some scholars, but the probability that the inputs and outputs change in the same proportion is very low or even 0. Moreover, the traditional radial DEA model has neglected the input and output slack variables (Li et al., 2021; Liu et al., 2021). Non-radial slack can often be found, with the possibility of improved slack non-proportionality as well as radial proportionality in the decision unit (Li and Shi, 2014). When the input (output) slack plays a significant role in the evaluation of the efficiency of a decision unit, the efficiency derived from the measurement of the model alone is inherently unreasonable (Hao et al., 2022). To fully capture the input (output) slack, Tone (2001) develops a super-efficient SBM model based on the SBM models. However, the SBM model, like the traditional DEA model, makes it difficult to further distinguish efficiency differences among efficient DMUs for DMUs that are all 1 efficient. Furthermore, the super-efficient SBM model can handle the "slack" problem better and provide a comparison for decision-making units (DMUs) with efficiency higher than or equal to 1. Therefore, the super-efficient SBM model is chosen for agricultural eco-efficiency measurement. The model construction is presented in the following form.

$$AEE = min \frac{(1/m)\sum_{i=1}^{m} (\bar{x}/x_{ik})}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\left(\overline{y^d} \middle/ y_{sk}^d\right) + \sum_{q=1}^{r_2}\left(\overline{y^u} \middle/ y_{qk}^u\right)\right)} \tag{2}$$

$$\begin{cases} \bar{x} \geq \sum_{j=1, j \neq k}^{n} x_{ij}\lambda_j; \ \overline{y^d} \leq \sum_{j=1, j \neq k}^{n} y_{sk}^d \lambda_j; \overline{y^d} \sum_{j=1, j \neq k}^{n} y_{qk}^u \lambda_j \\ \bar{x} \geq x_k; \quad \overline{y^d} \leq y_k^d; \quad \overline{y^u} \leq y_k^u \\ \lambda_j \geq 0, i = 1, 2, \ldots m; \quad \bar{\lambda}_j \geq 0, j = 1, 2, \ldots n, j \neq 0; \\ s = 1, 2, \cdots r_1; \quad q = 1, 2, \cdots r_2; \end{cases} \tag{3}$$

where AEE denotes the agricultural eco-efficiency value. There are n decision units, each of which includes m inputs, r_1 desired outputs, and r_2 undesired outputs. x denotes an element in the input matrix. y^d denotes an element in the desired output matrix. yu denotes an element in the undesired output matrix.

Agricultural eco-efficiency measurement system. Agriculture in a broad sense includes agriculture, livestock, and fishery, while agriculture in a narrow sense means plantation. This paper measures agricultural eco-efficiency with a narrow sense of agriculture as the focus of the survey. Based on the characteristics of plantation production, the input and output indicators are selected as follows.

3.2.1.1 Input Indicators

The inputs in agricultural production include fertilizer, irrigation, and mulch needed for crop growth, in addition to conventional labor and land inputs. This paper selects 8 input indicators that are associated with agricultural production, which basically cover the required inputs in the agricultural production cycle.

Labor input is quantified by the amount of labor input in agricultural production, which is the product of the number of people employed in the primary sector and the ratio of total agricultural output to total agricultural, forestry, animal husbandry, and fishery output. Land input, as one of the necessary elements of agricultural production, is denoted by the total sown area of crops. Fertilizers containing nitrogen, phosphorus, potassium, and other elements are usually applied in agricultural production, and fertilizer inputs are characterized by the amount of fertilizer applied after converting the sum of nitrogen, phosphorus, and compound fertilizers. Pesticide inputs are characterized by the number of pesticides used. The agricultural film, a breakthrough in modern agriculture, whose inputs significantly improve crop survival and growth, is characterized by the amount of agricultural film used. The input of machinery in modern agriculture has boosted labor efficiency and mechanization is an important feature of modern agriculture. The total power of agricultural machinery is denoted as agricultural machinery power input. The use of machinery in modern agriculture requires energy to power it. Energy inputs are denoted by the amount of agricultural diesel used. Water is an essential element in crop production. The effective irrigated area is used to express the irrigation input.

3.2.1.2 Desired Output

Following Liao et al. (2021) and Ma and Li (2021), the total agricultural output value is selected to denote the desired output of agriculture (to avoid the influence of price factors, this paper uses the price index of total agricultural, forestry, animal husbandry, and fishery output value, which is smoothed with the consumer price index in 2000 as the base period).

3.2.1.3 Undesired Output

Agricultural carbon emissions are characterized as non-desired outputs, which derive from 6 major direct or indirect sources such as fertilizers, pesticides, agricultural films, agricultural diesel, irrigation electricity and water consumption, and tillage loss. Referring to Shi et al. (2022) and Liao et al. (2021), the emission coefficients of 6 major carbon sources were 0.895 6 (kg/kg) for fertilizer, 4.934 1 (kg/kg) for pesticide, 5.18 (kg/kg) for agricultural film, 0.592 7 (kg/kg) for diesel, 20.476 (kg/km^2) for agricultural irrigation and 312.6 (kg/km^2) for agricultural tillage.

3.2.2 Core Explanatory Variables

Agro-tourism integration (ATI). Agro-tourism integration is a new business model based on the industrial connection between agriculture and tourism, which derives from the development of the rural tourism industry from rural agriculture, and the derivation of agrarian caravans, agricultural estates, melon and

TABLE 1 | Agro-tourism integration index system.

Guideline level	Indicator system
Industrial correlation degree	Agricultural added value Gross tourism revenue Gross tourist arrivals Domestic tourism revenue International foreign exchange tourism revenue
Tourism industry development	The added value of the accommodations and restaurants industry Travel agency business income Number of star-rated hotels Star-rated hotel business income Travel agency operating income
Integration benefits	Rural farming fixed-asset investment area of fruit orchards Number of employees in primary industry Value added in agriculture as a share of GDP Total tourism revenue as a share of GDP

fruit, and vegetable production bases (Astuti et al., 2019). Meanwhile, it fully utilizes rural natural resources, absorbs rural surplus labor, forms new economic growth points in rural areas, as well as realizes good economic and social benefits for the whole society. Thus, the degree of association between agriculture and tourism is the basis for evaluating agro-tourism integration, and the economic and social benefits of integration development serve as the outcome (Budiasa and Ambarawati, 2014) see (**Table 1**). Referring to Zhou et al. (2021), this paper establishes the following agro-tourism integration index system using the Entropy weight method.

Agro-tourism integration level measurement. For the synthesis of the agro-tourism integration index system, referring to Cao et al. (2021) and Cao et al. (2022), the more objective Entropy weight method is adopted to integrate each index. The specific steps are as follows.

Step 1. The indicators are normalized dimensionless using the extreme difference standardization method. Since the selected indicators all have a positive influence on agro-tourism integration, thus the indicators are processed as follows.

$$z_{ij} = \frac{x_{ij} - \min(x)}{max(x_j) - \min(x_j)} \tag{4}$$

Step 2. Calculating the relative share of the i_{th} region for the j_{th} indicator.

$$P_{ij} = z_{ij} \Big/ \sum\nolimits_{i=1}^{m} z_{ij} \tag{5}$$

In **Eq. 5**, P_{ij} is the relative weight and m is the number of samples.

Step 3. Calculating the entropy value of the j_{th} indicator.

TABLE 2 | Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
AEE	540	0.8032	0.3122	0.2656	1.6627
ATI	540	0.1636	0.1190	0.0124	0.7269
AEL	540	21.2562	12.0365	3.3526	75.5372
AMD	540	5.5758	2.6520	1.3932	13.9378
AET	540	0.3883	0.1596	0.0296	0.8183
INL	540	0.3767	0.0873	0.1109	0.5924
FSA	540	0.1016	0.0352	2.0213	2.1897
MAR	540	6.3718	1.954437	2.3700	11.4000
INF	540	0.0908	0.1417	0.0013	1.6450
HUM	540	8.7099	1.0994	6.0400	12.9200
RDI	540	0.2139	0.6882	0.0015	6.3100

$$e_j = -\frac{1}{lnm} \sum P_{ij} lnP_{ij} \tag{6}$$

In **Eq. 6**, e_j is the entropy value of the j_{th} indicator.

Step 4. Calculating the weight (ω_j).

$$\omega_j = \left(1 - e_j\right) \Big/ \sum\nolimits_{j=1}^{n} \left(1 - e_j\right) \tag{7}$$

In **Eq. 7**, $(1 - e_j)$ is the information utility value of j_{th}.

Step 5. Calculating the indicator of different years in each region.

$$ATI_{ij} = \sum\nolimits_{i=1}^{n} \omega_j * z_{ij} \tag{8}$$

3.2.3 Control Variables

Referring to Shi et al. (2022), Wang J. et al. (2022), and Zhao et al. (2021), the variables of agricultural economic level (AEL), agricultural machinery density (AMD), industrialization level (INL), agricultural employment level

TABLE 3 | Baseline regression results.

Variables	(1)	(2)	(3)	(4)
L.AEE			0.6390***	0.6184***
			(0.019)	(0.078)
ATI	0.3726***	0.4971***	0.1480***	0.2632***
	(0.110)	(0.171)	(0.029)	(0.092)
AEL		0.0016		0.0006
		(0.001)		(0.001)
AMD		−0.0279***		−0.0136***
		(0.005)		(0.004)
AET		−0.9469***		−0.4235***
		(0.177)		(0.158)
INL		−1.3928***		−0.4213***
		(0.148)		(0.099)
FSA		−3.0293***		−1.1077***
		(0.509)		(0.354)
MAR		−0.0223*		−0.0138*
		(0.012)		(0.008)
INF		−0.0500		−0.0252
		(0.148)		(0.030)
HUM		−0.0645***		−0.0193
		(0.021)		(0.013)
RDI		−0.0474**		−0.0189**
		(0.024)		(0.008)
_cons	0.7440***	2.7647***	0.2500***	1.0206***
	(0.022)	(0.288)	(0.022)	(0.247)
AR(2)			−1.46	−1.42
			[0.145]	[0.156]
Hansen test			28.38	26.08
			[1.000]	[1.000]
N	570	570	540	540

*Standard errors in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01. "[]" denotes the p-value.*

(AET), financial support for agriculture (FSA), human capital (HUM), Informatization level (INF), marketization level (MAR), and R&D investment (RDI) are considered to control for other factors affecting agricultural eco-efficiency. Agricultural economic level (AEL) is quantified using the ratio of total agricultural output to the resident population. Agricultural machinery density (AMD) is captured by the ratio of total agricultural machinery power to total crop sown area. Industrialization level (INL) is characterized by the ratio of industrial value-added to GDP. Agricultural employment level (AET) is characterized using the ratio of employment in the primary sector to the total number of employees. Financial support for agriculture (FSA) is summarized by the ratio of agricultural, forestry, and water expenditures to local general budget expenditures. The number of years of education per capita is selected to denote human capital (HUM). Informatization level (INF) is denoted by the volume of the postal and telecommunication business. Marketization level (MAR) is selected to measure the ratio of employees in private and individual enterprises to the resident population. R&D investment (RDI) is measured using R&D noted as a share of GDP.

3.3 Data Description

The study subjects are 30 provincial administrative regions in mainland China (limited to data availability and the special agricultural production conditions in Tibet and Hong Kong, Macao, and Taiwan, which are not included in the empirical study), and the time horizon is 2001–2019. The data involved in this paper are collected from "China Rural Statistical Yearbook", "China Agricultural Statistics", "Fifty Years of New China Agricultural Statistics", "China Tourism Statistical Yearbook", "China Statistical Yearbook" and provincial statistical yearbooks, the National Economic and Social Development Statistical Bulletin. Moreover, some of the missing data are supplemented by consulting the official websites of the relevant ministries and provincial statistical bureaus. The data measured in monetary units have been eliminated for inflation. Descriptive statistics are placed in **Table 2**.

4 RESULTS AND DISCUSSION

4.1 Baseline Regression Results and Discussion

For comparison, columns 1) and 2) of **Table 3** list the estimation results of the mixed least square method regression model. Columns 3) and 4) of **Table 3** show the estimation results of the SYS- GMM model. **Table 3**reports that the coefficients of AR (2) and the $Hansen\,test$ are not significant ($p-value > 0.1$), indicating that the disturbance terms do not have second-order serial autocorrelation as well as the validity of the instrumental variable selection, which confirms the rationality of employing the SYS- GMM to verify the effect of agro-tourism integration on agricultural eco-efficiency. Further, an interesting finding is that the coefficient of ATI is significantly positive ($p-value < 0.01$) with or without control variables introduced, i.e., agro-tourism integration can contribute to agricultural eco-efficiency. Our findings are in line with those of Liu et al. (2020) and Wang G. et al. (2022). One possible explanation is that agro-tourism integration converts the value of the agricultural ecological environment into economic benefits, which contributes to enhancing the agricultural producers' capital accumulation level (Wang J. et al., 2022). It allows them to have enough funds to purchase advanced and efficient agricultural equipment, thus diminishing factor inputs such as labor, arable land, and mechanical power and water, and ultimately improving agricultural production efficiency (Chemnasiri, 2012; Ana, 2017). Also, the development process of agro-tourism integration always adheres to scale, industrialization, intensification, and clean production and operation. Moreover, agro-tourism integration is mainly a direct regenerative use of natural and human resources, transforming them into scenic resources and attractive tourism products, which carry natural ecological attributes (Yi et al., 2019). During the process of agro-tourism integration development, the rural environment should be greened, purified, and beautified, which is conducive to the protection of the rural ecological environment (Budiasa and Ambarawati, 2014). Simultaneously, agro-tourism integration strengthens the economic base of the countryside and provides a financial guarantee for the maintenance and improvement of the rural

TABLE 4 | Regional heterogeneity results.

Variables	(1) Eastern region	(2) Eastern region	(3) Central-western region	(4) Central-western region
L.AEE	0.5825***	0.5672***	0.5299***	0.6155***
	(0.010)	(0.076)	(0.017)	(0.084)
ATI	0.2663***	0.3598***	−0.3845***	−0.3095**
	(0.045)	(0.074)	(0.046)	(0.150)
AEL		0.0013		0.0014
		(0.001)		(0.001)
AMD		−0.0200***		−0.0139***
		(0.004)		(0.003)
AET		−0.4423**		−0.2751*
		(0.201)		(0.144)
INL		−0.5499***		−0.3726***
		(0.081)		(0.102)
FSA		−1.1403***		−1.0285**
		(0.424)		(0.454)
MAR		−0.0172***		−0.0046
		(0.006)		(0.008)
INF		−0.0206		0.0938***
		(0.022)		(0.034)
HUM		−0.0325*		0.0011
		(0.019)		(0.012)
RDI		−0.0182***		−0.0240***
		(0.005)		(0.009)
_cons	0.2977***	1.3022***	0.4029***	0.7340***
	(0.017)	(0.296)	(0.013)	(0.242)
AR(2)	−1.48	−1.47	−1.54	−1.37
	[0.138]	[0.142]	[0.125]	[0.170]
Hansen test	28.48	21.88	28.57	24.24
	[1.000]	[1.000]	[1.000]	[1.000]
N	540	540	540	540

*Standard errors in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01. "[]" denotes the p-value.*

ecological environment (Qiu et al., 2021). During the process, agricultural producers gradually realize that ecological factors in the agricultural production process can create higher and more sustainable premiums. Therefore, to keep long-term sustainable economic returns, relevant practitioners will embrace the concept of low-carbon development and strengthen environmental awareness and behavior, such as reducing harmful environmental factors such as fertilizer and pesticide inputs and using low-carbon products, which minimize the negative impact of production and operation activities on the natural environment and thus contribute to the improvement of agricultural eco-efficiency (Rajović and Bulatović, 2015).

4.2 Heterogeneity Results and Discussion

Because of the influence of the economy, human history, and geographical environment, there are form differences among various regions in China (Yang et al., 2021b; Ren et al., 2022b; Wu et al., 2021b). The impact of agro-tourism integration on agro-ecological efficiency may yield significant variations in terms of different regions (Liu et al., 2020). Thus, this paper categorizes the research sample, which contains 30 provincial administrative divisions, into two regions (eastern and central-western). **Table 4** reports that a significant regional heterogeneity is found in the effect of agro-tourism integration on agricultural eco-efficiency, i.e., the coefficient of agro-tourism integration is significantly positive at the 1% level in the eastern region and significantly negative at the 5% level in the central-western region. It is not surprising that our findings correspond to the study of Wang and Zhou (2021). An underlying interpretation is that the eastern region has an advanced economy, sound agricultural infrastructure, and an interest in agricultural modernization (Xiao et al., 2022). Also, the eastern regions are highly exploited and experienced in developing tourism resources, with rich industrial advantages in transforming rural ecological resources into tourism resources (Wang Z. et al., 2021). Moreover, not only does the eastern region have more financial resources to align agricultural production, resource conservation, and environmental protection, but agro-tourism integration does not involve further sacrificing the rural environment as a cost (Nie, 2021). The development of agro-tourism integration can swiftly transform rural ecological values into economic benefits, and the enhancement of economic benefits further impels the improvement of the agricultural ecological environment, so that the integration of agro-tourism and agricultural eco-efficiency improvement is driven into a virtuous cycle (Wang and Zhou, 2021). However, although the rural ecological resources in the central and western regions are more abundant, the agricultural economic development mode is relatively rough and the agricultural technology level develops

TABLE 5 | Robustness checks.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	TSLS	TSLS	Removing outliers	Removing outliers	Excluding special years	Excluding special years
L.AEE			0.6456***	0.6169***	0.5917***	0.6727***
			(0.008)	(0.078)	(0.019)	(0.064)
ATI	0.4123***	0.4436**	0.1515***	0.2446**	0.1615***	0.2359**
	(0.115)	(0.179)	(0.025)	(0.100)	(0.030)	(0.097)
AEL		0.0030**		0.0007		0.0016
		(0.001)		(0.001)		(0.001)
AMD		−0.0262***		−0.0134***		−0.0098***
		(0.005)		(0.004)		(0.003)
AET		−0.9549***		−0.4342***		−0.3655***
		(0.184)		(0.155)		(0.109)
INL		−1.3165***		−0.4253***		−0.4503***
		(0.157)		(0.099)		(0.095)
FSA		−3.7554***		−1.1075***		−1.6541***
		(0.565)		(0.354)		(0.496)
MAR		−0.0267**		−0.0132*		−0.0126*
		(0.012)		(0.008)		(0.007)
INF		−0.0221		−0.0187		−0.0364
		(0.150)		(0.030)		(0.029)
HUM		−0.0617***		−0.0197		-0.0255**
		(0.022)		(0.013)		(0.010)
RDI		−0.0447*		−0.0193**		−0.0141**
		(0.024)		(0.008)		(0.006)
_cons	0.7290***	2.7773***	0.2462***	1.0252***	0.2947***	1.0216***
	(0.024)	(0.305)	(0.012)	(0.248)	(0.014)	(0.160)
AR(2)			−1.45	−1.41	−0.91	−0.75
			[0.146]	[0.157]	[0.362]	[0.452]
Hansen test			28.08	26.34	28.15	23.51
			[1.000]	[1.000]	[0.999]	[1.000]
N	510	510	540	540	480	480

*Standard errors in parentheses; *p < 0.1, **p < 0.05, ***p < 0.01. "[]" denotes the p-value.*

slowly (Hernández-Mogollón et al., 2011). Meanwhile, the agricultural production mode in the central and western regions is yet comparatively backward, with a lower degree of agricultural mechanization and insufficient market demand for agro-tourism integration, which is more driven by uncertain policies (Zhou et al., 2021). To fulfill agricultural tourism integration expeditiously, the central and western regions probably just emphasize economic benefits and forcefully graft on the agro-tourism integration model of the eastern regions, failing to apply strategies according to their local conditions and neglecting agro-ecological environmental protection, thus causing a reduction in agro-ecological efficiency.

4.3 Robustness Checks Results and Discussion

To ascertain that the benchmark regression results are robust, the following techniques are employed to perform robustness tests. First, aiming at the potential endogeneity problem, in addition to a dynamic panel model constructed by incorporating the lagged terms of the explanatory variables into the model, the instrumental variables approach can also be used to eliminate endogeneity. Following Wang J. et al. (2022), this paper performs two-stage least squares (TSLS) estimation by selecting the lagged second term of agro-tourism integration as the instrumental variable (Columns 1) and 2) of **Table 5**). Next, it is observed that, in general, the presence of outliers in the sample has a significant effect on the estimation of the results. Thus, this paper utilizes tailoring to remove the 1% outliers (Columns 3) and 4) of **Table 5**). Finally, the emergence of extreme events can also cause huge fluctuations in the sample data within a particular year. And the worldwide U.S. subprime mortgage crisis in 2008 will undoubtedly produce a tremendous shock to sample stability. Therefore, the 2008 years data were excluded to check the impact of agro-tourism integration on agricultural eco-efficiency (Columns 5) and 6) of **Table 5**). **Table 5** reports that the effect of agro-tourism integration on agricultural eco-efficiency remains significantly positive after using TSLS estimation, removing outliers, and excluding special years, implying that empirical results are robust and reliable.

5 CONCLUSIONS AND POLICY RECOMMENDATIONS

This paper evaluates the agro-tourism integration level utilizing the Entropy weight method on the basis of a dataset of 30 provincial administrative regions in China from 2001 to 2019. Also, considering the diverse factors of ecological environmental protection and green low-carbon development, agricultural

carbon emissions are incorporated into the measurement system of agricultural eco-efficiency, and the super-efficient SBM approach is employed to measure agricultural eco-efficiency. Further, the SYS-GMM approach is applied to investigate the effect of agro-tourism integration on agricultural eco-efficiency. The major findings are as follows: Both static and dynamic panel models demonstrate a significant positive correlation between agro-tourism integration and agricultural eco-efficiency, i.e., agro-tourism integration can have a significant contribution to agricultural eco-efficiency. A significant positive effect of agro-tourism integration in the previous period on agro-tourism integration in the current period suggests that agro-tourism integration has strong inertia. Regional heterogeneity results report that agro-tourism integration significantly contributes to agricultural eco-efficiency in the eastern region, while it significantly inhibits agricultural eco-efficiency in the central-western region. Accordingly, this paper introduces the following two policy recommendations.

1) Policymakers should scientifically assess the development potential for both agriculture and tourism as well as the carrying capacity of the local ecological environment to determine the reasonableness and feasibility of agro-tourism integration development. Also, policymakers should actively explore a win-win model of total factor ecological protection and industrial development for mountains, water, forests, fields, and grasses, depending on local resource factor endowments. For example, policymakers should adhere to modernized green agriculture as a guide, broaden the depth and breadth of the agricultural industry chain, and strive to create a modern, green, and low-carbon agricultural industry system, thereby improving agricultural eco-efficiency.
2) Policymakers should dynamically adjust the development policy of agro-tourism integration in light of local conditions from the actual situation. In the specific implementation process of the policy, the significant regional heterogeneity that exists in the development of agro-tourism integration should be fully considered, and a dynamic, refined, and differentiated strategy of agro-tourism integration should be implemented to make agro-tourism integration development an effective tool to promote agricultural eco-efficiency. For example, given the sufficient market for agro-tourism integration in the eastern region and the perfect infrastructure construction of agriculture and tourism, policymakers should vigorously support the development of agro-tourism integration and improve the supervision function and institutional environment to actively guide consumer demand and broaden the scope of agro-tourism integration. In the central-western regions, due to their regional conditions, the foundation for developing agro-tourism integration is weak, and farmers' ecological awareness is insufficient. Policymakers need not only to give strong financial support to agro-tourism integration but also to strengthen agricultural ecological education and agricultural ecological management.

Although this paper has thoroughly analyzed the impact of agro-tourism integration on agricultural eco-efficiency, some significant issues still deserve attention. First, this paper only quantifies the direct effect of agro-tourism integration on agricultural eco-efficiency. However, agro-tourism integration may indirectly affect agro-ecological efficiency through the paths of human capital, resource allocation, and environmental regulation. Therefore, future scholars can explore the diversified paths of agro-tourism integration on agricultural eco-efficiency from the above perspectives.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

GJ: conceived the idea and contribute to the writing of the manuscript, performed the data collection, and statistical analysis, revised the manuscript, and gave guidance throughout the process of this study. All authors have read and agreed to the published version of the manuscript.

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How Does Environmental Regulation and Digital Finance Affect Green Technological Innovation: Evidence From China

Ruowei Ma[1], *Feifei Li*[1,2]* *and Mingyue Du*[1]*

[1]*School of Economics, Beijing Technology and Business University, Beijing, China,* [2]*Department of Economics and Management, Yuncheng University, Yuncheng, China*

With the deteriorating ecological environment, green technological innovation (GTI) has become an effective way to strengthen environmental protection and promote economic development. Based on the 2011–2019 panel data of 30 provinces in China, this study constructs a spatial Durbin model to examine the spatial spillover effect of environmental regulation and digital finance on green technological innovation. Meanwhile, a moderating effect model and threshold effect model are employed to explore the function of digital finance in terms of the impact of environmental regulation on green technological innovation. The empirical results show that: 1) environmental regulation has significantly promoted local GTI, green invention patents (GIP) and green utility model patents (GUP), while having had negative spatial spillover effects on those three things in neighboring regions. Digital finance promotes GTI and GIP in both local and neighboring areas, but digital finance's direct and spatial spillover effects on GUP are not significant. 2) A regional analysis shows that different intensities of environmental regulation and different digital finance levels in different regions lead to the heterogeneity of green technological innovation's response to them. 3) Digital finance produces a positive moderating effect on environmental regulation affecting GTI and GIP in local and neighboring regions. However, digital finance's moderating effect in terms of the influence of environmental regulation on GUP is not significant. 4) When digital finance reaches a certain threshold, environmental regulation will have a stronger role in promoting GTI. Therefore, to improve regional green technology innovation and environmental governance, the government should strengthen the integration of digital technology and financial services, and promote the construction of environmental supervision systems and green innovation policy systems.

Keywords: digital finance, green technological innovation, spatial spillover effect, moderating effect, environmental regulation

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Muhammad Irfan,
Beijing Institute of Technology, China

Reviewed by:
Yunfeng Shang,
Zhejiang Yuexiu University of Foreign Languages, China
Xiaowei Song,
Ocean University of China, China

Correspondence:
Feifei Li
lff511935220@163.com
Mingyue Du
mydu@st.btbu.edu.cn

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1 INTRODUCTION

Since reform and opening up, relying on the extensive development model, the China's economy has achieved rapid growth (Ren et al., 2021a; Yang et al., 2021; Fang et al., 2022; Wang et al., 2022) and has become the second largest economy in the world (Wu et al., 2019; Abbasi et al., 2022; Irfan and Ahmad, 2022). However, this development model leads to excessive consumption of natural resources and a deteriorating ecological environment (Wu et al., 2021a; Yan et al., 2021; Ren et al., 2022b), which negatively affects the long-term high-quality development of the economy and society (Cao and Wang, 2017; Khan et al., 2020). Green technology innovation (hereafter "GTI") can be considered as an effective way to realize a "win-win" result between the ecological environment and economic development (Dong et al., 2020; Wang and Feng, 2021). As an important supporting factor in realizing China's green development goals (Rauf et al., 2021; Shao et al., 2021; Xiang et al., 2022), GTI refers to a form of the research and development of the industrial technology system that is conducive to energy conservation, pollution prevention and control, and elevating energy efficiency and recycling levels (Irfan et al., 2021; Qiu et al., 2022; Shi et al., 2022). GTI has both "innovation" and "green" characteristics. By incorporating green technology and environmental factors into the framework of technological innovation, GTI improves the utilization of resources and energy, and plays a critical role in reducing resource consumption and controlling pollution (Yi et al., 2022). Therefore, to guarantee the sustainable development of the economy, it is becoming increasingly urgent to promote green development and construct an ecological civilization through GTI.

The Chinese government has issued many policies that are intended to promote both green development and GTI. Examples include formulating and promulgating pollution prevention laws, implementing environmental regulation measures for enterprises, and increasing R&D investment (Cai et al., 2020; Ren et al., 2021b). According to China's "Annual Report of Ecological Environment Statistics," the total investment in environmental pollution control in 2020 was 1063.89 billion yuan, accounting for 2% of the government total investment in fixed assets. Meanwhile, the environmental protection investment system (urban environmental infrastructure construction investment, industrial pollution source control investment and construction project acceptance investment) have been consistently improved and developed. Environmental regulation has been adopted by policy makers as an important means to control environmental pollution. Nevertheless, there is still no consistent conclusion with regard to the impact of environmental regulation on GTI. Some scholars have stated that, for enterprises, environmental regulation raises the cost of pollution control, decreases R&D innovation investment and inhibits GTI (Stucki et al., 2018; Shang et al., 2022). Conversely, some scholars have maintained that, when enterprises carry out GTI based on long-term development needs, their production efficiency and profitability will be improved. This, in turn, will counteract the negative effects of environmental regulation (Chakraborty and Chatterjee, 2017; Hu et al., 2020).

In addition, in the background of increased environmental regulation, to exert environmental regulation's positive function in GTI, the financial industry must provide a stable and sufficient source of funds for innovation. Although China's financial development system has gradually improved in recent years; there is still a structural mismatch of funds when traditional banking institutions provide financial services to enterprises. As a result, enterprises often face financing constraints due to failure to obtain financial support for R&D investment activities (Wu et al., 2021b). Compared with general innovation activities, GTI activities have the features of being long-term, high-risk and irreversible, and also face the issues of high cost, resource constraints and failure risks in the transformation process. Therefore, enterprises frequently face greater financing constraints in the process of technological innovation (Ji and Zhang, 2019). Recently, under the background of the vigorous development of the digital economy, a new financial format is being formed with the extensive integration of digital technology and financial products and services (Guo et al., 2020). With advanced technologies (such as blockchain and big data), digital finance has strengthened the connection between financial entities, expanded the content and boundary of traditional financial services, and provided new methods for solving the existing problems in traditional financial services (Gomber et al., 2018; Cao et al., 2021). However, the relationship between digital finance and corporate GTI has not been discussed in detail in the previous literature.

Nowadays, the impact of environmental regulation on GTI has become a hot research topic, and a few scholars have analyzed the mechanism of digital finance on GTI. However, few studies incorporate environmental regulation, digital finance and GTI into a unified analytical framework. In addition, the existing research has not yet studied the impact of environmental regulation on GTI from the perspective of digital finance. Under the macro background of tightening environmental regulations, digital finance provides effective financial support for green technological innovation activities by expanding corporate financing channels and reducing information asymmetry (Dendramis et al., 2018; Liao et al., 2020; Cao et al., 2021). Therefore, this paper aims to analyze the following issues. How do environmental regulation and digital finance affect GTI? Will digital finance indirectly affect the effect of environmental regulation on GTI? Is there a threshold effect on the impact of environmental regulation on GTI?

The rest of the paper is arranged as follows: **Section 2** reviews the related literature. **Section 3** presents the mechanism analysis. **Section 4** constructs the econometric model and explains the data sources. Empirical results and analysis of the benchmark research are reported in **Section 5**, and **Section 6** further explores the moderating effect and threshold effect of digital finance. Finally, **Section 7** summarizes the full text and puts forward corresponding policy suggestions.

2 LITERATURE REVIEW

Current literature about environmental regulation, digital finance and GTI mainly focuses on both the relationship between

environmental regulation and GTI, and the relationship between digital finance and GTI. Therefore, this section also reviews the relevant research from these two aspects.

2.1 Environmental Regulation and Green Technological Innovation

Environmental regulation is an effective way to manage environmental problems; this has been verified in practice (Porter and Van der Linde, 1995a). However, research on environmental regulation's impact on GTI (and the corresponding conclusions) is still controversial. At present, there are mainly three viewpoints regarding environmental regulation's impact: positive promotion, negative inhibition and uncertain effect. First, the positive promotion view holds that, when the government implements environmental regulations, enterprises will actively carry out GTI to reduce production costs and strengthen competitiveness. These enterprises obtain high profits by developing green processes and products (Guellec and Van Pottelsberghe De La Potterie, 2003), thus resulting in an "innovation compensation" effect. Perino and Requate (2012) put forward the hypothesis of green advanced production technology diffusion. Specifically, to decrease the pollution discharge expenses caused by an environmental protection policy, enterprises will have the motivation to introduce new green technology or buy green production technology in the market. This will promote the emergence and diffusion of green advanced production technology. Bréchet and Meunier (2014) analyzed the influence of technological innovation diffusion on environmental regulation by building a model. The study found that the implementation of either a pollution emission tax or a pollution permit will increase the rate of adoption of environmental innovation technology. Second, the view of reverse inhibition holds that environmental regulation is unfavorable to GTI. This is mainly manifested in the fact that environmental regulation has brought about high costs to enterprises, which in turn makes them unable to engage in GTI. This is called the "following cost" effect (Stucki et al., 2018; Li et al., 2019). Further, the cost borne by enterprises mainly includes two parts. One is the direct cost of dealing with pollution emissions; the other is the opportunity cost of investment activities abandoned to meet the requisite environmental protection policy standards (Rubashkina et al., 2015). Third, the view of uncertain effect maintains that a non-monotonic or insignificant correlation exists between environment regulation and GTI, and the relationship between them is complicated and unsure (Yuan et al., 2017; Fan et al., 2021). Scherer et al. (2001) took U.S. and German patents as samples, and concluded that environmental regulation is not related to GTI. Perino and Requate (2012) pointed outed that, when a company's new technology paradigm intersects the marginal "abatement" cost curve of the traditional technological paradigm, environmental regulation affects GTI in an inverted "U" shape. In addition, some scholars have classified environmental regulations and have found that command-controlled environmental regulations and market-driven environmental regulations produce different effects on GTI (Kesidou and Wu, 2020; Peng, 2020).

2.2 Digital Finance and Green Technological Innovation

Related literature in this field mainly falls into two categories. One discusses digital finance's impact on regional GTI from a macro view. Sun (2020) showed that the level of digitalization has a positive correlation with the benefits of the green economy, among which technological innovation is a factor that cannot be ignored if the former is to influence the latter. Cao et al. (2021) believed that digital finance has obviously improved regional GTI, thus improving the energy and environmental performance. Feng et al. (2022) drew the conclusion that digital finance promotes regional GTI by elevating the efficiency of capital allocation and optimizing the industrial structure. The second category explores the relationship of digital finance and GTI from a corporate micro view. For example, Yu et al. (2021) claimed that many enterprises often cannot obtain the necessary financial support for green innovation; rather, these enterprises usually face the problem of financing constraints. With the help of advanced technical means, digital finance effectively deals with this problem, generating a positive influence on enterprises' GTI. Frost et al. (2019) took the micro-loan data of Ant Financial as the research sample. The study found that digital finance has changed the traditional financial service mode by means of an internet platform and digital technology. This approach has greatly shortened the credit approval process and reduced the financing cost of enterprises, thus promoting enterprise innovation. Utilizing a sample of Chinese enterprises, Liu et al. (2022) showed that digital finance can greatly elevate the availability and inclusiveness of finance. As such, digital finance improves the normal situation in which financing is difficult and expensive for enterprises, and then promotes enterprises' GTI. Moreover, the promotion of digital finance to GTI is more obvious in economically underdeveloped areas and high-pollution industries. However, most of the above-mentioned studies were conducted from a spatially independent perspective, without considering the spatial spillover effect of financial resources.

To sum up, the existing research on environmental regulation, digital finance and GTI is relatively fruitful, but the following points still need to be further discussed: first, current research mainly concentrates on the relationship between environmental regulation and GTI, or between digital finance and GTI. These studies generally fail to incorporate the three (digital finance, GTI and environmental regulation) into the same research framework for systematic analysis. In addition, existing literature has classified the different means of environmental regulation to make differential analyses, but the differentiation analysis of different kinds of GTI still needs further detailed research. Second, most related researches are based on the spatial independence perspective. However, environmental regulation will influence the migration of enterprises, thus affecting the GTI in adjacent regions. Financial elements also have spatial spillover effects, so an independent perspective will inevitably lead to neglecting the spatial connection between regions. Third, the

tightening of an environmental regulation policy will inevitably impose higher requirements on enterprises' capital and technology resources. At present, there is an extreme lack of research on whether or not digital finance can modulate environmental regulation's impact on GTI.

The possible contributions of this study are as follows: First, from the research perspective, environmental regulation, digital finance and GTI are incorporated into the same research framework to comprehensively analyze the spatial spillover effects between them. Furthermore, unlike existing studies that only consider the overall GTI, GTI is further subdivided into green invention patents (hereafter GIP) and green utility model patents (hereafter GUP) to analyze the impact of environmental regulations on different innovation models. Secondly, in terms of research methods, given the spatial dependence of economic activities, the spatial Durbin model is adopted to empirically explore the direct impact and spatial spillover effects of environmental regulation and digital finance on cross-provincial GTI. Thirdly, the moderating effect model and threshold effect model are employed to explore the moderating and nonlinear influence of environmental regulation on GTI under different digital finance development levels.

3 MECHANISM ANALYSIS

The spatial correlation of economic activities will produce a spillover effect. Therefore, the mechanism between environmental regulation, digital finance and GTI should be discussed from the spatial perspective.

3.1 Mechanism of Environmental Regulation on Green Technological Innovation

Direct effect of environmental regulation on local GTI: To meet environmental protection requirements, enterprises' pollution control expenses will provisionally rise. However, in the long term, under the innovation compensation effect, enterprises will take measures to raise investment in R&D, driven by the pursuit of their own profits. These enterprises will also improve their competitiveness and the overall technical level of the industry by elevating production efficiency and changing production methods, in order to adapt to environmental standards (Peuckert, 2014; Wang and Shen, 2016; Chakraborty and Chatterjee, 2017; Cainelli et al., 2020). Moreover, due to the implementation of environmental protection policies, enterprises will decrease the consumption of high-pollution energy. Consumers will also turn to the consumption of environmentally friendly products, resulting in a consumption substitution effect. The changes in consumption concept and consumption structure will impel enterprises to conduct GTI. Therefore, environmental regulation will promote the level of GTI through both the innovation compensation effect and consumption substitution effect.

Spatial spillover effect of environmental regulation on GTI in neighboring regions: The "Pollution Shelter Hypothesis" (Porter and Van der Linde, 1995b) pointed out that, if a region's environmental regulations become strict, polluting enterprises will choose to move out of that region, because of rising costs (List and Co., 2000; Xing and Kolstad, 2002; Yin et al., 2015; Wu et al., 2017). Under the transfer effect of polluting industries, the green innovation capability of the areas where the polluting industries transferred is solidified at a low level. At the same time, China's current political system framework is made up of "political centralization and fiscal decentralization." Local economic performance is also often used as a standard for the promotion of government officials. When a certain place implements a stricter environmental access policy, the neighboring regional governments take on the mode of "bottom-to-bottom competition," in order to achieve GDP growth (Wheeler, 2001). These areas do not raise or even lower environmental standards to attract an inflow of resources, thus inhibiting GTI. However, even when the level of economic development varies among regions, some studies have pointed out that, under the background of high-quality economic development, a central environmental protection inspector will require the region's environmental regulation policies to be upgraded. In addition, the intergovernmental competition mode may also be expressed as being in the mode of "top-to-top competition" (Bu and Wagner, 2016). When one region improves the regulatory intensity, and adjacent places follow suit, the result will be a demonstration learning effect. Therefore, enhancing environmental regulation intensity may also produce a positive spillover effect on GTI in neighboring areas.

3.2 Mechanism of Digital Finance on Green Technological Innovation

Direct effect of digital finance on local GTI: The characteristics of high risk and high investment in GTI automatically mean that GTI requires long-term financial support (Stanko and Henard, 2017). The advantages of digital finance (such as wide coverage and low cost) mean the financial needs of green innovation can easily be met. Specifically, first of all, digital finance can enrich the sources of corporate funds and broaden the boundaries of financial services. Under the traditional financial service mode, a great deal of small and medium-sized enterprises with active innovation cannot obtain the required funding support from formal and traditional financial services. In the era of the digital economy, a new financial format has broken the constraints of the traditional modes of financial service through hardware facilities and geographical location. Digital finance offers coverage to a wider range of customers, as well as more modes of financial services. Digital finance has greatly improved the availability of corporate credit resources and provided a continuous capital supply for enterprises' GTI (Liao et al., 2020; Ozili, 2021). Secondly, digital finance can improve information transparency and financial service efficiency. The asymmetric information between enterprises and the traditional capital suppliers is one of the reasons why enterprises have difficulty obtaining external financing (Kaplan and Zingales, 1997). Digital finance is able to accurately obtain the enterprises' relevant data

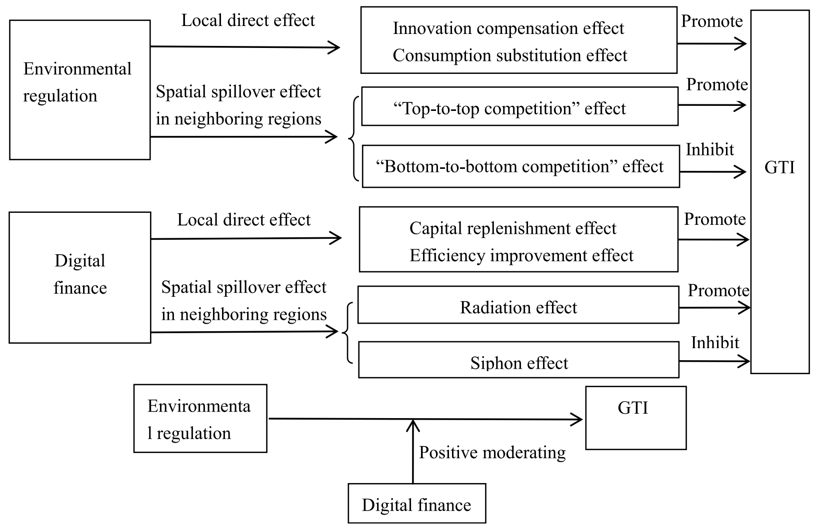

FIGURE 1 | Mechanism analysis diagram.

(and that of their innovative projects) by means of emerging technologies. Thus, a complete information monitoring system and risk assessment system can be set up accordingly (Du et al., 2021). This method not only improves the information transparency of enterprises and avoids credit discrimination under the influence of information asymmetry (Kshetri, 2016; Dendramis et al., 2018), but also simplifies the credit review and evaluation process of enterprises and improves their financing efficiency (Gomber et al., 2018; Feng et al., 2022). Therefore, digital finance can meet the capital needs of enterprises through the capital replenishment effect and efficiency improvement effect, thereby mobilizing the innovation initiative of enterprises, and enhancing the innovation ability of green technology.

Spatial spillover effect of digital finance on GTI in neighboring regions: Digital finance has strong spatial correlation and an agglomeration effect (Wang and Guan, 2017; Shen et al., 2021). This not only affects the local technological innovation activities, but also affects the neighboring technological innovation activities through the "correlation effect." For one thing, local digital finance can produce a radiation effect. Capital flow, personnel flow and data sharing drive the promotion of digital finance in adjacent areas and also alleviate the financing constraints faced by those adjacent areas. Thus, the innovation environment in adjacent areas is improved, and the level of GTI in those areas is elevated. For another thing, the development of digital finance will also produce a siphon effect. Relying on the first-mover advantage, a characteristic of digital finance, a better financial support and innovation environment has been created locally, thus attracting investment and consumption from the surrounding areas. Shortages of supply-side investment and demand-side consumption have simultaneously inhibited the innovation vitality of the surrounding areas. Meanwhile, the "digital divide" caused by the continuous improvement of local digital finance, as well as the high technical threshold of digital finance itself, makes it impossible for neighboring areas to quickly improve the level of digital finance in a short time. This inhibits the improvement of GTI levels in neighboring areas.

3.3 Coordination Mechanism of Environmental Regulation and Digital Finance on Green Technological Innovation

The implementation of an environmental regulation policy will impose higher standards on enterprise production. Enterprises will adopt technological innovation to meet environmental protection requirements, but this will put pressure on their ability to invest. Under the background of tightening environmental regulations, enterprises' production funds are facing constraint pressure. Meanwhile, traditional finance methods and sources lead to capital mismatch, due to the asymmetric information between banks and enterprises; financial discrimination also exists (Talavera et al., 2012). The development of digital finance, which relies on information processing, can effectively achieve accurate data matching and more accurate risk assessment, thus realizing a more effective allocation of funds (Li et al., 2020). Meanwhile, digital finance can use its own information and technology advantages to broaden enterprises' financing channels. Digital finance can touch more long tail groups that are facing the pressure of financial constraints due to the tightening of environmental regulations, alleviate the phenomenon of financial discrimination, and help inclusive finance to realize its due meaning. Therefore, with the strengthening of environmental regulation, the development of digital finance can optimize the resource allocation structure, slow down financial discrimination, promote the continuous improvement of the financial system, and ultimately provide potential fund support for enterprises. Finally, digital finance will positively modulate the influence of environmental regulation on GTI.

According to the above analysis, the mechanism of environmental regulation and digital finance on GTI is organized in **Figure 1**.

4 METHODOLOGY AND DATA

4.1 Econometric Methodology

4.1.1 Spatial Durbin Model

The development of environmental policies and digital finance in China's provinces has significant spatial dependence. Meanwhile, many studies have shown that when the variables are spatially correlated, traditional econometric estimation models will lead to biased estimation results (Feng and Chen, 2018; Feng et al., 2019). Therefore, to better reflect the spatial effect of economic variables, this paper adopts a spatial econometric model to explore the influence of environmental regulation and digital finance on GTI in the spatial category. The spatial Durbin model comprehensively considers the spatial effects of independent variables and dependent variables, thereby effectively capturing the spillover effects of economic activities (LeSage and Pace, 2009; Ren et al., 2022a). Therefore, this study employs the spatial Durbin model for empirical analysis. The specific model setting is as follows:

$$GTI_{it} = \alpha + \rho\sum_{j=1}^{n} W_{ij}GTI_{it} + \alpha_1 er_{it} + \alpha_2 dfi_{it} + \gamma controls_{it} + \beta_1\sum_{j=1}^{n} W_{ij}*er_{it} + \beta_2\sum_{j=1}^{n} W_{ij}*dfi_{it} + \phi\sum_{j=1}^{n} W_{ij}*controls_{it} + u_i + v_t + \varepsilon_{it} \quad (1)$$

Here, GTI_{it} is the green technology innovation index of the i province in the t year; *er* is environmental regulation; *dfi* is digital financial index, and *controls* is the series of control variables in this paper. Next, W_{ij} is the spatial weight matrix, α is the intercept term, $\rho, \alpha_1, \alpha_2, \gamma, \beta_1, \beta_2$, and ϕ are the parameters to be estimated; u_i is the time effect, v_t is the individual effect, and ε_{it} is a random error term. As for the choice of spatial weight matrix, this paper selects the adjacent weight matrix (W_{ij}^1) for empirical analysis; the geographic distance weight matrix (W_{ij}^2) and economic distance weight matrix (W_{ij}^3) are used for the robustness test. The formulas are:

$$W_{ij}^1 = \begin{cases} 1, & i \neq j \\ 0, & i = j \end{cases} \quad (2)$$

If the province i and province j are geographically adjacent, $W_{ij}^1 = 1$; otherwise $W_{ij}^1 = 0$.

$$W_{ij}^2 = \begin{cases} \dfrac{1}{(d_{ij})^2}, & i \neq j \\ 0, & i = j \end{cases} \quad (3)$$

where d_{ij} is the spherical distance between cities, calculated according to the longitude and latitude coordinates of municipalities and provincial capitals.

$$W_{ij}^3 = \begin{cases} \dfrac{1}{\left|\overline{Y_i} - \overline{Y_j}\right|}, & i \neq j \\ 0, & i = j \end{cases} \quad (4)$$

where $\overline{Y_i}$ indicates the average GDP of i province.

4.1.2 Moderating Effect Model

To investigate the moderating role of digital finance (dfi) in the influence of environmental regulation on GTI, the interaction term er*dfi between environmental regulation and digital finance, and its spatial lag term W*er*dfi, are added into the benchmark model. When a model contains interactive terms, it is generally necessary to centralize the interactive variables. This approach can alleviate the problem of multicollinearity to some extent, and make the interactive variables more economical (Balli and Sørensen, 2013). The moderating effect model is designed as follows:

$$GTI_{it} = \alpha + \rho\sum_{j=1}^{n} W_{ij}GTI_{it} + \alpha_1 er_{it} + \alpha_2 dfi_{it} + \alpha_3 er_{it}*dfi_{it} + \gamma controls_{it} + \beta_1\sum_{j=1}^{n} W_{ij}*er_{it} + \beta_2\sum_{j=1}^{n} W_{ij}*dfi_{it} + \beta_3\sum_{j=1}^{n} W_{ij}er_{it}*dfi_{it} + \phi\sum_{j=1}^{n} W_{ij}*controls_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

4.1.3 Threshold Effect Model

Under different levels of digital finance, environmental regulations are likely to have varying degrees of impact on GTI. To further verify the above moderating effect, this study sets up a panel threshold model to examine the nonlinear effect of environmental regulation on GTI, under the influence of different levels of digital finance. Referring to Hansen (1999), the panel threshold model is built as follows:

$$GTI_{it} = \alpha + \lambda_1 er_{it} \times I(dfi \le \mu_1) + \lambda_2 er_{it} \times I(\mu_1 < dfi \le \mu_2) + \cdots \lambda_n er_{it} \times I(\mu_{n-1} < dfi \le \mu_n) + \lambda_{n+1} er_{it} \times I(dfi > \mu_n) + \beta control_{it} + \phi_{it} \quad (6)$$

Here, the explained variable is GTI; the core explanatory variable is environmental regulation (er); the threshold variable is digital finance (dfi); *control* represents the control variables set for the model; λ1, λ2. . .λn, λn+1 are the staged influence of environmental regulation on GTI under different threshold variable values; I(·) is an instruction function; u_i is a specific threshold value, and ϕ_{it} is a random interference term.

4.2 Explanation of the Variables

4.2.1 Explained Variables

Green technological innovation (GTI): Existing research mainly takes the number of green patents to represent the level of GTI (Wagner, 2007; Johnstone et al., 2010). Furthermore, the number of green patents includes the number of both applications and authorizations. To some extent, the number of patent applications merely reflects the willingness to carry out GTI, but the number itself does not represent the actual upgrading of the technical level. Based on this and referring to Liu et al. (2020), this paper chooses the number of granted green patents to represent the level of GTI in each province and city. Specifically, according to all the patent application information published by the Intellectual Property Office of China, combined with the international patent classification code of green patents provided by the World Intellectual Property Organization

(WIPO), the patent data of different provinces have been obtained. The logarithm values of patent data are taken to construct the GTI index.

Green invention patents (GIP) and green utility model patents (GUP): GTI includes both GIP and GUP. Therefore, to further discuss the impact of environmental regulation and digital finance on different GTI, the authorized number of GIP and GUP are sorted out, and their logarithmic values are utilized as the proxy variables of GIP and GUP, respectively.

4.2.2 Core Explanatory Variables

Environmental regulation: To reflect the implementation effect of environmental regulation as a whole and to overcome the defect whereby a single index has difficulty in fully expressing environmental regulation, this study refers to Du and Li (2020) and Wang and Zhang (2022). Specifically, four indicators of 1) industrial solid waste, 2) industrial wastewater discharge, 3) sulfur dioxide discharge in industrial waste gas and 4) energy consumption in various regions are selected, in order to construct comprehensive indicators of environmental regulation intensity. Because these four indexes can comprehensively represent the control of the three wastes in a region, they have good representativeness. In addition, the entropy method is adopted in the determination of index weights. Specifically, after standardizing the indicators of different dimensions and units, the weight, entropy value and coefficient of difference are further calculated. Finally, the annual comprehensive score of each province is obtained; that is, the environmental regulation intensity index of each province, which is denoted by *er*.

Digital finance: Following Guo et al. (2020), the digital inclusive finance index developed by the Peking University Digital Financial Center is used as the proxy variable of digital finance. This index includes multidimensional data, such as coverage, depth of use, degree of digitization, etc. These data can comprehensively measure the current status of digital finance in China, and have certain representativeness and reliability. This study selects the provincial-level digital financial inclusion index, from 2014 to 2019, as the proxy variable of digital finance in the empirical analysis, represented by *dfi*.

4.2.3 Control Variables

Referring to existing studies (Luo and Liang, 2016; Feng et al., 2020; Shang et al., 2022), we select a series of control variables that affect GTI in the basic model.

Economic development (pergdp): Economic development can influence the industrial structure and energy utilization efficiency and plays an important role in GTI. We adopt the per capita GDP of each province to measure it.

Governmental support (gov): Government public financial support can help optimize resource allocation, improve economic efficiency, and promote GTI. We use the proportion of government public financial expenditure in GDP to express the size of the government.

Financial development (fiance): Financial development can provide more convenient financial services for enterprises to carry out technological innovation activities by lowering the threshold of financial services and improving the efficiency of financial services (Ren et al., 2022c). It is expressed by the proportion of the balance of loans from financial institutions to GDP at the end of the year.

Information level (inform): Information technology development can influence industrial agglomeration, promote industrial structure adjustment and promote enterprise innovation. Per capita post and telecommunications are used to measure the level of representative informatization (inform).

Economic openness (open): Economic openness can affect the regional GTI by introducing the leading energy-saving technology in developed countries. This paper uses the proportion of actual foreign investment and GDP to measure it.

R&D investment (rd): Green technology innovation is inseparable from a large amount of financial support. Therefore, increasing R&D investment can increase innovation output and improve GTI. This paper uses the ratio of R&D investment to GDP in each province to represent.

TABLE 1 | Statistical description of variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
GTI	270	7.399	1.338	2.996	10.262
GIP	270	5.837	1.369	1.609	8.626
GUP	270	7.144	1.345	2.708	10.097
dfi	270	5.151	0.670	2.909	6.017
er	270	0.585	0.086	0.188	0.683
pergdp	270	0.003	1.014	−1.337	4.270
gov	270	0.007	1.016	−0.628	6.125
finance	270	−0.038	0.939	−1.669	2.389
inform	270	0.022	1.009	−0.641	9.146
open	270	0.007	1.001	−1.085	5.274
rd	270	1.640	1.122	0.412	6.310

4.2.4 Date Sources

In this study, China's provincial panel data from 2011 to 2019 are used for empirical analysis. Digital finance index comes from the website of Institute of Digital Finance, Peking University. The environmental regulation data, GTI, GIP, GUP and control variables come from the State Intellectual Property Office, the website of the National Bureau of Statistics, the China Statistical Yearbook, China Regional Economic Statistical Yearbook and the statistical yearbooks of various provinces. Some missing data are filled in according to the linear interpolation method. The descriptive statistics of sample data are displayed in **Table 1**.

5 EMPIRICAL RESULTS AND ANALYSIS

5.1 Estimation Results of Spatial Model

5.1.1 Spatial Correlation Test

To explore whether spatial auto correlation exists between environmental regulation, digital finance and GTI, the global Moran's indexes of 2011–2019 are calculated respectively. **Table 2** demonstrates the results. As can be seen, from 2011 to 2019, the Moran's I indexes of environmental regulation, digital finance and GTI are all significantly positive.

TABLE 2 | Global correlation test: Moran index.

Variable	Moran's I	2011	2012	2013	2014	2015	2016	2017	2018	2019
GTI	Moran's I	0.323**	0.361***	0.356**	0.364***	0.407***	0.431***	0.402***	0.427***	0.451***
	Z-value	3.009	3.309	3.267	3.371	3.681	3.878	3.648	3.854	4.038
er	Moran's I	0.345**	0.353***	0.351***	0.341**	0.379***	0.381***	0.403***	0.398***	0.346***
	Z-value	3.394	3.495	3.514	3.465	3.810	3.743	3.960	3.817	3.321
dfi	Moran's I	0.160**	0.111**	0.122**	0.126**	0.100*	0.119**	0.116**	0.112**	0.097*
	Z-value	1.840	1.892	2.034	2.106	1.749	1.989	1.948	1.904	1.702

*Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.*

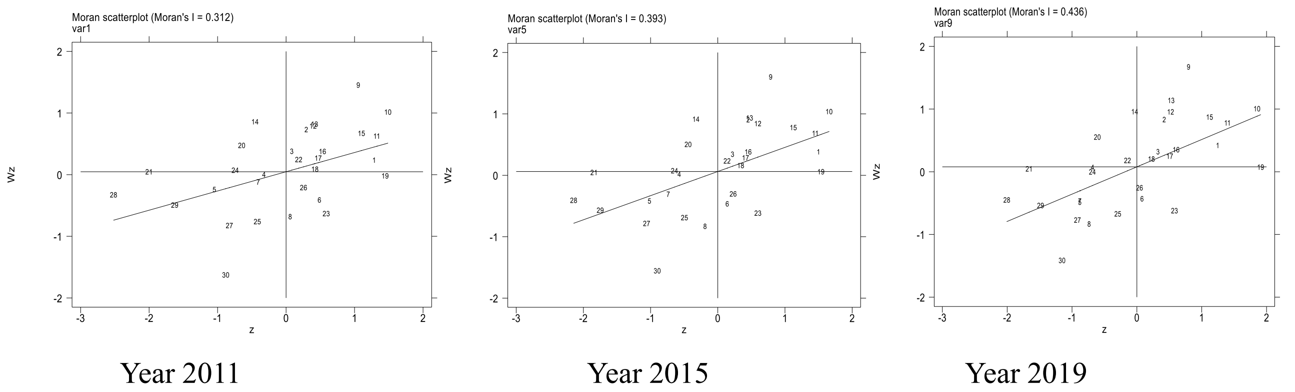

FIGURE 2 | Scatter plot of the Moran's I of China's green technology innovation in 2011, 2015, and 2019.

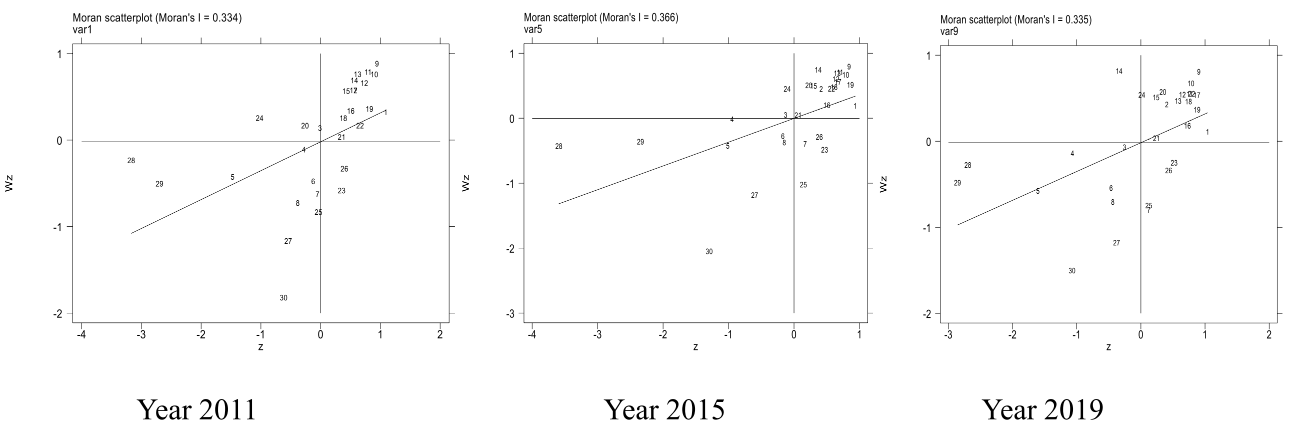

FIGURE 3 | Scatter plot of the Moran's I of China's environmental regulation in 2011, 2015, and 2019.

Next, this paper tests the local spatial correlation of GTI, environmental regulation and digital finance. According to the average values of the three in 2011–2019, Moran's index scatter plots were drawn, as shown in **Figures 2–4**. Due to space limitations, only the scatter plots for 2011, 2015, and 2019 are presented. One can intuitively see that most provinces in the scatter chart of the three indicators are distributed in the first and third quadrants, whether in 2011, 2015 or 2019. These findings show that the three factors have a significant spatial agglomeration effect, showing obvious characteristics of high agglomeration and low agglomeration. All the evidence shows that environmental regulation, digital finance and GTI have significant positive spatial correlations in the spatial scope, as well as having the characteristics of spatial agglomeration. Therefore, the spatial effect should be considered when constructing a model of the influence of environmental regulation and digital finance on GTI.

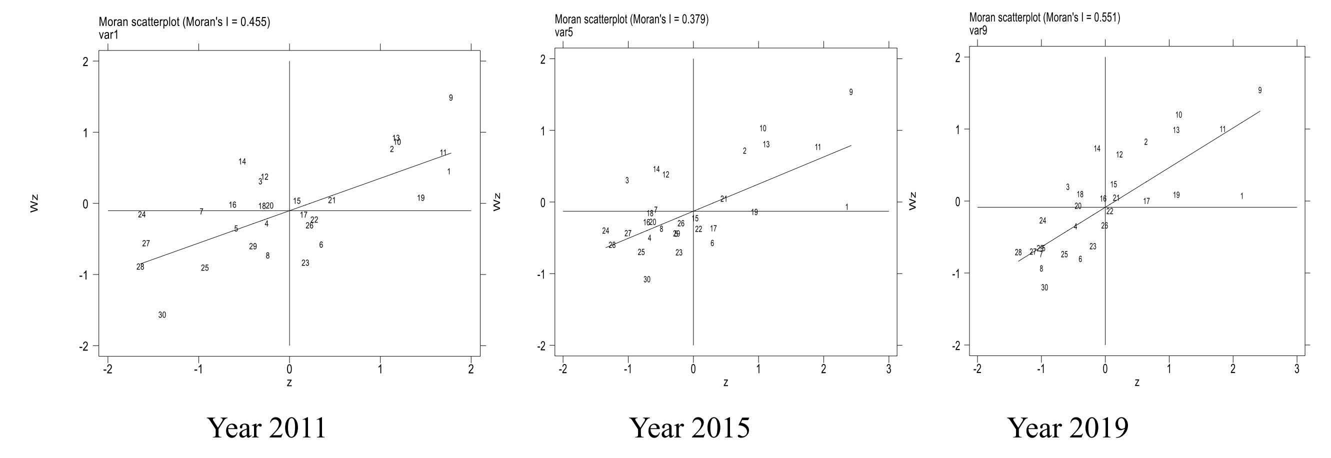

FIGURE 4 | Scatter plot of the Moran's I of China's digital finance in 2011, 2015, and 2019.

5.1.2 Estimation Results of the Spatial Durbin Model

Table 3 displays the GTI, GIP and GUP regression results. For comparative analysis, the regression results of fixed effect (FE) and the 0-1 weight matrix SDM model are both reported. From **Table 3**, the regression of principal variables suggests that both environmental regulation (er) and digital finance (dfi) promote GTI, but there are differences in terms of promoting GIP and GUP. As for control variables, the regression coefficients of economic development level (pergdp), financial development (finance) and R&D investment (rd) are all significantly positive and in accordance with economic significance. The higher a region's economic development level (pergdp), financial development level (finance) and R&D investment intensity (rd) are, the more effectively that region can promote their own GTI level. The impact of informatization (inform) on GTI is significantly negative. This finding suggests that the flow and diffusion of information technology may not be the driving force of GTI, and may not even produce an inhibitory effect on GTI. In addition, the coefficients of government expenditure (gov) and the degree of openness (open) in the SDM model do not pass the significance test. This finding means that government expenditure and the degree of external development are not the main driving forces behind promoting GTI.

5.1.3 Estimation Results for the Decomposition Effects

To further investigate the spatial influence of environmental regulation and digital finance on GTI, this study made a partial differential decomposition of the SDM model to analyze the impact's direct effects and indirect effects (spatial spillover effects). The GTI partial decomposition results show that the direct impact of environmental regulation on GTI is significantly positive (see **Table 4**). This finding suggests that the enhancement of environmental regulation intensity in one area will improve the local GTI capability. The conclusion is consistent with the "innovation compensation effect" of environmental regulation (Guellec and Van Pottelsberghe De La Potterie, 2003; Bréchet and Meunier, 2014). Digital finance also has a positive effect on GTI, which is consistent with the research results of Cao et al. (2021) and Feng et al. (2022). The main reason is that digital finance can provide financial guarantees for innovation activities. For the spatial spillover effect, the results imply that environmental regulation's spillover effect on GTI is significantly negative. One possible reason for this finding is that strict environmental regulation makes local governments more competitive compared to surrounding regions, which has a spatially inhibiting effect on GTI in neighboring regions (Wheeler, 2001). Digital finance's indirect effect on GTI is positive. This finding implies that the spatial interaction of digital finance will produce a positive spillover effect and promote GTI in adjacent regions.

From the spatial decomposition results of GIP, environmental regulation (er) and digital finance (dfi) have direct positive effects on local GIP. The spatial spillover effects of both er and dfi on GIP in neighboring regions are consistent with the effects on GTI.

The GUP spatial decomposition results indicate that environmental regulation can promote local GUP, while negatively inhibiting GUP in neighboring regions. Neither the direct effect nor the spillover effect of digital finance on GUP is significant. This is because digital finance has greatly improved the financing environment for enterprises. With a stable source of funds, enterprises are more likely to carry out GIP, which in turn can bring them core competitiveness. However, the research and development of GUP is less difficult; the cost is low, and the financing constraints are minimal (Tong et al., 2014). Therefore, the promotion effect of digital finance on GUP is not significant.

5.2 Heterogeneity Analysis

Considering China's vast territory, the strength of environmental regulation, the level of digital finance and the innovation ability all vary from region to region. This may cause the heterogeneity of GTI's response to environmental regulation and digital finance. Therefore, this study divided the 30 provinces into eastern, central, and western regions for further heterogeneity analysis. **Table 5** presents the regression results.

In terms of the GTI regression results, environmental regulation's direct effects on GTI were significantly positive

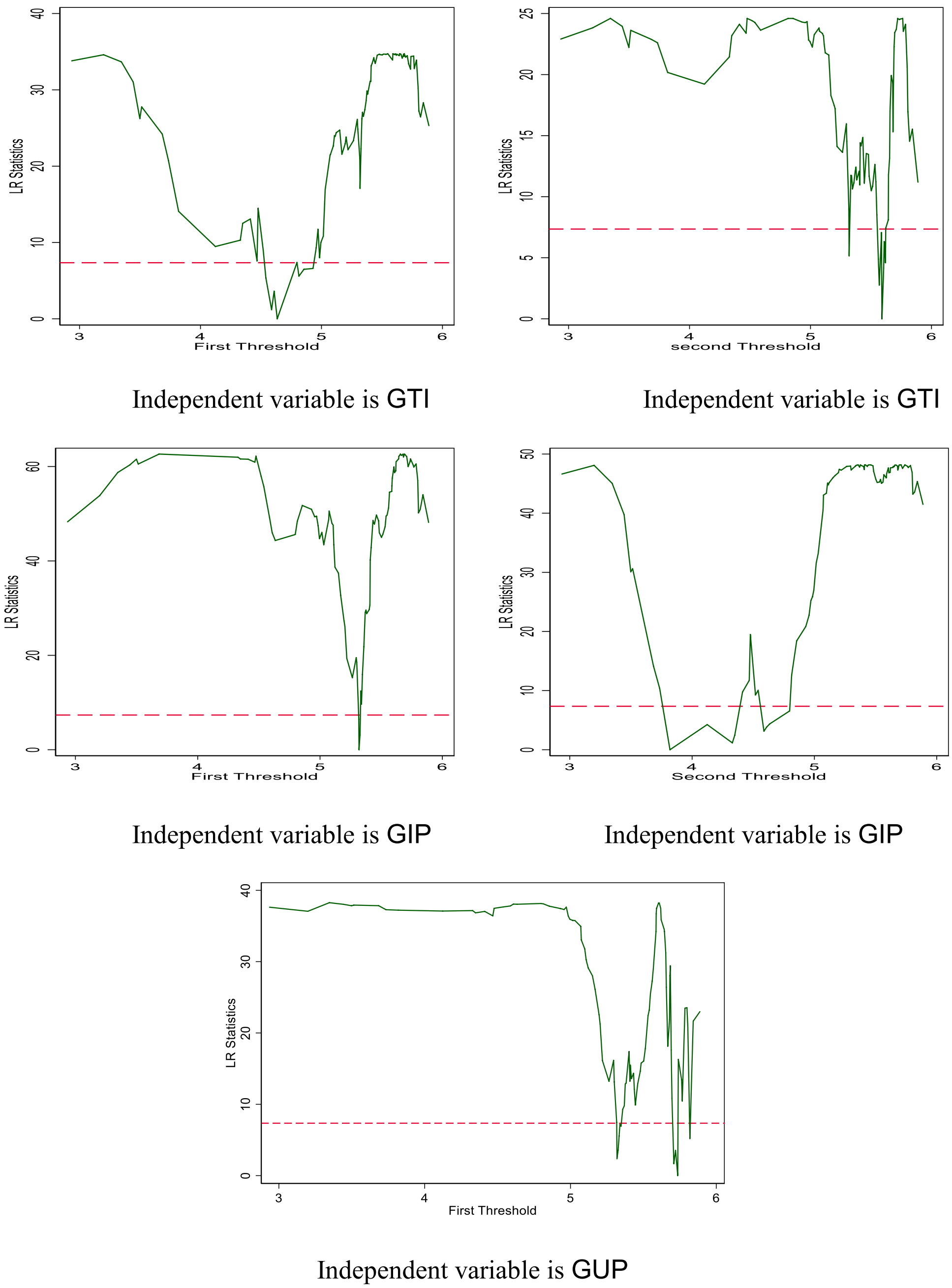

FIGURE 5 | Threshold values of different independent variables.

in all three regions during the study period. However, the spillover effects of environmental regulation on GTI varied in the three regions. Specifically, in the eastern region, this spillover effect was significantly positive. The economies of the eastern provinces and cities are relatively developed, and the tightening of environmental protection may produce a demonstration effect, thus prompting the GTI in neighboring areas. In the central region, this spillover effect is not significant, while in the western region, the effect is significantly negative. This negative effect occurs because most western provinces and cities are underdeveloped. Therefore, to achieve economic growth, local governments choose the "bottom-to-bottom" mode of competition and allow inefficient polluting industries to develop. This results in a spatial inhibition effect. As for the influence of digital finance on GTI, only in the western region has digital finance's direct effect on GTI not appeared. The reason may be that the development of digital finance in western provinces and cities is still immature, so digital finance's promotion effect on GTI is not obvious. The spillover effect of digital finance on GTI only

TABLE 3 | Estimation results of the basic model.

Variable	GTI		GIP		GUP	
	FE	SDM	FE	SDM	FE	SDM
er	4.265***	3.175***	3.256***	1.817***	5.036***	3.404***
	(0.650)	(0.477)	(0.640)	(0.494)	(0.828)	(0.504)
dfi	0.172***	0.238***	0.253***	0.319***	0.104	0.120
	(0.050)	(0.065)	(0.049)	(0.067)	(0.063)	(0.111)
pergdp	0.400***	0.193***	0.388***	0.219***	0.390***	0.176***
	(0.066)	(0.052)	(0.065)	(0.053)	(0.084)	(0.068)
gov	−0.200	−0.026	−0.293**	−0.084	−0.099	−0.025
	(0.128)	(0.089)	(0.126)	(0.092)	(0.163)	(0.091)
finance	0.302***	0.115**	0.164**	−0.004	0.451***	0.207***
	(0.066)	(0.049)	(0.065)	(0.051)	(0.084)	(0.057)
inform	−0.256***	−0.063**	−0.165***	−0.068**	−0.366***	−0.099***
	(0.032)	(0.027)	(0.031)	(0.027)	(0.041)	(0.028)
open	0.021	−0.014	0.026	0.007	0.010	−0.002
	(0.027)	(0.018)	(0.026)	(0.018)	(0.034)	(0.019)
rd	0.219*	0.240***	0.452***	0.224***	−0.016	0.187**
	(0.122)	(0.078)	(0.120)	(0.081)	(0.156)	(0.081)
cons	4.176***		3.260***		3.738***	
	(0.398)		(0.392)		(0.507)	
W*er		−2.877***		−2.277**		−1.354
		(0.958)		(0.981)		(1.105)
W*dfi		0.126		0.209***		0.329***
		(0.071)		(0.074)		(0.121)
rho		0.219***		0.375***		−0.201*
		(0.077)		(0.071)		(0.119)
sigma2_e		0.023***		0.024***		0.022***
		(0.002)		(0.002)		(0.002)
N	270	270		270		270
R^2	0.804	0.462	0.824	0.394	0.700	0.288

*Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Figures in () are the* t*-values of the coefficients. The following tables are the same.*

TABLE 4 | Estimation results of decomposition effects.

Variable	GTI			GIP			GUP		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
er	3.021***	−2.591**	0.431	1.622***	−2.340*	−0.718	3.446***	−1.703*	1.743*
	(0.473)	(1.113)	(1.262)	(0.505)	(1.421)	(1.637)	(0.496)	(0.934)	(1.023)
dfi	0.236***	0.085*	0.321***	0.313***	0.125*	0.438***	0.107	0.253	0.360**
	(0.064)	(0.068)	(0.047)	(0.065)	(0.075)	(0.060)	(0.114)	(0.209)	(0.159)
pergdp	0.226***	0.570***	0.796***	0.255***	0.430***	0.685***	0.164***	0.495***	0.659***
	(0.050)	(0.106)	(0.125)	(0.053)	(0.136)	(0.162)	(0.062)	(0.100)	(0.127)
gov	−0.015	0.246	0.231	−0.088	−0.039	−0.128	−0.030	0.105	0.075
	(0.087)	(0.192)	(0.210)	(0.091)	(0.246)	(0.276)	(0.090)	(0.166)	(0.163)
finance	0.129***	0.242***	0.370***	0.039	0.577***	0.616***	0.204***	0.196*	0.400***
	(0.047)	(0.093)	(0.111)	(0.050)	(0.121)	(0.145)	(0.056)	(0.106)	(0.132)
inform	−0.063**	−0.019	−0.082**	−0.076***	−0.121***	−0.198***	−0.097***	−0.026	−0.123***
	(0.025)	(0.034)	(0.035)	(0.026)	(0.042)	(0.046)	(0.028)	(0.042)	(0.042)
open	−0.018	−0.080*	−0.098*	0.012	0.067	0.079	0.000	−0.058*	−0.058
	(0.019)	(0.045)	(0.055)	(0.021)	(0.061)	(0.074)	(0.019)	(0.031)	(0.038)
rd	0.232***	−0.074	0.158	0.208***	−0.155	0.053	0.186**	−0.038	0.148
	(0.074)	(0.182)	(0.210)	(0.079)	(0.234)	(0.273)	(0.076)	(0.138)	(0.147)
N	270	270	270	270	270	270	270	270	270
R^2	0.462	0.462	0.462	0.394	0.394	0.394	0.288	0.288	0.288

passed the significance test in the eastern region. This occurred because the eastern region has a relatively complete financial infrastructure and a high degree of digitalization, so the spatial spillover effect is more obvious.

In terms of the GIP regression results, environmental regulation's direct effects on GIP are significantly positive in all three regions, while the spillover effects are regional heterogeneous. Specifically, only in the eastern region did

TABLE 5 | The estimation results for regional heterogeneity.

Variable	Eastern region			Central region			Western region		
	GTI	GIP	GUP	GTI	GIP	GUP	GTI	GIP	GUP
Direct-er	3.470*	5.904***	3.063*	2.112*	2.018*	1.868	3.425***	1.683*	3.706**
	(1.854)	(1.822)	(2.228)	(1.108)	(1.473)	(1.260)	(0.741)	(1.016)	(0.762)
Direct-dfi	0.201***	0.316***	0.190**	0.087*	0.154**	0.081	0.171	0.052	0.012
	(0.076)	(0.073)	(0.092)	(0.050)	(0.063)	(0.057)	(0.154)	(0.174)	(0.168)
Indirect-er	2.079*	2.533**	1.644	−0.791	−0.826	−0.592	−4.657**	−1.548	−5.083**
	(1.257)	(1.039)	(1.341)	(0.584)	(0.745)	(0.540)	(2.244)	(3.545)	(2.042)
Indirect-dfi	0.117**	0.135***	0.098*	0.029	0.058*	0.022	0.088	0.227	0.215
	(0.049)	(0.047)	(0.052)	(0.020)	(0.031)	(0.019)	(0.176)	(0.223)	(0.384)
Total-er	5.549*	8.438***	4.707	1.321*	1.192	1.276	−1.232	0.135	−1.377
	(3.039)	(2.684)	(3.501)	(1.615)	(2.153)	(1.725)	(2.809)	(4.407)	(2.585)
Total-dfi	0.318***	0.451***	0.288**	0.116*	0.212**	0.103	0.259	0.279	0.227
	(0.120)	(0.109)	(0.139)	(0.066)	(0.087)	(0.072)	(0.232)	(0.194)	(0.225)
N	99	99	99	72	72	72	99	99	99
R^2	0.494	0.421	0.396	0.228	0.216	0.173	0.452	0.315	0.360

TABLE 6 | Estimation results of the robustness test.

Variable	Geographic matrix			Economic distance matrix		
	GTI	GIP	GUP	GTI	GIP	GUP
er	2.943***	3.814***	3.755***	3.114***	1.674***	3.633***
	(0.481)	(0.547)	(0.531)	(0.459)	(0.600)	(0.547)
breadth	0.160***	0.087*	0.002	0.073*	0.183***	0.068
	(0.044)	(0.050)	(0.114)	(0.041)	(0.054)	(0.049)
pergdp	0.038	−0.014	0.043	0.070	0.048	0.002
	(0.059)	(0.067)	(0.065)	(0.054)	(0.070)	(0.064)
gov	−0.020	0.030	0.076	0.047	−0.058	0.037
	(0.073)	(0.083)	(0.082)	(0.070)	(0.090)	(0.082)
finance	0.039	0.158***	0.161***	0.106**	−0.100	0.152***
	(0.050)	(0.057)	(0.056)	(0.048)	(0.063)	(0.057)
inform	−0.075***	−0.099***	−0.070***	−0.070***	−0.052**	−0.085***
	(0.020)	(0.023)	(0.022)	(0.019)	(0.025)	(0.023)
open	0.026	0.007	−0.003	−0.017	0.030	−0.004
	(0.019)	(0.021)	(0.021)	(0.018)	(0.023)	(0.021)
rd	0.276***	0.188*	0.189**	0.178**	0.323***	0.158
	(0.086)	(0.098)	(0.094)	(0.081)	(0.106)	(0.098)
rho	0.641***	0.701***	0.380***	0.376***	0.266**	0.652***
	(0.062)	(0.051)	(0.087)	(0.088)	(0.105)	(0.056)
sigma2_e	0.025***	0.032***	0.030***	0.022***	0.038***	0.031***
	(0.002)	(0.003)	(0.003)	(0.002)	(0.003)	(0.003)
W*breadth	0.163*	0.127**	0.038	0.014	0.088*	0.086
	(0.155)	(0.062)	(0.118)	(0.055)	(0.071)	(0.064)
W*er	−1.792*	−2.075*	−1.183	−2.274**	−3.289***	−1.576
	(1.058)	(1.193)	(1.193)	(1.042)	(1.215)	(1.322)
N	270	270	270	270	270	270
R^2	0.645	0.497	0.512	0.479	0.616	0.356

environmental regulation produce a spillover effect and improve GIP in neighboring regions. Digital finance's direct and spillover effects on GIP are generally consistent with its impact on GTI. However, in the central region, digital finance's spillover effect on GIP passed the significance test for the studied period, while this effect still had not appeared in the western region. The reason for this lies mainly in the low level of digital finance resources in western provinces and cities; digital finance's spillover effects may also be limited by geographical factors. Only when digital finance rises to a certain level can more of the small and medium-sized enterprises obtain its benefits, realize the coming together of enterprise goals and inclusive goals, and promote an improvement of the GIP level.

In terms of the GUP regression results, the direct effects of environmental regulation on GUP were significantly positive in the eastern and western regions, but the effects were not significant in the central region during the study period. Meanwhile, environmental regulation's spillover effects on GUP were completely different in these three regions. This is mainly the result of the differences in environmental regulation intensity in various regions, as well as the differences in the competition modes adopted by the government. The influence of digital finance on local

TABLE 7 | Spatial effect decomposition considering interaction terms.

Variable	GTI	GIP	GUP
Direct-er	3.218***	2.124***	3.416***
	(0.528)	(0.548)	(0.595)
Direct-dfi	0.239***	0.385***	0.211***
	(0.067)	(0.068)	(0.076)
Direct-er*dfi	0.187*	0.626***	−0.036
	(0.18)	(0.205)	(0.209)
Indirect-er	−2.869**		−0.110
	(1.221)	(1.510)	(1.328)
Indirect-dfi	−0.038	0.157	−0.068
	(0.088)	(0.102)	(0.097)
Indirect-er*dfi	0.265	2.819***	−0.136
	(0.578)	(0.767)	(0.625)
Tatal-er	0.350	2.014	0.088
	(1.298)	(1.652)	(1.399)
Total-dfi	0.201***	0.542***	0.143*
	(0.074)	(0.100)	(0.079)
Total-er*dfi	0.452	3.445***	−0.172
	(0.657)	(0.877)	(0.707)
N	270	270	270
R^2	0.459	0.480	0.407

and neighboring GUP also varies across regions. In underdeveloped areas, such as central and western regions, the degree of digitalization is low, and the financial market is underdeveloped. As such, the influence of digital finance on GUP has not yet appeared.

5.3 The Robustness Test

To enhance the reliability of the conclusions, the following robustness tests were conducted. First, to avoid the bias of regression results caused by the choice of spatial weights, the geographic distance matrix and economic distance matrix were utilized to regress. Second, we sought alternative indicators of the main explanatory variable (digital finance) for a robustness analysis. Based on Guo et al. (2020), digital financial index includes breadth of coverage, depth of usage and level of digitalization. Among them, the breadth of coverage index accounts for the highest proportion of the digital financial index, at 54%. Therefore, as an important part of the digital finance index, this study chooses the breadth index as a proxy variable to regress the SDM model. **Table 6** reports the robustness test, which shows that the results after regression are roughly the same as the previous results. All these tests indicate that the conclusions of this paper are still valid after changing the weight matrix and the measurement methods of core variables.

6 THE MODERATING EFFECT AND THRESHOLD EFFECT OF DIGITAL FINANCE

The above research confirms that environmental regulation and digital finance have direct effects on local GTI, as well as spatial spillover effects on the GTI in adjacent regions. This section will empirically analyze the moderating role and threshold role of digital finance in environmental regulation's effect on GTI from the perspectives of coordination and interaction.

6.1 Empirical Verification of Moderating Effect

To verify the moderating role of digital finance, the interaction term er*dfi between environmental regulation and digital finance is introduced into the benchmark model. The decomposition results of spatial effects after adding interactive terms are displayed in **Table 7**. As can be seen from the results of GTI, the coefficient of interaction term Direct-er*dfi is significantly positive. This finding suggests that digital finance has played an active role in environmental regulation's effect on local GTI. Digital finance can provide inclusive financial support to enterprises faced with tightening environmental regulations, allowing enterprises to have stable and sufficient funds for green production innovation, ultimately stimulating GTI. In addition, the results show that the indirect effect of er*dfi failed the significance test. The GIP results reveal that the coefficients of interaction terms Direct-er*dfi and Indirect-er*dfi are both significantly positive. This finding suggests that digital finance can act an important moderating function in environmental regulation's influence on GIP. In addition to significantly alleviating the local financial constraints caused by environmental regulations and promoting the GIP level in the relevant region, the financial support provided by digital finance will also

TABLE 8 | Test results of threshold effect.

Independent variable	Threshold variable	Model	F-test	*p*-value	BS	1%	5%	10%
GTI	Digital finance	Single threshold	23.93	0.000	300	21.435	18.560	16.499
		Double threshold	25.48	0.003	300	23.862	15.960	14.019
		Triple threshold	20.34	0.660	300	65.711	57.871	47.746
GIP	Digital finance	Single threshold	46.52	0.053	300	55.306	46.871	38.338
		Double threshold	49.90	0.000	300	22.161	13.698	12.267
		Triple threshold	18.66	0.170	300	32.533	27.029	23.182
GUP	Digital finance	Single threshold	39.48	0.030	300	43.808	35.876	32.564
		Double threshold	27.43	0.167	300	38.399	32.147	29.471

TABLE 9 | Value of threshold estimation and its confidence interval.

Independent variable	Threshold variable	Model	Threshold value	95% confidence interval
GTI	Digital finance	Double threshold	4.634	[4.564, 4.806]
			5.590	[5.568, 5.604]
GIP	Digital finance	Double threshold	5.319	[5.309, 5.327]
			3.819	[3.735, 4.123]
GUP	Digital finance	Single threshold	5.736	[5.708, 5.779]

TABLE 10 | Threshold regression results.

Variables	Model (1)	Model (2)	Model (3)
	Independent variable = GTI	Independent variable = GIP	Independent variable = GUP
er_0 (dfi ≤ 4.634)	4.629***		
	(0.487)		
er_1 (4.634 < dfi ≤ 5.590)	5.043***		
	(0.483)		
er_2 (dfi > 5.590)	5.361***		
	(0.482)		
er_0 (dfi ≤ 3.819)		2.164***	
		(0.488)	
er_1 (3.819 < dfi ≤ 5.319)		2.790***	
		(0.498)	
er_2 (dfi > 5.319)		3.303***	
		(0.509)	
er_0 (dfi ≤ 5.736)			4.663***
			(0.641)
er_1 (dfi > 5.736)			3.853***
			(0.705)
pergdp	0.260***	0.371***	0.718***
	(0.060)	(0.053)	(0.090)
gov	0.047	−0.191*	0.092
	(0.078)	(0.100)	(0.139)
finance	0.258***	0.134*	0.520***
	(0.077)	(0.073)	(0.084)
inform	−0.073	−0.130***	−0.334***
	(0.048)	(0.016)	(0.073)
open	−0.032	0.003	−0.012
	(0.044)	(0.018)	(0.031)
rd	0.297**	0.228*	−0.029
	(0.135)	(0.119)	(0.162)
Constant	3.955***	3.690***	4.568***
	(0.303)	(0.242)	(0.448)
N	270	270	270
R^2	0.905	0.879	0.742

promote the GIP in neighboring regions. However, the GUP results reveal that the coefficients of interaction terms Direct-er*dfi and Indirect-er*dfi are not significant. This finding implies that digital finance has not acted as a moderating function in environmental regulation's influence on GUP. Previous empirical analyses have suggested that GUP has not been affected by digital finance, so the moderating effect of digital finance is not obvious.

6.2 Estimation Results of Threshold Effect

Considering that the level of digital finance may influence the correlation between environmental regulation and GTI and lead to a nonlinear relationship between them, this study further investigates the effect of environmental regulation on GTI at different levels of digital finance. This is achieved by building a threshold effect model. Referring to Hansen's threshold effect model design (1999), digital finance is taken as a threshold variable for further research and analysis.

By using the self-sampling method (bootstrap) iteration 300 times, we tested the existence of the threshold effect of digital finance, and further estimated the specific threshold number. The results in **Table 8** suggest that, when the explained variable is GTI, the influence of environmental regulation on GTI has double thresholds. When the explained variable is GIP, once

again, there are double thresholds. When the explained variable is GUP, there is only a single threshold.

Table 9 presents the threshold estimation results. The double thresholds of the GTI model are 4.634 and 5.590; for the GIP model, they are 5.319 and 3.819, and the threshold of the GUP model is 5.736. The confidence intervals of the above threshold values are all narrow, indicating that the estimated threshold values are accurate. Further, this paper has drawn a likelihood ratio function diagram, to check whether the estimated values are consistent with the actual values of the threshold. The results are shown in **Figure 5**. One can observe that the LR values corresponding to the threshold values estimated by the model are obviously smaller than the critical value of 7.35. This finding proves that the above estimated threshold values are true and effective.

Table 10 displays the regression results of the panel threshold model. The GTI results show that, when the digital financial index is below 4.634 (i.e., with a coefficient of 4.629), environmental regulation can significantly promote GTI. When the digital financial index is between 4.634 and 5.590 (i.e., with a coefficient of 5.043), the promotion effect of environmental regulation intensity on GTI becomes greater. When the level of digital finance is above 5.590 (i.e., with a coefficient of 5.361), the influence effect is further enhanced. The above results mean that, when digital finance is in different stages of development, environmental regulation's impact on GTI is not invariable. Rather, the impact presents a nonlinear characteristic of positive and increasing marginal effect.

The GIP regression results show that, when the digital financial index exceeds the threshold values of 3.819 and 5.319, the estimated coefficients of environmental regulation's effect on GIP rises from 2.164 to 2.790 and 3.303, respectively. This finding indicates that a rise of the digital financial level can also cause the promotion effect of environmental regulation on GIP to increase marginally.

The GUP regression results reveal that, if the digital financial index is below the threshold value of 5.736 (i.e., with a coefficient of 4.663) digital finance can significantly promote GUP. When the digital financial index crosses the threshold value, the estimated parameter is still significantly positive, but the coefficient drops to 3.853. That is to say, environmental regulation can effectively elevate the GUP level, but under the threshold effect of digital finance, the marginal effect is decreasing.

7 CONCLUSION AND POLICY RECOMMENDATIONS

Under the macro background of tightening environmental regulations, digital finance, with its digital and inclusive characteristics, plays a particularly important role in green technology innovation (GTI). Using provincial panel data from China, covering the period from 2011 to 2019, this study discusses the direct effects and spatial spillover effects of environmental regulation and digital finance on GTI, by building a spatial Durbin model. In addition, the moderating effect and threshold effect of digital finance in environmental regulation's influence on GTI is deeply analyzed. The following conclusions are obtained:

(1) Environmental regulation has significant positive effects on local GTI, GIP and GUP, while having negative spatial spillover effects on the three in neighboring regions. Furthermore, environmental regulation's influence on the three is obviously different from region to region.
(2) Digital finance can significantly promote GTI and GUP. Specifically, the improvement of the digital financial level not only promotes local GTI and GIP in the relevant region, but also produces positive spillover effects on adjacent regions' GTI and GIP. Moreover, in the eastern and central regions, the direct effect of digital finance on both GTI and GIP is significantly positive, while in the western region, this effect is not obvious. The spatial spillover effect in the three regions is also heterogeneous. Furthermore, the effect of digital finance on GUP in both local and neighboring areas is not significant. A regional analysis suggests that the influence of digital finance on GUP obviously varies between regions.
(3) Digital finance is an important moderating variable of environmental regulation's effect on GTI. Environmental regulation's effect on GTI and GIP in local and neighboring areas will also become stronger with the continuous improvement of digital finance. However, digital finance has not played a moderating role in the impact of environmental regulation on GUP.
(4) Digital finance is the threshold variable of environmental regulation's effect on GTI. If the digital finance index exceeds a certain threshold, the promotion impact of environmental regulation on GTI and GIP will be greater. However, if the digital finance index crosses the threshold value, the role of environmental regulation in promoting GUP will weaken.

According to the above conclusions, the following policy recommendations are made:

First, environmental regulation can effectively promote GTI. For that reason, government departments should unswervingly adhere to and improve environmental protection laws and policies. At present, given the country's severe environmental problems, enhanced environmental regulation must be part of China's sustainable economic development. In the short term, enterprises' production costs will rise to meet the prescribed environmental standards, and this will crowd out R&D investment and restrain GTI. However, with the optimization and adjustment of enterprises' production processes, environmental regulation will help restrain the pollution behavior of enterprises by forcing enterprises to take the development road of a low-carbon life, and thereby promoting enterprises' technological innovation.

Secondly, government departments and related financial institutions should focus on promoting the level of digital finance by insisting that digital finance plays an active role in funding GTI under the background of tightening environmental regulations. Specifically, this can be done

from two aspects. First, the government should make full use of scientific and technological means to build a financial service platform. They should encourage the financial industry to transform into an industry characterized by digitalization and informatization, and they should enhance the mutual integration of the digital economy industry and financial industry. In addition, the government should expand the coverage of digital finance in central and western provinces and cities. The digital service level should be improved, and the application depth of digital financial innovations should be enhanced. Secondly, the government should actively guide and encourage digital finance to give targeted financial support to the research and application of green, low-pollution, low energy consumption and recyclable new technologies and products. This would promote the GTI of enterprises and achieve high-quality economic development.

Thirdly, economic activities have significant spatial spillover effects, so all regions should strengthen regional cooperation to jointly promote green development. The spillover effects of GTI show that, in addition to the impact on local GTI, environmental regulation and digital finance in one province will also have a significant impact on GTI in neighboring provinces. To promote high-quality economic development of the whole society, it is suggested that the government should strengthen the coordination and cooperation between neighboring regions when formulating relevant policies. The central and regional governments should jointly explore and improve the regional cooperation mechanism and coordination mechanism of environmental regulation and digital finance. Specifically, the government should carry out cross-regional cooperation in environmental law enforcement and the implementation of financial instruments. A cautious view should be taken with regard to the phenomenon of "bottom-to-bottom competition" among different areas, as well as the unbalanced level of digital finance. Addressing these issues would help build a harmonious environment and financial and economic ecosystem in various regions, and would jointly promote green innovation.

This paper makes a preliminary exploration of the influence of environmental regulation and digital finance on GTI, but there are still limitations, which can be further expanded in the following aspects in the future. Firstly, although this paper discusses the direct effect and spatial spillover effect of environmental regulation and digital finance on GTI, there is no in-depth discussion on their specific influence mechanisms on GTI. Therefore, the discussion of these influence mechanisms will be of great significance for future research. Secondly, the data used in this paper are macro data at the provincial level. Because the economic development level, environmental regulation level, digital financial development status and innovation level of different cities in the same province are obviously heterogeneous, the future research can use city level data to do further detailed research.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://data.stats.gov.cn/.

AUTHOR CONTRIBUTIONS

RM: Conceptualization, Methodology, Funding acquisition, Supervision. FL: Software, Visualization, Writing -original draft, Conceptualization. MD: Formal analysis, Writing -review and editing, Visualization.

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Environmental Regulations and Energy Efficiency: The Mediating Role of Climate Change and Technological Innovation

Peng Wang and Shuai Liang**

Guizhou University of Finance and Economics, Guiyang, China

Low-carbon energy transformation increases energy efficiency, and environmental regulation is necessary for carbon neutrality. Energy efficiency is widely accepted As a cost-effective method of reducing air pollution and improving the economic performance of manufacturing industries. In order to make their manufacturing sectors more energy-efficient, a large number of countries have implemented legislation. It is possible to tailor these interventions to a specific company or industry by using measures to control and direct interventions in the marketplace. These policies might be beneficial, but the experiential study of the impacts of these interferences on energy-saving technology acceptance has not been conclusive. Many environmental policy measures have an effect on the level of the asset in energy efficiency machinery. The years 2010–2019 are covered in this research, which compiles a database of Chinese industries from various sources. As a result, we have access to a wide range of factors and strategy devices that could influence the adoption of energy efficiency measures. Regulation, taxes, subsidies, and exemptions are among the instruments we will examine. These findings support the development of environmental regulations in China that will further improve energy efficiency and carbon neutrality.

Keywords: environment regulations, green technology innovation, sustainable development, tobit regression model, network DEA model

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Muhammad Irfan,
Beijing Institute of Technology, China

Reviewed by:
Arooj Fatima,
Yanshan University, China
Wasim Iqbal,
Shenzhen University, China

****Correspondence:***
Peng Wang
565856776@qq.com
Shuai Liang
354001346@qq.com

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1 INTRODUCTION

Since its inception as a hidden fuel, energy efficiency has been elevated to the first fuel in a maintainable worldwide energy system, says the International Energy Agency (Chandio et al., 2021; Hao et al., 2021; Tanveer et al., 2021). Energy efficacy is at the topmost of both international and national policy and science schedules because it provides significant and growing benefits to all sectors of the economy (Irfan et al., 2019, 2020; Madurai Elavarasan et al., 2021). There are numerous economic and social advantages to strategies meant to increase energy efficacy and the more conventional approaches to decrease utilization, save money, and reduce airborne pollution (Elavarasan et al., 2021; Irfan and Ahmad 2021; Irfan et al., 2021). In energy supply, a reduction in imported energy dependence can significantly influence energy security (Rehman et al., 2020; Işık et al., 2021; Yang et al., 2021). Additionally, the rise in international energy raw material prices, exacerbated by the decrease in energy consumption, contributes to lower inflationary tensions (Dagar et al., 2021; Jinru et al., 2021; Fang et al., 2022). In order to summarize: Increased efficiency and reliability in the sector can positively impact the macroeconomic environment, from increasing

economic activity to creating more jobs to improving the health and well-being of employees, all of which directly influence the economy (Li L. et al., 2021).

The Chinese management has set aspiring goals for energy competence reduction for 2020 and 2030. (at least 20.0% and 32.50% developments in energy efficacy likened to a baseline, correspondingly) (Quan et al., 2021; Yu et al., 2022). As the industrial sector accounts for 25% of final energy preservation and 15% of worldwide air secretions, meeting these targets will require contributions from all energy-consuming sectors (Shao et al., 2021), even though businesses might be enticed to finance energy-competent technologies because of government incentives. Research has shown a space amid the publicly ideal level of an asset in power-saving skills and the quantities invested in reducing costs and becoming more environmentally friendly (Dorsey-Palmateer and Niu 2020). The gap in energy efficiency is known as the efficacy gap. Based on their evaluation of the experiential fiction on the drivers of energy efficacy in industrial organizations (Wang and Luo 2022), conclude that the most crucial reason for organizations to finance energy efficacy is still unclear. According to the authors, researchers are unable to agree on the primary drivers of energy efficiency because of their multidisciplinary approach (Pan and Chen 2021).

Additionally, environmental regulations (ERs) also offer external inducements for the industry to modify its manufacturing procedures in accordance with some restrictions imposed on firms by governments. Scientists have found some advantages to environmental regulations, but theyhave also found some drawbacks. Ai et al. (2021) found that while environmental regulations effectively encourage green technology innovation in trade, such a revolution will move to arise in the prices associated with new product development and, thus, a reduction in the inclination of the industry to innovate. According to (Liu L. et al., 2021), strict environmental regulations directly influence the willingness of international stockholders to enter the local market place in the first place because they raise the environmental prices of innovation. There is a consensus that the government should implement appropriate environmental regulations (ERs) to increase the efficacy of green technology innovation in the industry, but this is not universally agreed upon (Qudrat-Ullah and Nevo 2021).

Green innovation efficacy (GIE) is a metric used to assess how effectively the industry utilizes resources when developing green technologies. Resources invested vs. benefits received are commonly referred to as a return on investment. In order for the industry to better assign funds, gain more profits with a small number of assets, and lower the costs of innovation while maintaining or improving productivity, innovation efficiency must be improved (Xing et al., 2021). Since ERs and GIE have been linked in previous studies e.g., (Andrei et al., 2021), it is clear that more research is needed to grasp how ERs and GIE are interrelated fully. The real-world effects of various ER types and the variety of ER characteristics make it difficult to generalize about ERs.

Since the modification and inaugural strategy, China's budget has increased and reached significant fall outs. On the other hand, this rapid expansion was fueled by pollution and energy consumption that were out of control. China will accelerate the construction of a resource-saving and environmentally friendly society, according to the Central Committee's Fifth Plenary Session of the 18th CPC, which met in Beijing. In affirmation of previous decisions, this proposal was a part of implementing a strategy for sustainable development and promoting synchronization between humans and nature (Li et al., 2018; Hu et al., 2022). In order to build a society that is both resource-efficient and environmentally friendly, solid environmental regulation is essential. While improving the environment, energy consumption can be controlled using analytical and active regulatory tools (Andersson et al., 2020). However, it remains to be seen whether China's energy efficiency will improve due to stricter environmental regulations or as a result of technological advancements. It is essential to understand the relationship between technological innovation and environmental regulation and energy to formulate effective environmental regulation policies. Previous studies have examined environmental regulation, technological innovation, and energy competence separately. Understanding the interrelation between environmental regulation, technological innovation, and energy efficacy has proven difficult due to the scarcity of studies. For this reason, to attain our energy-saving goals through the advancement of technological innovation and energy efficacy, we will investigate the association between environmental regulation, innovation, and effectiveness and their intersection.

A significant contribution is made in two ways. Incentives available in the marketplace environmental regulation and command and control over the environment are subcategories. Once we've built a connection amid environmental regulation based on command and market incentives, along with technological advancements and energy efficiency within the same framework, we used direct acyclic graph (DAG) methods to extract three conduct pathways for each of the four variables. Another approach is to utilize a Tobit regression model to track the long-term trends in the command control has a significant impact on the environment regulations, technological innovation, market incentives for environmental regulation, and energy efficacy are four regulated variables.

The remaining article is arranged as follows: For the construction industry and emergency response systems, **Section 2** examines the literature on GIE and its impact on these industries. Before moving on to **Section 4**, **Section 3** provides an overview of datasets, indicators/variables, and the data analysis process. Outcomes of the GIE study and regression are written in **Section 5** in great detail. **Section 6** explains the implications of these findings. Conclusions and upcoming study directions are debated in **Section 7** of the paper.

2 LITERATURE REVIEW

As far as assessing energy efficiency, single-factor and total-factor methods are the most commonly used. Single-factor energy efficacy has two subcategories: intensity and productivity (see **Figure 1**). The ratio of energy input to GDP multiplied by the

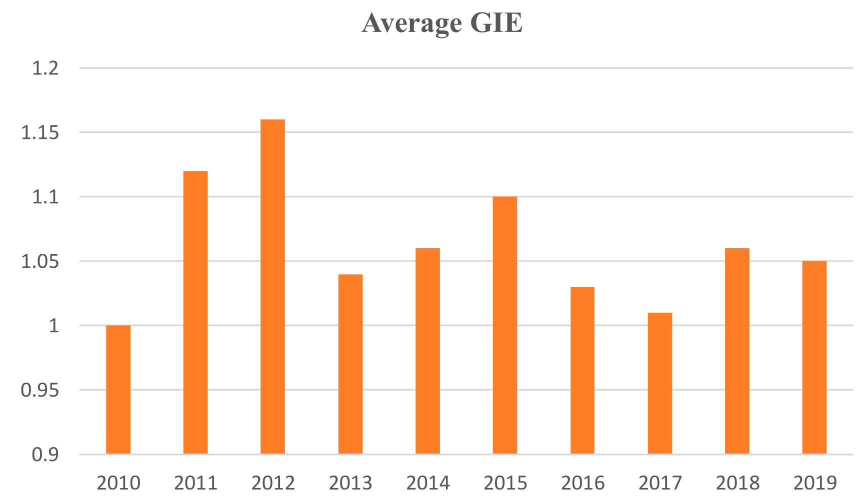

FIGURE 1 | Average green innovation efficiency.

term energy intensity is known as energy productivity (Desvallées 2022). Because of its simplicity, this approach has been used by a large number of scientists in their investigations into energy efficacy and the factors that affect it. By applying this method, the energy intensity trends in the number of major OECD countries since 1973 were estimated by Zheng et al. (2021). For their study, they focused on implementing energy efficacy strategies in the United States, Japan, and Western Europe. The findings are parallel to (M. Wang and Feng 2020), who used panel data spanning 2000 to 2009 to examine how different economic structures, consumption patterns, and technological advancements impacted energy intensity in other parts of Eastern Asia. The impact of government spending on energy intensity was examined by (D. Q. Zhou et al., 2016) using regional panel information. According to the researchers, in spite of regional economic discrepancies, the effect remained significant. Conclusions drawn from these findings include the significance of analyzing single-factor efficiencies for economic growth and the extent to which it is energy-dependent (Martelli et al., 2020). Aside from energy, other important factors such as labor and capital are overlooked when this method is examined from the perspective of the entire production process. Since it doesn't give a complete picture of energy efficiency, structural changes may result in lower energy intensity, but the energy efficiency may not change. A region's or an industry's increase in energy efficiency cannot be estimated using this method because it is also affected by the energy value (Khalfaoui et al., 2019, 2021; Sarwar 2019; Sarwar and Alsaggaf 2020; Waheed et al., 2020).

Using (Mehta et al., 2019) energy efficiency concept, which incorporates facets aside from energy consumption like labor and investment into the single-factor efficacy, the concept of total-factor energy efficacy is proposed. This idea came about due to the problems with traditional single-factor energy efficacy. The entire feature energy efficacy of member countries of the Asia-Pacific Economic Cooperation (APEC) countries amid 1991 and 2000 (Su and Urban 2021) found that meeting the energy-saving target without decreasing GDP could be discussed. To find out why China's energy efficacy is so low, (Jebali et al., 2017), calculated the efficacy of energy from China's petroleum, char, and sources of clean, renewable power from 1998 to 2010. Due to a low GIE, they concluded that this was the main problem. According to this table, using total-factor energy efficacy improved the exactness of energy efficacy assessments, but the studies above only measured earnings, such as GDP, when determining efficiency levels. As more people become concerned about climate change and environmental issues like carbon dioxide emissions, scientists are beginning to consider the negative consequences. A growing number of academics believe that when evaluating output factors, it is necessary to consider both predictable earnings and unpredicted outputs (toxins like carbon dioxide and sulfur dioxide). As part of their investigation into China's energy efficiency, (Ren et al., 2020), measured and then planned the total factor energy of 29 Chinese shires between 1997 and 2011. According to (Wu et al., 2021), this study examined the ability to utilize all of a system's energy sources and latent of China's provincially based industries from 2000 to 2014, focusing on technological differences and management practices, and scale. Using data from 2008 to 2012, Adua (2021) discovered that the vast majority of Chinese cities are inefficient energy consumers. Almost all academics agree that carbon dioxide emissions are primarily responsible for the adverse effects of human activity. As a result of the manufacturing process, pollutants such as Sulphur dioxide and nitrogen dioxide will be out. Despite the widespread belief that these gases are the primary contributors to warming the planet, acid rain, and diminishing the ozone layer, only a few researchers (Li et al., 2021b) have found their harmful emissions.

In order to examine the relative efficacy of multiple inputs and outputs, the DEA is the most widely used method for calculating total-factor energy efficacy. Total-factor energy efficacy is most commonly calculated using the DEA method. Because the traditional DEA model results differ depending on whether the starting point is a constant or variable scale earnings model. It cannot be used to compare multiple effective units at once. Instead, it employs the CCR and BCC models, both of

which have varying scale earnings. In order to improve the model, researchers constantly tweak it. Sedlmeir et al. (2020) devised a super-efficiency DEA model to overcome the drawbacks of traditional DEA models, allowing them to determine the efficiency difference between efficient units as well as the effective order in which decision-making units should be placed. Calculate environmental efficiency in 31 Chinese provinces between 2000 and 2010. Fan et al. used this model to analyze the energy competence of carbon dioxide utilization skills in China (Sun et al., 2020).

Scholars assessing China's energy competence in specific industries or at the microscopic area level have paid little attention to the country's energy efficiency. (Gondal et al., 2017) calculated the scale incomes and indemnities of energy efficacy in different regions of China between 2006 and 2010 and provided China's government with strategies and policies to implement. Researchers in 29 Chinese provinces used the three-dimensional panel econometric model between 1997 and 2011 to examine cluster and influence factors and total-factor energy competence. Between 2002 and 2010, city trade in Beijing, Chongqing, Shanghai, and Tianjin increased emission loads and geological sources, according to a study by (Kiara 2013). Environmental total-factor energy efficiency in China's industries that use a lot of energy from 2000 to 2013 was significantly lower in four sub-departments than the national average (Zhuo and Qamruzzaman 2022). Li et al. (2021c) used state-owned coal-fired power plants as a case study and calculated how much energy could be saved and how much CO2 could be avoided. Similar studies were carried out by (Huang et al., 2022; Liu et al., 2022; Wen et al., 2022). China's coal consumption was examined at the regional and industrial levels using the DEA-Malmquist index. Based on an industrial utilization perspective, the DEA-Malmquist model was used in this study. Furthermore, it explains why China's coal consumption efficiency has fluctuated over time from 2006 to 2015.

2.1 Green Technology Innovation Efficiency

Significant research is being done into improving GIE for use in industry (Luo Q. et al., 2019), nology innovation (Wang et al., 2021). In other words, the GIE is a measure of the industry's ability to utilize available innovation resources and resources. To see if an industry can get the most out of a given level of investment, it uses this formula (Abdul-Rahaman et al., 2021).

The GIE, on the other hand, needs to be improved in order to promote long-term industry growth (Hodson et al., 2018). The performance of the GIE has so far been assessed using a variety of schemes based on indicators developed by researchers. For example (Dias et al., 2022), examined the practical green technology innovation process and developed a system based on administration, process, technological, and product innovation indicators. Q. Wang et al. (2019) discussed China's green technology innovation environmental factors and projected a system that included non-expected productions (CO2, SO2, etc.).

In addition, prior studies intensive on the variables that affect the GIE score. To study GIE in the high-end industrial industry (Horbach et al., 2012; Saguy 2022), developed an SFA (Stochastic Frontier Analysis) model, which they then applied to GIE in the automotive industry. According to their findings, all of these variables had a substantial influence on GIE: government funding, company size; maturity of the market; and industrial agglomeration. Technology spillover in reverse effects on GIE is primarily determined by the institutional environment, as (Deng et al., 2021) noted in their study.

While previous research on GIE has failed to account for the staggered nature of GTI fully, it becomes clear when reviewing previous literature on the subject. GTI is typically thought of as a one-step process. This simplification may lead to inaccuracies in the estimation of efficiency. Technology innovation resources are transformed into technological R&D accomplishments through the multi-stage process known as the Global Technology Innovation Process (GTI). The company can then reap the benefits of these technological innovations and R&D accomplishments in the form of financial gains (Khan et al., 2021). It necessitates the division of green technology innovation into various phases in order to assess GIE fairly.

2.2 Green Innovation Efficiency and Environmental Regulation

Industrial growth and economic growth could be stifled by environmental pollution, a global problem (Isaksen and Trippl 2017). In order to encourage long-term fiscal growth, nationwide administrations have devised a number of strategy devices known as economic development instruments (ERs) (Xie et al., 2019).

The term environmental regulations (ERs) are used to describe a broad range of legislation to protect the environment. Green innovation in the United States is also being driven by environmental regulations, according to (Khalil et al., 2021). To address industrial pollution, environmental remediation (ER) is a highly effective method (K. Du et al., 2021). Environmental regulatory agencies (ERs) can use mandatory measures like environmental taxes to limit pollutant emissions. It is expected that businesses will voluntarily reduce their pollution emissions in order to avoid paying the extra tax imposed by the environmental contamination. Companies must pay a tax on the environment for polluting the environment.

In the industrial sector, ERs can also recover or avert GIE (Dias et al., 2022). On the one hand, manufacturing will typically bear the bulk of the costs associated with innovation; on the other side, it will not always reap the benefits of innovation (H. Khan et al., 2022). This marvel is referred to as the positive externality of innovation. Governments frequently make efforts to rouse manufacturing *via* subsidies and other resources in order to reduce the adverse effect of positive outwardness on GTI (Dong et al., 2022). As an alternative argument, the industry must continuously recover its GIE and make the most of the profits of innovation in order to decrease the high price of innovation (Anser et al., 2020).

Only a few studies have been done to confirm the consequence of ERs on GIE. An investigation into the United Kingdom by (Luo S. et al., 2019) found that ERs could only improve GIE in the industry under certain circumstances. There is no clear linear relationship between ERs and GIE, as (J. Wang 2011; Zhu et al.,

2021) stated. Although ERs initially inhibit GIE, the intensity of these ER increases after an inflection point, according to (Lemieux et al., 2021). As a whole, previous studies have not yielded a definitive answer, and there appear to be discrepancies between the findings of different studies.

There are numerous ways to distinguish ERs from other types of cells. There is no doubt that the industrial Environment is affected differently by different ERs (García-Pérez-de-Lema et al., 2021; Zheng et al., 2021). According to the government's mandates, three kinds of environmental regulations (ERs) fall into three categories: volunteer regulation, market-based environmental regulation, and command and control environmental regulations (Bayarçelik et al., 2014; Liu Y. et al., 2021). As a result, rather than combining the effects of different ER types, it is necessary to examine each one separately to assess the influence of ERs on GIE accurately.

3 METHODOLOGY AND DATA DESCRIPTION

3.1 Data Envelopment Analysis Technology to Measure Efficiency

Unlike traditional economic methods such as ratio analysis or regression, data envelopment analysis (DEA) is considered a more active tool for measuring efficiency in business operations. Efficiency has been defined by a number of academics in this particular context. In this research, we consider (Tang et al., 2019) definition of productivity, which was derived from the research (Curtis and Lee 2019) and is used to define the measure of efficacy comprised of several inputs. According to (Xu and Lin 2020), an organization's efficiency comprises two gears: technical efficacy and a locative efficacy (or allocation efficiency). Practical efficacy is defined as the ratio of the optimal input to the actual input in input-oriented efficiency measurement. It is defined as the % of the actual output to the optimal output in output-oriented efficiency measurement.

On the other hand, a locative efficiency demonstrates an organization's ability to utilize its inputs to the greatest extent possible in light of its prices and technological capabilities. The production Frontier or cost Frontier is used to determine the optimal output and input for Decision-Making Units (DMUs) based on the objectives of Decision-Making Units (DMU). In this regard, two approaches are recommended in the literature: a parametric approach and a non-parametric approach. The Frontier of the parametric approach is assigned an efficient method. In contrast, the Frontier of the non-parametric method is not assigned a functional method and instead is defined by the preceding specification. To develop the DEA model for measuring the efficiency of a single DMU for the first time, Lin and Xu (2020) used a non-parametric approach, which the authors of the paper followed. They devised an input-oriented DEA model that assumed a constant return to scale as a starting point. Following studies of the DEA model, on the other hand, take into account a variety of assumptions. The variable returns to scale (VRS) concept was projected by (Harrison et al., 2017), who used mathematical programming in his DEA model to generate a linear best practice Frontier based solely on experimental input-output data. This new approach of the DEA has gained a wider acceptance for measuring the efficiency of different DMUs across industries or countries than the previous approach (Zhang et al., 2020).

A relational and non-rational decrease in contribution was used in two applied DEA variants. In order to calculate hospital efficacy from both DEA variants, an input-oriented TE model with inconstant revenues to scale is quantified. A vector of inputs I = 1, 2, ... m inputs) is formed by n numbers of firms (j = 1, 2, n) using y j = y 1, y 2, . . . , y J as outputs. x_j = x_1,x_2, . . . ,x_J; This is the input bundle used by the jth hospital (where j is a number). There is a production relation between the set of inputs and outputs.

$$P(X) = \{(x, y) \in R; x\ can\ produce\ y\} \tag{1}$$

where P comprises all possible output and inputs package, the efficacy of jth DMU with the input-output pack $(x_o,\ y_o)$ can be assessed through the following model:

$$\theta^* = \min \theta \tag{2}$$

Subject to

$$\sum\nolimits_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{io} n = 1, 2, \ldots, N \tag{2a}$$

$$\sum\nolimits_{j=1}^{n} \lambda_j y_{ij} \ge \theta y_{io} m = 1, 2, \ldots, M \tag{2b}$$

$$\sum\nolimits_{j=1}^{n} = \lambda_j j = 1, 2, \ldots, J \tag{2c}$$

$\lambda_j \ge o$ and $j = 1, 2, \ldots, n$

The linear programming model described above is used to reduce all inputs proportionally to a given output level. The technical efficiency of a facility is measured by a proportionate reduction in all its inputs based on scaled-down inputs to get to a certain point (where represents the scalar magnitude). The efficacy notch of the hospital under assessment can be planned as the proportion of the negligible input with mention of the built border to the actual input in the hospital under evaluation after resolving the optimization problem. The minimal input requirement includes the proportionally reduced input and some types of denim related to input as a result of the only relative decrease (Ngo 2022). To indicate radial efficiency, the score is denoted by the symbol *. Efficiency equals TE (* = *) because there is no slack in the system with respect to the input. On the other hand, radial efficiency is limited in its ability to provide a comprehensive measure because it only considers the reduction in inputs proportional to the reduction in output.

Researchers are moving toward the submission of a DEA with a non-circular variation, which is founded on non-relational alteration, to increase greater precision and biased power. In order to circumvent the difficulties associated with the radical approach, the slack-based measure (SBM) of efficacy approximation has been projected by (Xiang et al., 2022) in order to achieve greater biased power and wanted scientific properties. Achieving the maximum amount of loss linked with the outputs and inputs used in the manufacturing process to account for the various features of non-proportional lessening is at the heart of this method. One way

to look at it is as a by-product of incompetence caused by equally the inputs and outputting factors combined. You can find the derivation of the SBM of competence, along with its measured properties, in (Ye and Wang 2019). The following is a description of the model, which is the SBM of technical efficiency.

$$\min \rho = \frac{1 - \left(\frac{1}{m}\right)\sum_{i=1}^{m} s - i/_{x_{io}}}{1 + \left(\frac{1}{s}\right)\sum_{r=1}^{s} s + r/_{y_{ro}}} \tag{3}$$

Here, the output vector Y and input matrix X have slacks associated with them. The Charnels-Cooper conversion, used in the (Guo and Yuan 2020) CCR model, can quickly transform the fractional form of the above SBM model into a simple linear programming optimization.

3.1.1 Input-Output Indexes

Energy use can be alienated into two broad classes: energy input and energy output. There are two subcategories within each of these categories: total and single-factor energy inputs. Each of these categories can be broken down into desirable and undesirable outcomes. The GIE, which includes coal input and output, is the primary focus of this investigation (Khoshnevisan et al., 2013). There are two types of models: one considers only the country's economic output and the other looks at both the greenhouse gas emissions and the pollution caused by coal consumption in terms of air emitted. The following is an illustration of an input-output indicator:

This system is composed of three distinct components. Begin by looking at the coal standby input index, which measures the amount of standard coal used per 1,000 metric tones of coal consumed. The second index measures the output of coal resources. It is equivalent to one hundred million dollars in Chinese currency; the capital input index is another index that is commonly used. In the end, the output metric is the only metric. According to Yijun Zhang and Song (2021), a fixed asset's current value is equal to its original value minus its accumulated depreciation value, calculated using the 2005 Fixed Investment Price Index. In other words, 1,000,000 people are equal to 10,000 employees and are expressed as the whole number employed in a specified year. Another way to look at it is to compare all employees' beginning and ending mean values.

System for showing the results of a task. There are two parts to this system. As a starting point, we can look at the industry's revenue in 100-million-yuan units, which is known as the financial output index. (Pardo-Bosch et al., 2019) use the 2010 ex-factory price index of manufacturing makers to deflate the impressive statistics from the China Industry Statistical Yearbook to arrive at the final value. Index of environmental and climate change impact also among undesirable outputs (also referred to as the unwanted output). NOX, SO2, and CO2emissions are added together to calculate this index, which is expressed in tones per ten thousand tones of CO2. There are three main factors that led to the selection of these three outputs, according to (Martínez-Moya et al., 2019). The three most concerning aspects of air pollution are acid rain, ozone exhaustion, and global warming. According to popular belief, these problems are caused by too much CO2, SO2, and NOX being emitted into the atmosphere. China's government has proposed emission reduction targets for the country, which has been the world's main transmitter of NOX, SO2, and CO2.

The China Industry Statistical Yearbook (2010–2019) was used to gather industry-related data, including data on the industry's capital stock, workforce, and sales value. 2010 IPCC guidelines for national greenhouse gas inventories were printed in 2010 and used to calculate the CO2 emissions. Following (X. Yu and Li 2020), we calculate carbon dioxide emissions by multiplying each type of energy consumption by its carbon emission coefficient and then totaling up the results to get the full carbon dioxide discharges. The China Energy Statistical Yearbook (2010–2019) was obtained from the Chinese government and used to calculate CO2 emissions. The China Statistical Yearbook on Atmosphere (2010–2019) was used to calculate SO2 emissions for the past 14 years. c) The China Statistical Yearbook on Environmental Statistics has published data on NOX emissions since 2011. This study follows Zeyun Li et al. (2022) and uses a variety of energy consumption factors and NOX emission factors to estimate NOX emissions for unobserved data. The original data are depicted in **Table 1** with the descriptive statistics.

3.2 Tobit Regression Analysis

A panel of random effects Tobit's regression is considered for the second stage of the analysis. In this step, the efficiency scores of the DEA gained in the first stage are generated as reliant on variables with the limited (0, 1) series. The Tobit regression model employed in this work is well-defined as follows:

$$y*it = \beta x_{it} + u_{it}$$

Where y_{it}^* Signifies the efficacy slash of area in the time period measured, t; β is a vector of criticisms to be assessed; x_{it} is a vector of the exogamic, sovereign variable quantity stated in the calculation (4); u_{it} signifies for the common error term composed of a time-invariant individual random effect v_i. Which is i.i.d., $N(0, \sigma_\varepsilon^2)$ and a time-varying idiosyncratic random error (ε_{it}), which is also i.i.d., $N(0, \sigma_\varepsilon^2)$. Hence, $u_{it} = v_i + \varepsilon_{it}$. The observed variables are.

$$y_{it} = \begin{cases} y*it - if - y\frac{*}{it} \geq 0 \\ 0\_otherwise \end{cases}$$

The maximum likelihood method is applied to estimate the Tobit regression. This model is used as a substitute for ordinary least squares regression. This model gives an effective result if the dependent variable is a limit or cut value. Numerous writers used this model by considering the DEA not chasing adequate to the interval (0, 1). The Tobit regression model fixes the issues with asymmetry that make the usage of ordinary least squares. However, academic arguments exist in relation to the functional appropriateness of this model in carrying out second stage examination. For example (Xiang et al., 2022), declares that Tobit regression is not the only method for modelling DEA scores, but in most cases, it generates valuable results. But (Pardo-Bosch et al., 2019), argues that as the DEA scores generated through Tobit contain fractions, it is not a suitable measure. He suggests that the ordinary least squares estimator is instead a reliable estimator.

TABLE 1 | Descriptive statistics of input-output from 2010 to 2019.

Variables	Mean	Std. dev	Medium	Minimum	Maximum
Coal consumption (I)	4480.01	6668.25	1308.26	463.21	21883.67
Capital stock (I)	13653.45	15815.91	8560.40	1839.17	63729.55
Labor (I)	313.91	176.98	270.64	49.45	625.25
Gross industrial products	37828.52	24392.36	31598.97	8940.99	85940.30
CO2 emissions	6007.12	11398.78	1046.44	321.01	40918.76
SO2 emissions	101.62	143.70	32.36	8.06	536.18
NOX emissions	80.62	148.88	13.80	3.92	527.45

However, this study applies the Tobit model and a linear random-effects model to test the results' statistical robustness.

3.3 Variable Selection

3.3.1 Tobit Regression Model and Variable Description

In order to protect the environment, CERs must be applied by government sectors or environmental safety firms. CERs, or climate-related emissions reductions, are a standard tool in Chinese environmental regulation. According to previous research, the intensity of CER was previously measured by the number of new regulations enacted. Despite their best efforts, governments often fail to put into effect the legislation they pass, according to (Singhai and Sushil 2021). It was thus decided to use the annual number of environmental administrative penalty cases as an indicator to gauge government CER intensity in accordance with Xu and Lin (2016) recommendation. In the wake of the MER, governments and environmental agencies are able to use market-based mechanisms to switch industrial contamination. Before this study, the strength of MER in the Environment was estimated using contaminant expulsion charges. Since 2003, China's pollutant expulsion charges system has been broadly applied all over the country's various regions, and the system's results have been thoroughly documented in the country's official statistical yearbooks. China's regional pollution expulsion payments are used as an indicator of the MER to calculate the MER. Vlontzos et al. (2014) says that by keeping an eye on the industry's production practices, the public can help protect the environment. VER (China's Environmental Responsibility) was measured by the number of letters of complaint received by the government regarding environmental pollution and related issues. People are more susceptible to changes in public opinion when they are in their immediate surroundings. Supporters of VER believe that the number of petitions received from the Ministry of Environmental science and Environment's petitions office is a good indicator of the organization's strength (China).

As an additional safeguard, the following control variables are employed: As a percentage of provincial GDP, GDP growth is measured by GDP (Gross Domestic Product), industrial growth is measured by IG (Industrial Development Potential), and technology innovation is measured by TI (Scale of Technological Innovation).

4 RESULTS AND DISCUSSION

4.1 Green Technology Efficiency

Figure 1 presents the average green innovation efficiency of carbon-intensive industries. China's industrial GIE was estimated from 2010 to 2019 using the super-efficacy DEA model, and the outcomes are exposed in **Table 2** of this research. It was clear that the GIE had changed significantly among the sample industries, and the overall trend was upward, from 1.00 to 1.16. According to (Rasoulinezhad and Taghizadeh-Hesary 2022) and the results of this study, which are summarized in **Table 3**, this was the case. As can be seen from this development, China's coal consumption is shifting from a high to a low level. GIE growth in the coal industry has lagged behind China's industrial sector, which has seen rapid increases in energy efficiency.

TABLE 2 | Descriptive statistics and variable selection.

Indicators	Min	Max	Mean	SD
EE	0.71	1.05	0.91	0.11
CER	57969.45	146011.95	105122.96	21851.07
MER	608587.35	2308950.00	1562896.65	575335.11
VER	1713.60	7389.90	3538.38	1417.65
GDP	105294.11	861792.02	402291.54	251111.60
IG	0.13	0.29	0.22	0.05
TI	683.55	14095.43	4775.03	4225.70

Because despite China's significant efforts to promote discharges reduction and energy preservation over the last decade to confirm the consolidation of energy technology innovation and structure of a coal united energy structure, the Chinese government needs to emphasize char manufacturing. The total amount of energy consumed could be reduced, while air pollution and greenhouse gas emissions could be reduced if the coal industry's energy efficiency improved. It would also have a positive impact on the environment.

4.2 Econometric Analysis

4.2.1 Unit Root and Co-integration Test

The stationary test of the data is required in order to guarantee that the estimated consequences are valid and that pseudo-regression problems are avoided to the greatest extent possible. The ADF method is used for the root-cause analysis in this study, and the fallouts of the test are presented in **Table 4**. The root-cause analysis outcomes for GIE, TI, and CER are essential at the 1% confidence level, indicating that there is no unit root under the condition of the first alteration, which is the case in this study. However, while the unit roots of the variables in the first variance are significant at 1% after the second difference, the null hypothesis is rejected for all of the variables in this difference. Because all of the models' orders are fixed, it is possible to observe that the difference between them is stationary. Furthermore, the second-order variance exam does not comprise any unit roots, indicating that it has a high level of stationary.

TABLE 3 | Results of the GIE in China's industries.

Industries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Coal Mining and Dressing	0.41	0.41	0.45	0.35	0.38	1.10	0.43	0.42	0.45	0.40	0.48
Petroleum and Natural Gas Extraction	1.91	1.67	1.44	1.34	1.25	1.18	1.26	1.24	1.04	1.04	1.34
Ferrous Metals Mining and Dressing	0.75	0.90	0.90	0.86	0.87	0.90	0.88	0.90	0.91	0.92	0.88
Non-ferrous Metals Mining and Dressing	0.63	0.70	0.77	0.82	0.88	0.95	0.90	0.91	0.91	0.86	0.83
Non-metal Minerals Mining and Dressing	0.88	0.97	1.12	1.05	1.12	0.80	0.74	0.81	0.90	0.91	0.93
Manufacture of paper and paper products	0.50	0.56	0.61	0.68	0.75	0.76	0.79	0.76	0.80	0.76	0.70
Processing of petroleum, coking, processing of nuclear fuel	2.27	1.87	1.85	1.64	1.63	1.53	1.45	1.35	1.27	1.26	1.61
Manufacture of raw chemical materials and chemical products	0.68	0.75	0.77	0.90	0.93	0.99	0.99	1.01	0.99	0.92	0.89
Manufacture of medicines	0.79	0.85	0.89	1.08	1.11	1.65	1.32	0.90	0.90	0.95	1.04
Manufacture of chemical fibers	1.06	3.19	2.23	1.57	1.35	1.19	1.34	1.43	1.60	1.68	1.66
Manufacture of non-metallic mineral products	0.49	0.57	0.62	0.66	0.70	0.72	0.73	0.76	0.79	0.77	0.68
Smelting and pressing of ferrous metals	0.78	0.83	0.82	0.96	0.98	1.02	1.09	1.07	1.08	1.08	0.97
Smelting and pressing of non-ferrous metals	0.93	1.02	1.05	1.14	1.16	1.25	1.26	1.40	1.35	1.37	1.19
Production and supply of power for electricity and heat	2.00	1.77	3.15	1.84	2.04	1.80	1.61	1.54	2.35	2.27	2.04
Rubber Products	0.92	0.93	0.94	0.88	0.90	0.99	0.84	0.85	0.84	0.83	0.89
Plastic Products	0.94	0.96	0.97	0.95	0.98	0.92	0.91	0.92	0.91	0.90	0.94
Transportation Equipment	1.01	1.00	1.05	1.01	1.05	0.99	0.95	0.95	0.96	0.94	0.99
Mean	1.00	1.12	1.16	1.04	1.06	1.10	1.03	1.01	1.06	1.05	1.06

TABLE 4 | Unit root test result.

	ADF	*p*-value
GIE	−1.35***	0.0021
ΔGIE	−2.815***	0.0003
Δ^2GIE	−3.54***	0.0012
MER	−0.585***	0.0009
ΔMER	−1.305***	0.0051
Δ^2MER	−2.436***	0.0001
CER	−1.525**	0.0205
ΔCER	−2.545***	0.0005
Δ^2CER	−3.235***	0.0007
VER	−0.15***	0.0002
ΔVER	−1.355*	0.0535
Δ^2VER	−2.015***	0.0016
GDP	−2.335	0.5023
ΔGDP	−1.115	0.0009
Δ^2GDP	−2.22	0.0004
IG	−1.12	0.0003
ΔIG	−1.205**	0.0305
Δ^2IG	−2.14***	0.0007
TI	−4.78**	0.0057
ΔTI	−2.02***	0.0016
Δ^2TI	−3.575***	0.0054

** = 10% significance level.*

TABLE 5 | EG-ADF test result.

Tests	e
Statistic	3.77
1% threshold	2.79
5% threshold	2.05
10% threshold	1.68

Performing a co-integration test on each variable is required in order to regulate whether or not a co-integration association exists among them. This is based on the results of the root-cause analysis, which indicates that the order of variable quantity in the replica has integration in the second order; therefore, the co-integration test is required. The Johansen and EG-ADF tests are used in this study to conduct the co-integration test, and both of these tests have been validated. EG-ADF testing yielded the following results, which are presented in the following table: **Table 5** shows the results of the survey. This results in an ADF number for the remaining order being statistically meaningful at the 1% confidence level. This indicates the presence of statistically influential co-integration relationships between the variables in the data.

Suppose one is used as the lag order. In that case, the co-integration rank calculation can be performed after a lag order for the variable has been determined (Kordej-De Villa and Slijepcevic 2019), which is consistent with the information criterion. **Table 6** presents the findings of the investigation in more detail. When the maximum rank is two, each variable in the model has two co integration relations. There are two co integration relations for each variable if the maximum rank of 2 is exceeded, as indicated by the trace statistic, less than the 5% threshold. To sum it up, data tested for co-integration and found to be significant can mean that the variables have a strong relationship.

4.2.2 Regression Result

There was a dependent variable for the construction industry, an independent variable for each of the three types of ERs, and control variables for the level of fiscal growth, manufacturing growth, and technical and industrial innovation were selected. Between 2000 and 2017, the GIE in the construction industry was examined in relation to three different types of ERs using the Tobit regression model. **Table 7** shows the results of the regression analysis which was used in this study. Because all models had LR2 values that were statistically significant with a 95% confidence level, the mockups passed the general worth test (Yuan et al., 2017; Zhang et al., 2021).

CER and GIE have a negative but non-significant linear relationship, as evidenced by the current-period regression model. CER's current-period effects on GIE construction are not statistically significant, as evidenced by the negative and

TABLE 6 | Johansen test result.

Co-integration rank (Max)	0	1	2	3	4	5	6	7
Eigenvalue	–	0.938	0.896	0.847	0.661	0.3607	0.34276	0.16158
Trace Statistics	145.172	100.437	64.1703*	34.041	16.694	9.5351	2.8197	–
5% Threshold	124.24	94.15	68.52	47.21	29.68	15.41	3.76	–

** = 10% significance level.*

TABLE 7 | Results of regression analysis.

Variable	(1)	(2)	(3)
Constant	7.259***	4.2607***	3.4061***
	(2.457)	(1.232)	(1.303)
MER	0.080***		
	(0.581)		
MER_Lag1	0.030***		
	(0.259)		
CER		0.174**	
		(0.343)	
CER_Lag1		0.130*	
		(0.637)	
VER			0.636***
			(2.576)
VER			0.611***
			(2.044)
GDP	−1.184***	−1.663***	−0.166***
	(2.163)	(3.164)	(0.329)
IG	−3.924***	−3.838***	−3.469***
	(2.555)	(2.723)	(2.611)
TI	0.338***	0.271***	0.415***
	(0.405)	(0.717)	(0.134)
LR χ^2	17.948	24.507	17.024
Log-likelihood	12.368	15.649	13.262

** = 10% significance level.*

TABLE 8 | Robustness test.

Variable	Lag_0		Lag_1	
	(1)	(2)	(3)	(4)
CER	−0.0063	3.672*	0.1145	−2.0650**
	(0.06)	(1.724)	(1.343)	(4.196)
MER	0.315**	3.458**	−0.1745	3.7052***
	(1.992)	(1.697)	(0.837)	(4.092)
VER	−0.2341**	1.566*	−0.0295	2.824
	−2.54	(1.015)	(0.362)	(1.477)
GDP	−1.150***	−2.2468***	−0.2141	0.9794**
	−3.37	−3.24	−0.45	2
IG	−5.8266***	−5.9354***	−6.6206***	−9.8934***
	−3.84	−2.70	−3.68	−7.63
STI	1.2160***	1.6336***	0.5046	0.0327
	3.68	3.9	1.56	0.11
C	8.0751***	25.028	2.3129	−56.2718
	4.79	0.95	1.14	−3.15
LR $\chi 2$	−2.3017	−2.3202	−2.4040	−2.7939
Log-likelihood	−31.7456	−25.9753	−28.2927	−19.8137

** = 10% significance level.*

positive coefficients of the first and second terms. There is a mathematically significant 90% correlation between MER and GIE in the present period; The initial term's coefficient is negative, while the subsequent term's coefficient is positive; these coefficients are statistically significant at 95% assurance. Non-linearity amid GIE and MER in the present period is depicted as a U-shape in the association between the two variables.

The rectilinear association between the present GIE and VER was negative and statistically significant, according to a 95 % assurance interval (CFI). The first term's coefficient is positive, while the second term's coefficient is negative, but these differences are not significant statistically. A direct association exists between the present GIE and VER in energy-intensive industries. According to a regression model used for the lagged phase, the CER of the lagged stage and the GIE of the intensive energy industries have an optimistic but non-statistically significant linear correlation (Cheng et al., 2021). When the coefficient of the non-linear relationship's primary term is negative, the coefficient of the quadratic term is positive, and the coefficient of the quadratic term is negative, the coefficient is statistically significant. Furthermore, the regression model demonstrates a statistically important inconsistent association between the energy-intensive industries commerce GIE and the lag phase CER.

At the 99 %assurance level, there is no mathematically important association amid MER in the GIE and the lag phase in the energy-intensive industries. Still, there is a negative correlation between MER and GIE. The primary term of the coefficient of a non-linear relationship is positive, but there is no statistically significant connection between MER and GIE. The inverted U-shaped relationship between the mean lag phase error rate and the construction industry GIE is found to be a significant non-linear relationship (Brent and Ward 2018). Although the VER and the GIE for the energy-intensive industries show a negative linear relationship, this relationship is not statistically significant. Despite the fact that a non-linear relationship's primary term has a positive coefficient and the quadratic polynomial term has a negative one, neither is statistically significant, suggesting that the lag phase's VER has little impact on the construction industry's GIE.

4.3 Robustness Check

This study employs a reversion model to examine the heftiness of the approximation outcomes in order to assess their heftiness in the Tobit model approximation. Fallouts are said to be robust if

they still have statistical significance for the test's core variables. If the most important variables are statistically insignificant, the results will not be taken seriously. Rather than using the Tobit model, we used the GLM model and the gathering robust standard error technique to estimate the standard deviation. **Table 8** displays the test results. It may be understood that the GLM model's analysis results are robust, as both the core variable coefficient and significance are unaffected following the regression.

5 DISCUSSION

This study found a significant U-shape association between the construction industry's green technology innovation efficiency (GIE) and the environment's control and lag phase regulation. Given the time it takes for government administrative rights to take effect, CER exhibits a significant temporal lag, which is understandable (Abbas et al., 2021). According to the graph below, the impact of CER on GIE in China's construction industry has reached a clearly defined inflection point. CER implementation intensity appears to have an effect on GIE, which first declines and then rises as the intensity of CER implementation is gradually increased. Because of this, the Chinese government should continue to encourage the adoption of the CER, better environmental laws and regulations, and increased administrative penalties for environmental offenses.

The construction industry's global trade in environmental goods has a significant inverted U-shape association with market-based environmental regulations (MERs) in the lag phase (GIE). Market-based environmental regulations (MER) are more significant in the lag phase than now because of the market's openness and dynamic nature. In the construction industry, it could be seen that MER are the most common ERs and have the most significant influence on the GIE of the industry at this time. The GIE of the energy-intensive sectors first increases and then decreases as a result of an increase in the intensity of MER implementation. According to Y. Zhou et al. (2013), reasonable implementation strength of MER improves the GIE in the energy-intensive industries. The market has a moderate incentive. The construction industry GIE can be enhanced by increasing the MER intensity (Hou et al., 2019). The construction industry is expected to actively pursue green technology innovation in order to evade high ecological safety prices while ensuring that it remains competitive (Tan and Lin 2020). High-strength MER, on the other hand, may force the energy-intensive industries to rise the costs of ecological contamination switch and investment contribution, which might result in the asset being diverted from other features of the manufacturing and have a bad influence on its overall operations, according to the MER report (Z. Cheng et al., 2020).

In the current period, there is a mathematically substantial negative correlation between GDP in the construction industry and voluntary environmental regulations (VER) (GIE). There are a number of environmental protection initiatives included in the VER program, which is carried out by a variety of stakeholders such as local residents, construction companies, and non-governmental organizations. GTI efficiency in the construction industry, on the other hand, is negatively impacted by VER, contrary to previous research. The higher the VER, the more expensive the energy-intensive industries (W. Du et al., 2020; Liu et al., 2018). According to previous research, it is clear that excessive VER strength in the construction industry is likely to stifle the advancements of GTI.

A summary of this study's findings can be summarized: The Chinese construction industry's GIE is affected by environmental regulations to varying degrees. However, it is possible to encourage a more environmentally friendly development of this industry by combining various environmental regulations (Luo Q. et al., 2019). Undoubtedly, the Multilateral Environmental Agreement (MER) has the most significant influence on the three kinds of environmental regulations. In order to promote green construction, it is essential to recover MER presentation by encouraging the broader operation of discharges transactions and enhancing the use of market mechanisms to address outwardness issues in the construction industry as a result of this. According to this report, the government should tool MER and CER in their entirety to strengthen green technological innovation in the energy-intensive industries.

6 CONCLUSION

It was determined that the phases of green technology development and research (GTRD) and commercialization (GTC) in the construction industry are distinct from one another in terms of their timing. A network SBM model has assessed the effectiveness of green technology innovation in the Chinese energy-intensive sector. For the final step, a Tobit regression model was applied to investigate the influence of three distinct types of environmental regulations (ERs) on the efficiency of green technology innovation (GIE). The following are the most significant findings of the study:

There is a misalignment between research and commercialization in the energy-intensive industries of green technology innovation. Since 2001, with the exception of 2000, the efficiency of green technology study and growth has consistently outperformed the efficiency of commercialization in the construction industry. Taking new technologies and turning them into a profit center is something that the construction industry is adept at. There is a lot of duplication in green technology's research and growth stage, which means that a lot of money is spent on research that does not result in any breakthroughs. Greater R&D efficiency in green technology can be achieved by increasing the number of R&D accomplishments delivered with the resources allocated to green technology during the R&D stage.

The efficacy of green technology innovation can vary depending on the regulation. Implementing all three kinds of environmental regulations simultaneously has the potential to improve the GIE score significantly. In the first place, environmental regulations that are easy to understand and

implement have a U-designed association with the GIE, with a significant time delay between the two events. In other words, the rule's command-and-control approach to environmental regulations wills almost certainly reduce GIE. When the inflection point is crossed, environmental regulations systems for command and control can have a helpful influence on GIE systems. Considering that environmental regulations based on command and control will not be implemented directly, it is essential to be patient. However, they will not have an immediate impact until they have been in place for a period of time. Second, the connection between market place environmental regulations and GIE is shaped like are versed U. Market place environmental regulation can be beneficial to GIE in the beginning, but after the inflection point, market environmental regulations will become a hindrance to GIE's development and growth. Even though voluntary environmental regulations are linked to GIE, this is only true for the time being. One of the primary reasons is that current volunteer environmental regulation is not flawless and, therefore, cannot have an optimistic impact on improving green technology innovation in the short term. As a result, the general public must be educated on the importance of environmental regulation and the necessity of voluntary regulations. Environmental regulations, on the whole, have been found to have no significant impact on GIE in general. Environmental regulations should be combined as a means of increasing GIE's effectiveness.

There are two ways in which this research subsidizes the body of information about the efficacy of green technology invention: first, it increases the amount of information available about green technology innovation competence; second, it increases the amount of information available about green technology innovation efficiency. As a first and foremost result of the investigation, a new and more effective method of evaluating the efficacy of green technology innovation in energy-intensive industries has been proposed. Until recently, the innovation process for green technology was regarded as a black box with no way to see inside. Therefore, we were able to divide the process into two stages (green technology study and growth) and commercialize the results of these researches so that we could better understand the impact of green technology study and growth on manufacturing firms in the energy-intensive industries. In addition, this adds to the body of previous theoretical research on the effectiveness of green technology innovation, which has been conducted.

Moreover, it provides governments with specific guidance on developing more active environmental regulations. As demonstrated in this study, various environmental regulations have dissimilar impacts on the effectiveness of green technology innovation. They also have an effect on the development of green technology at different stages throughout history. Because of this, when developing environmental regulations for energy-intensive industries, governments should take into consideration the varying effects and time lags that may be present.

The scope of this investigation has also been limited in some ways. As a result, because the market mechanism is limited, the study begins by examining how environmental regulations affect GIE and then moves on to other topics. The government is increasingly being called upon to play a role in encouraging industry to improve its ability to innovate efficiently. Despite this, it is important to recognize that the market place machinery is not without significance. In the upcoming study, it will be necessary to examine the pouring mechanisms of GIE in the context of the double role played by government strategies and marketplace mechanisms. To carry out this research, the Chinese energy-intensive industries will be used as a case study to demonstrate how environmental regulations can improve GIE in other countries throughout the world. Even though the findings of this study can be applied in other frameworks, the operation process must take into consideration the conditions of other countries. Regarding these topics, there is still a lot to discover.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Modeling the Impact of Foreign Direct Investment on China's Carbon Emissions: An Economic and Environmental Paradigm

Yuanzhi Xiao [1]***, Ke Gao*** [2]*** and Ruiqi Sun*** [3]*

[1]*Department of Economics, Texas A&M University, College Station, TX, United States,* [2]*School of Economics, Peking University, Beijing, China,* [3]*The Center for Economic Research, Shandong University, Jinan, China*

Under the background of high-quality development, the impact of foreign direct investment on carbon emissions has attracted increasing attention. This research studies the impact of foreign direct investment on carbon emissions under the effect of institutional quality regulation. Specifically, this study uses China's provincial panel data from 2010 to 2019, taking political system quality, economic system quality, and legal system quality as the external environment of system quality, this research studies the threshold effect of foreign direct investment on carbon emissions. The results show that foreign direct investment can effectively restrain the increase in carbon emissions. The impact of FDI on China's carbon emissions has an obvious economic threshold effect: with the increase of regional corruption, the political quality is gradually declining, and the inhibition effect of foreign direct investment on carbon emissions is declining. With the increase of marketization and intellectual property protection, the regional economic system and legal system have gradually improved, and the role of foreign direct investment in carbon emissions has been further increased. Therefore, China should create a good institutional environment for FDI technology spillovers.

Keywords: foreign direct investment, carbon emissions, institutional quality, econimic, environmental paradigm

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Muhammad Irfan,
Beijing Institute of Technology, China

Reviewed by:
Mubeen Abdur Rehman,
The University of Lahore, Pakistan
Kiran Batool,
North China Electric Power University, China

****Correspondence:***
Ke Gao
gkfly@126.com
Ruiqi Sun
ruiqi_sun1990@126.com

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INTRODUCTION

Since the reform and opening up, China has introduced foreign direct investment (FDI) to develop its export-oriented economy (Rauf et al., 2021; Abbasi et al., 2022; Fang et al., 2022), which has made the domestic economic development a great success (Hao et al., 2021a; Iqbal et al., 2021; Irfan et al., 2021), and is known as "China's growth miracle" (Lan et al., 2012; Wu et al., 2019; Zhu et al., 2019). According to the report of the Ministry of Commerce of the People's Republic of China, in 2020, China's foreign direct investment reached 999.98 billion yuan, making it the largest FDI recipient country in the world that year. The contribution of FDI to China's economic growth is unquestionable, but behind it is at the expense of the environment (Wu et al., 2021a; Shao et al., 2021; Shi et al., 2022). In recent years, China's carbon emissions continue to increase, and the environmental quality continues to deteriorate (Hao et al., 2021b; Li et al., 2021; Irfan and Ahmad 2022). The State Council issued the "Comprehensive Work Plan for Energy Conservation and Emission Reduction in the 14th Five-Year Plan" (hereinafter referred to as the "Plan"), proposing that by 2025, the national energy consumption per unit of GDP will be reduced by 13.5% compared with 2020. The total energy consumption has been reasonably controlled, and the total emissions of

chemical oxygen demand, ammonia nitrogen, nitrogen oxides, and volatile organic compounds have decreased by 8%, 8%, more than 10% and more than 10% respectively compared with 2020 (Li et al., 2020). At the same time, it is necessary to achieve remarkable results in air pollution prevention and control, and the situation of carbon emission reduction in China is extremely severe (Hao et al., 2020; Jinru et al., 2021; Khan et al., 2021; Wu et al., 2021b).

Under the background of frequent cross-border investment and high voice of environmental protection, the impact of FDI on the host country's environment has become the focus of many scholars' attention. One view is that FDI not only brings advanced management experience and production technology to the host country through the technology spillover effect, but also improves the energy utilization efficiency of local enterprises, and it also improves the degree of global specialized division of labor through the transnational flow of funds. Making production activities and pollution control activities produce scale-increasing effects, which are beneficial to the reduction of carbon emissions (Rezza, 2013; Chandio et al., 2021; Ren et al., 2022; Wang et al., 2022). Another view is that, in order to evade domestic environmental regulations, developed countries have transferred high-energy and high-pollution enterprises to developing countries with relatively loose environmental regulations (Tanveer et al., 2021; Ahmad et al., 2022), and the inflow of FDI has exerted tremendous pressure on the carbon emissions of the host countries (Hoffmann et al., 2005; Lee, 2009; Singhania and Saini, 2021). It makes developing countries become shelters for the transfer of polluting industries to developed countries. With the deepening of research, some scholars have begun to pay attention to the nonlinear relationship between FDI and carbon emissions. Because the threshold regression model can break through the limitation of linear analysis in previous studies, it can examine the different directions and degrees of action of explanatory variables on the explained variables in different ranges. This model has been widely used in nonlinear relationship verification. Scholars have confirmed that FDI has an obvious threshold effect on carbon emissions from the perspectives of income level, human capital level, financial development level, and industry technology level (Hoffmann et al., 2005; Chai et al., 2021).

In recent years, the political, economic, and legal environment of various countries has been changing constantly, and the impact of traumatic direct investment on carbon emissions may be influenced by economic externalities. Unfortunately, few scholars deeply and systematically analyzed the impact mechanism of FDI on carbon emissions from the perspective of the economic system environment, ignoring the important promoter in the transformation of China's economic growth mode (Hoffmann et al., 2005). So it is difficult to truly describe the impact of FDI on carbon emissions. In view of this, based on the panel data of 30 provinces in China from 2010 to 2019, this study examines the threshold effect of FDI on China's carbon emissions from three externalities of politics, economy, and law, and answers the following three questions: First, does the impact of FDI on China's carbon emissions have a flat threshold effect of economic externalities? Second, if it exists, what channel or mechanism does the threshold effect mainly occur? Third, how to formulate corresponding carbon emission reduction policies according to different thresholds and influencing mechanisms? It is expected to provide a theoretical reference for the rational introduction of foreign direct investment in the region and the realization of green and low-carbon sustainable development.

RESEARCH DESIGN

Basic Model Design

According to the aforementioned analysis, this study uses the research of Grossman and Krueger (1995) to construct the basic econometric model of this study from three aspects: scale, technology, and structure.

$$CO_2 = GDP \cdot TECH \cdot IND. \tag{1}$$

Among them, CO_2 Represents carbon emissions, GDP represents economic scale, TECH represents the technical level, and IND represents industrial structure. In order to test whether there is an "environmental Kuznets curve (EKC)" relationship between the level of economic development and carbon emissions, this study introduces the square of GDP into the economic scale (Wu et al., 2020; Tang et al., 2021). In an open economy, technological progress is influenced by international technology spillover (FDI) and R&D investment (RD). Consider comprehensively transforming model (1) into:

$$CO_2 = F\left(GDP, GDP^2\right) \cdot H\left(FDI, RD\right) \cdot IND. \tag{2}$$

By taking logarithms on both sides of formula **(2)** at the same time, the basic econometric model of this study is obtained:

$$\begin{aligned} LNCO_{2_{it}} = \beta_0 + \beta_1 LNFDI_{it} + \beta_2 LNGDP_{it} + \beta_3 LNGDP^2_{it} \\ + \beta_4 LNIND_{it} + \beta_5 LNRD_{it} + e_{it}, \end{aligned} \tag{3}$$

where I represents the province (I = 1, 2, 3 ... 30), and T represents the time, CO_{2it} indicates carbon emissions, FDI_{it} indicates the actual utilization of foreign direct investment, GDP_{it}, GDP^2_{it}, IND_{it}, and RD_{it} represents the level of economic development, the quadratic term of the level of economic development, the industrial structure adjustment index, and the R&D investment intensity, respectively, e_{it} said random disturbance term, LN said logarithm, β_0 and $\beta_1, \beta_2, \ldots, \beta_5$ represent constant items and parameters to be estimated.

Dynamic Threshold Panel Model

In order to study the impact of FDI on carbon emissions under the condition of economic externalities and solve the endogenous problems, this study introduces the dynamic threshold panel model and further transforms the model (3) into the following dynamic threshold model by referring to the research of Wu et al. (2020):

$$\begin{aligned} lnco_{2_{it}} = \beta_0 + \beta_1 lnco_{2_{it-1}} + \beta_2 \mathrm{lnfdi}_{it} I\left(q_{it} \leqq c\right) + \beta_3 \mathrm{lnfdi}_{it} I\left(q_{it} > c\right) \\ + \beta_n x_{it} + \alpha_i + e_{it}. \end{aligned} \tag{4}$$

Among them, $lnco_{2_{it-1}}$ a lag term represents carbon emissions, q_{it} for simplicity, we assume that the threshold variable does not change with time and is exogenous, i (·) indicates the index function, and c is the specific threshold value. x_{it} represents a series of control variables, α_i indicates the individual fixation effect, e_{it} is a random error term.

Explanation and Explanation of Variables

Explained Variable

Emissions of carbon (CO_2. at present, China's carbon emissions mainly come from fossil fuel combustion and industrial production. Fossil fuels mainly include coal, coke, petroleum (divided into fuel oil, gasoline, kerosene, and diesel oil), and natural gas. The emission of CO_2 in industrial production mainly includes CO_2 produced in cement, lime, calcium carbide, and other production processes. Among them, CO_2 produced in the cement production process accounts for the largest proportion. Considering the availability and integrity of data, only the carbon emissions released in the cement production process are considered.

The carbon emissions from fossil fuel combustion can be obtained by multiplying various energy consumption (standard tons of coal) by the carbon dioxide emission coefficient, and the specific calculation formula is as follows:

$$TCO_2 = \sum\nolimits_{i=1}^{7} CO_{2i} = \sum\nolimits_{i=1}^{7} Q_i \times CF_i \times CC_i \times COF_i \frac{44}{12}. \quad (5)$$

In the aforementioned formula, TCO_2 represents the total amount of carbon dioxide released by various fossil energy consumption, Q_i represents the final consumption of the I energy in 30 provinces (regions and municipalities directly under the Central Government) (except Tibet), CF_i represents the calorific value released by each energy consumption, CC_i I represents the carbon content in energy, COF_i stands for carbon oxidation factor, $CF_i \times CC_i \times COF_i$ stands for carbon emission coefficient, and $CF_i \times CC_i \times COF_i \times \frac{44}{12}$ represents carbon dioxide emission coefficient. The calculation formula of carbon emission in the cement production process is:

$$CCO_2 = QC \times EC_{cement}. \quad (6)$$

Among them, CCO_2 represents the release during cement production. CO_2 represents the total amount, QC represents the total amount of cement produced in industry, EC_{cement} represents the cement production process. CO_2 represents emission coefficient. The data mainly come from China Energy Statistical Yearbook, China Statistical Yearbook, and wind database.

Core Explanatory Variables

Foreign direct investment (FDI). With the deepening of China's opening to the outside world, foreign direct investment has become a key factor to promote China's rapid economic development. Many scholars at home and abroad have studied whether China will become a "pollution refuge" in developed countries. FDI plays a role in promoting or inhibiting the green development of China's economy and the green adjustment of its industrial structure. The conclusion is controversial. The data on actual foreign direct investment (USD 10,000) in each province comes from the China Statistical Yearbook.

Threshold Variables

This study adopts the quality of the political system, economic system, and the legal system as threshold variables. Follow the research of Ren et al. (2022). This research adopts regional corruption, marketization index, and intellectual property protection to represent the quality of the political system, economic system, and legal system, respectively. Relevant data come from the official website, National Bureau of Statistics, State Intellectual Property Protection Bureau, and China Legal Yearbook.

Control Variables

Economic development level (GDP). Since the revolution, throughout the history of world economic development, the economic development of major countries has always been accompanied by environmental pollution. Although most developed countries have crossed the turning point of "environmental Kuznets," most developing countries still advocate high-speed economic development at the expense of the environment. To study the relationship between economic development level and carbon emissions, the inter-provincial industrial GDP is used as an explanatory variable to reflect the regional economic development level. In order to test whether there is an "environmental Kuznets curve" relationship between the level of economic development and carbon emissions, the square of GDP is introduced, and in order to eliminate the influence of price fluctuations, it is reduced in 2005 as the base period. Source: China Statistical Yearbook.

Industrial structure adjustment index (IND). The optimization of industrial structure is conducive to the improvement of environmental quality, so this study selects the ratio of the added value of the tertiary and secondary industries in each province to measure the industrial adjustment. When the ratio is greater than one, it means that the increased proportion of tertiary industry is greater than that of secondary industry, and the larger the industrial structure adjustment index is, the lower the carbon dioxide emissions will be. On the other hand, the higher the carbon emissions. The industrial adjustment index is calculated, and the added value of the secondary and tertiary industries comes from the China Statistical Yearbook.

R&D intensity (RD). R&D intensity directly reflects the level of regional investment in science and technology. The more R&D investment and the higher R&D intensity in a region, the more resources the region will use for scientific and technological innovation, and the faster the technological progress and the transformation of the economic development mode will be. If these resources are used in the development of environmental protection technology, they can directly promote the reduction of pollution emissions. The R&D intensity of this study is expressed by the proportion of regional R&D expenditure to regional GDP, and the data comes from the China Science and Technology Statistics Yearbook 2. For the convenience of analysis, the term

TABLE 1 | Statistical description of table variables.

Variable name	code	Sample size	Average/mean value	Standard deviation	Minimum value	Maximum
Carbon dioxide emission	co2	300	2.616993	1.785305	0.188	8.745
Foreign direct investment (FDI)	fdi	300	626247.3	998450.4	2044	1.31E+07
Level of economic development	gdp	300	43887.81	554903.1	543.32	9621381
Industry restructuring	ind	300	0.8491735	0.401726	0.4909	2.831642
Research and development intensity	rd	300	0.847091	0.404499	0.000795	2.831642
Economic system	Economic	300	7.835733	2.254093	3.09	14.45
Political system	Politic	300	24.71402	6.854427	7.909968	46.32269
Property right system	Law	300	1.600317	0.8346874	0.6957681	5.210585

TABLE 2 | Self-sampling test of dynamic threshold effect.

Institutional variable	Threshold value	Wald statistics	*p* value	BS times	95% confidence interval	
Political system	3.8903179***	14.905822	0.000	1,000	2.0202796	5.8528128
Economic system	10.395***	20.127274	0.000	1,000	4.6599998	12.28
Property right system	2.8689389***	18.111161	0.000	1,000	0.89472002	3.5456843

** * *, * *, and * are significant at the levels of 1, 5, and 10%, respectively (the same below). The* p-value *and critical value are obtained by repeated sampling of the GMM threshold panel regression program 1,000 times. Wald statistics are used to judge whether the threshold features are obvious, and the smaller the corresponding probability, the more obvious the threshold features are.*

"province" is utilized to represent all provincial administrative units in China, including provinces, municipalities, and minority autonomous regions. Descriptive statistics of variables are shown in **Table 1**.

RESULTS AND EMPIRICAL ANALYSIS

Threshold Effect Test and Determination of Threshold Value

Using stata14.0, based on the dynamic threshold panel model Wald test self-sampling method (Bootstrap), the significance of the threshold effect of the political system (political), economic system (economic), and legal system (law) is tested under the assumption of no threshold effect. The results show that, according to Wald statistics and its *p*-value, The level of infrastructure construction, regional marketization, regional innovation capability, and intellectual property protection all rejected the original hypothesis of no threshold effect at the significance level of 1%, and the threshold value is obvious. See **Table 2** for its threshold value and confidence interval. This shows that the impact of foreign direct investment on China's carbon emissions varies with the quality of inter-provincial systems.

Parameter Estimation and Result Analysis of GMM Threshold Model

GMM Threshold Model Correlation Test

Table 3 reports the relevant test results of the two-step GMM threshold model regression, in which models (1–3) respectively represent the models constructed with the political system, economic system, and legal system as threshold variables. According to the correlation test of residual sequence, the difference GMM has no strict requirements for AR (1) test, but strict requirements for the AR (2) test, and the *p*-values of the AR (2) test are all greater than 10% significance level. Accept the original assumption (H_0: random error term, e_{it}: no second-order autocorrelation), therefore, there is no second-order autocorrelation in the difference of random error terms, and differential GMM can be used; according to the Sargan test results, the p-values of all model test results are greater than 0.1, and the original assumption that "all tool variables are valid" cannot be rejected, so the selection of model tool variables is valid; Wald statistics also show that the overall model is highly significant.

Parameter Estimation and Result Analysis

(1) Regional corruption

Model (1) reports the regression results with regional corruption as the threshold variable, from which it can be seen that the impact of foreign direct investment on China's carbon emissions also has a significant threshold effect. Specifically, with the increase in corruption, the energy-saving, and emission-reducing effect of FDI on carbon emissions weaken. The possible reason is that local officials, some foreign capital with high pollution, high energy consumption, and high emissions may be introduced. These FDI aggravated environmental pollution and weakened the proportion of technology-intensive FDI (Welsch, 2004; Cole, 2007; Ren et al., 2021).

(2) Regional marketization

Model (2) reports the regression results with the marketization index as the threshold variable, from which it can be seen that the

TABLE 3 | Dynamic threshold regression results.

Explanatory variable	Model (1)	Model (2)	Model (3)
llnco2	0.3742747***	0.302053***	0.502367***
	[3.35]	[4.08]	[6.34]
lngdp1	0.8959271***	0.801279***	0.623692***
	[4.45]	[3.77]	[4.27]
lngdp2	−0.0351378***	−0.02513**	−0.01682**
	[−3.77]	[−2.13]	[−2.13]
lnrd	−0.053452**	−0.04408	−0.08551***
	[−2.45]	[−1.35]	[−3.04]
lnind	−0.002231	−0.00203	−0.00155
	[−1.07]	[−0.91]	[−0.8]
lnfdi1	−0.0640822***	−0.0792***	−0.04545**
	[−4.52]	[−3.19]	[−2.51]
lnfdi2	−0.060112***	−0.08285***	−0.05014***
	[−4.22]	[−3.54]	[−2.87]
Constant term	0.0125395	0.009669	−0.00149
	[0.92]	[0.37]	[−0.08]
AR(1)	−2.20	−1.26	−1.32
	(0.028)	(0.209)	(0.188)
AR(2)	1.00	0.54	0.96
	(0.316)	(0.59)	(0.335)
Sargan test	26.34	24.81	24.77
	(0.285)	(0.36)	(0.362)
Wald statistics	7204.41***	36542.67***	12088.07***
	(0.000)	(0.000)	(0.000)
Sample size	240	240	240

[] indicates Z value, () indicates p*-value, and the aforementioned results are obtained according to xtabond2 two-step GMM threshold model regression.*

impact of foreign direct investment on China's carbon emissions also has a significant marketization index threshold effect. When the marketization index value is less than the threshold value, the impact of FDI on carbon emissions is negative at a 1% confidence level. When the marketization index is greater than the threshold value, the estimated coefficient of foreign direct investment is further reduced. This result shows that the level of marketization plays an important role in the impact of foreign direct investment on the environment. The negative coefficient of FDI on the environment indicates that the hypothesis of the environmental "pollution halo" is established in China, and the inhibition effect of FDI on carbon emissions is more obvious in areas with high marketization. Areas with a high degree of marketization usually have relatively complete public facilities, better government execution, a relatively mature market of elements and products, and human resources platform that encourages innovation, which injects vitality into the economy, thus creating conditions for foreign-invested enterprises to carry out technology research and development and technology diffusion, and continuously improving environmental pollution problems. A good institutional environment can even overcome problems such as poor foreign investment structure, insufficient economic openness, and policy failure. Therefore, to expand the technology spillover effect of FDI on local enterprises, it is necessary to improve the degree of marketization in this region (Lopez and Mitra, 2000; Biswas et al., 2012).

(3) Level of intellectual property protection

It can be seen from the model (4) that when the level of intellectual property protection is taken as the threshold variable, the impact of FDI on China's carbon emissions also have a significant threshold effect on the intellectual property protection level. When the level of intellectual property protection is lower than the threshold value, the elasticity coefficient of FDI to carbon emissions is small. This result shows that the level of intellectual property protection plays an important role in the impact of foreign direct investment on the environment, and the negative coefficient of FDI on the environment shows that the hypothesis of the environmental "pollution halo" is established in China. When the level of intellectual property protection is higher than the threshold value, the elasticity coefficient of FDI to carbon emissions becomes larger, and it passes the significance test of 5% confidence level. In areas with a low level of intellectual property protection, FDI has a weak inhibitory effect on carbon emissions. Only in areas with a high level of intellectual property protection, does FDI has a significant inhibitory effect on carbon emissions. The possible reasons are: 1) On the one hand, the protection of intellectual property rights in the host country can affect the quantity and quality of inflow, thus affecting the spillover. 2) On the other hand, it affects the absorptive capacity of the host country to technology spillovers through its independent innovation and technology stock (Irfan et al., 2021a; Irfan et al., 2021b).

The economic development of areas with a low level of intellectual property protection is relatively backward, people's legal awareness is weak, and law enforcement intensity is relatively low, which leads to a lower level of intellectual property protection than the eastern and central regions of China. The strong protection of intellectual property rights in these areas has increased the difficulty of imitation, resulting in the waste of resources and frustration of imitation. A lot of resources are wasted on imitation, while few resources are left for production, thus crowding out FDI (Rezza, 2013). As far as the western region of China is concerned, the ownership advantage and location advantage are not obvious, and the internalization advantage plays a greater role. From the analysis of internalization advantage, the level of intellectual property protection not only affects FDI but also affects the technology transfer in this region. The more perfect the intellectual property protection system in these areas, the better the multinational companies can control their intellectual assets and reduce the implementation cost of technology licensing, so that more enterprises can switch from FDI to technology licensing, and then the inflow of FDI will decrease. In areas with a high level of intellectual property protection, all aspects of the system are relatively perfect, people's comprehensive quality and legal awareness have also improved obviously. Therefore, the more perfect the intellectual property system in these areas, the more the ownership of multinational companies in these areas are protected, and the ownership advantage of international enterprises in the local area is enhanced. At the same time, with the deepening of international economic integration in these areas, multinational enterprises are paying more and more attention to the soft environment such as information,

TABLE 4 | Number of provinces crossing the threshold.

Threshold variable	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Political system	19	18	14	16	15	12	10	10	12	9
Market	0	0	1	3	4	5	6	6	8	10
Protect	2	2	2	2	2	2	3	3	3	3

TABLE 5 | Number of provinces in different threshold intervals in 2019.

Threshold variable	$q_{it} > C$	$q_{it} \le C$
Political system	Jilin, Anhui, Fujian, Henan, Hubei, Guangxi, Chongqing, Yunnan, and Ningxia	Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia Liaoning, Heilongjiang, Shanghai, Jiangsu, and Zhejiang Jiangxi, Shandong, Hunan, Guangdong, and Hainan Sichuan, Guizhou, Shanxi, Gansu, Qinghai, and Xinjiang
Economic system	Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Chongqing	Shanxi, Hebei, Inner Mongolia, Jilin, and Heilongjiang Anhui, Jiangxi, Henan, Hubei, and Hunan Guangxi, Hainan, Sichuan, Guizhou, and Yunnan Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang
Legal system quality	Beijing, Tianjin, and Shanghai	Shanxi, Hebei, Inner Mongolia, and Liaoning Jilin, Heilongjiang, Jiangsu, and Zhejiang Anhui, Fujian, Jiangxi, Shandong, and Henan Hubei, Hunan, Guangdong, Guangxi, and Hainan Chongqing, Sichuan, Guizhou, and Yunnan Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang

services, and laws to ensure the effective operation of the enterprise management system, which means that the protection of intellectual property rights also strengthens the regional advantages of these areas. Therefore, the higher the level of intellectual property protection in these areas, the more it can promote the inflow of local FDI.

Further Discussion

Taking the quality of the political system, economic system, and legal system of 30 provinces in 2010–2019 as research samples, this study divides them into two different regions according to the threshold variable values. **Table 4** reports the number of provinces crossing the threshold area each year during the inspection period, and **Table 5** reports the specific provinces in different threshold areas in 2019. It can be seen from the following results that in the area where the threshold value is not crossed, the international technology spillovers brought by FDI have little ability to restrain China's carbon emissions, and the pollution halo effect is also relatively small. For the provinces that have crossed the threshold, the absolute value of the influence coefficient of FDI on carbon emissions increases and is significantly negative. It shows that the international technology spillover effect is restricted by external conditions, and the external production conditions of foreign-funded enterprises are improved. It is conducive to the generation of international technology spillover effects. Therefore, local governments should fully consider the external conditions of foreign direct investment when promoting energy conservation and emission reduction through international technology spillovers.

The Robustness Test

In order to further study the relationship between FDI and China's carbon emissions under externalities, this study uses the whole sample interaction test to verify the robustness of the above dynamic threshold regression results. In **Table 6**, models (5–7) respectively show the estimated results of the interaction between FDI and regional corruption, marketization index, and intellectual property protection.

It can be seen from model (5) that the coefficient of FDI is significantly negative at the level of 1%, and the cross-term coefficient is also significantly positive at the level of 1%. Therefore, after the interaction between FDI and regional corruption is added, the effect of FDI on carbon emission reduction in China is weakened. It shows that when the degree of regional corruption is relatively high, the positive externalities that foreign-funded enterprises can get are relatively small. Therefore, the effect of FDI on carbon emission reduction is weak. With the further reduction of corruption level, foreign-funded enterprises get more and more positive external effects, and FDI has more and more inhibitory effects on carbon emissions. The regression results of model (6) show that the interaction coefficient between FDI and marketization index and intellectual property protection level is significantly negative. It shows that with the enhancement of market-oriented level and knowledge-based protection level, FDI

TABLE 6 | All-sample interaction test.

Explanatory variable	Model (4)	Model (5)	Model (6)	Model (7)
llnco2	0.262868***	0.241671***	0.277647***	0.250681***
	[5.56]	[4.8]	[9.26]	[4.8]
lnfdi	−0.00826***	−0.01554***	0.058878***	−0.00683***
	[−2.82]	[−3.85]	[9.34]	[−2.98]
lngdp1	1.238112***	1.215369***	1.181667***	1.20392***
	[10.9]	[10.14]	[11.93]	[9.7]
lngdp2	−0.04982***	−0.04788***	−0.03927***	−0.04399***
	[−8.62]	[−7.85]	[−7.14]	[−7.29]
lnrd	−0.00187	−0.00654	−0.02212	−0.01111
	[−1.04]	[−0.4]	[−1.37]	[−0.7]
lnind	−0.01312	−0.00133	0.000668	−0.00351*
	[−0.96]	[−0.72]	[0.39]	[−1.73]
lnpolitic*lnfdi		0.001806**		
		[2.48]		
lnarket*lnfdi			−0.03507***	
			[−10.03]	
lnprotect*lnfdi				−0.01007***
				[−4.14]
constant term	−6.14656***	−6.06878***	−6.37139***	−6.23739
	[−11.48]	[−10.56]	[−13.99]	[−10.28]
AR(1)	−0.86244	−0.52984	−1.0804	−0.72395
	(0.3884)	(0.5962)	(0.28)	(0.4691)
AR(2)	−0.25856	−0.56677	−0.00354	−0.26832
	(0.796)	(0.5709)	(0.9972)	(0.7885)
Sargan test	29.26565	27.81628	26.09099	28.77939
	(0.7408)	(0.8008)	(0.8621)	(0.7617)
Wald statistics	4675.79***	6883.64***	6433.26***	7304.51***
	(0.000)	(0.000)	(0.000)	(0.000)
sample size	240	240	240	240

[] indicates Z value and () indicates pvalue. *The aforementioned results are obtained by two-step differential GMM regression.*

will play a more and more important role in inhibiting carbon emissions, and the "pollution halo" effect will gradually appear. In addition, the coefficients and symbols of other control variables are not much different from the threshold regression results. The level of economic development promotes the rise of carbon emissions, and its quadratic term is negatively correlated with carbon emissions. "environmental Kuznets curve" still exists in China, and the industrial structure adjustment index and R&D investment intensity have promoted the reduction of carbon emissions, which is consistent with the previous conclusion of dynamic threshold regression. To sum up, the threshold regression results in this study are robust.

CONCLUSION AND ENLIGHTENMENT

Based on China's provincial panel data from 2010 to 2019, this study examines the threshold effect of FDI on China's carbon emissions from the perspective of external conditions (political system quality, economic system quality, and legal system quality) of foreign-funded enterprises in the host country. The results show that foreign direct investment can effectively restrain the increase in carbon emissions. FDI has an obvious economic threshold effect on China's carbon emissions: with the increase of regional corruption, the quality of the political system gradually declines, and the inhibition effect of foreign direct investment on carbon emissions declines. With the increase in marketization and intellectual property protection, the regional economic system and legal system have gradually improved. The role of foreign direct investment in carbon emissions has been further increased. In view of this, in order to achieve the goal of energy conservation and emission reduction in China, this study puts forward the following suggestions:

1. Promote the process of marketization and improve the degree of market opening. At present, China is still in the process of marketization, and the market structure is still unreasonable and imperfect, which to some extent restricts the development of China's technology market and affects the innovation, transfer, digestion, and absorption of China's technology. The Third Plenary Session of the 18th CPC Central Committee clearly pointed out that, we should make the market play a decisive role in resource allocation, constantly push forward the marketization process, fully release the reform dividend, and promote sustained and healthy economic and social development. While continuing to introduce FDI, constantly promoting market-oriented reform and perfecting laws and regulations will provide more ways for China to obtain FDI technology spillovers, so that the spillover effect of FDI technology can be brought into greater play. In the end, it will play a great role in promoting China's energy conservation and emission reduction.
2. Increase investment in scientific research and technological transformation to improve the independent innovation capability of local enterprises.

The improvement of local enterprises' independent innovation capability and the technology spillover of acquiring technology-based FDI are effective ways to promote energy conservation and emission reduction in China. In view of this, from the national level, government investment should focus on basic research, national defense, aviation, and other fields, increase investment in high-tech industries with higher risks, and ensure the formation of an effective investment mechanism in the country. It directly improves China's scientific and technological level in some fields; in addition, enterprises should become the main body of R&D investment, but although the comprehensive strength of large enterprises represented by the top 50 Chinese enterprises is still following the extensional development road characterized by expanding scale. Therefore, we should improve the policy system to encourage enterprises to invest in R&D as soon as possible, such as: increasing the fiscal and tax incentives for enterprise R&D, giving more tax incentives for enterprise R&D links, increasing the pre-tax deduction ratio of enterprise R&D investors, and introduce new tax incentives such as enterprise R&D reserve and accelerated depreciation of R&D equipment as soon as possible to reduce the cost of enterprise R&D.

In recent years, China has emphasized the improvement of independent innovation capability, with increasing R&D investment, technology introduction, and patent applications. However, the empirical research results show that the coefficient of R&D investment on technological progress in China is small, and the effect of technology spillover caused by the quality of foreign capital on technological progress is limited, which is related to China's low absorptive capacity. Although China's R&D investment is increasing year by year, the proportion of R&D investment in enterprises is also increasing year by year. However, due to the low capability of independent innovation, the input-output performance of R&D investment is not high, and the proportion of R&D investment used for digestion and absorption is small, so it can't effectively absorb foreign capital spillovers. Therefore, policies should be guided, a certain proportion or even most of R&D investment will be used for the digestion and absorption of spilled technology and imported technology, so as to improve the level of independent innovation, save R&D resources and make foreign technology spillovers promote technological progress more effectively.

3. Improve the level of regional intellectual property protection and improve laws and regulations.

The empirical results show that the improvement of intellectual property protection level can produce positive externalities to the technology spillover effect of FDI, so the government should consider strengthening intellectual property protection while promoting the goal of energy conservation and emission reduction through FDI technology spillover channels. Specifically, on the one hand, we should improve the legislation on intellectual property protection and formulate different levels of intellectual property protection according to the characteristics of different industries.

When formulating intellectual property protection policies, we should comprehensively consider the role of intellectual property protection in innovation and diffusion, formulate different intellectual property protection efforts for different industries, and establish high-intensity intellectual property protection for technology-intensive industries, so as to promote large-scale foreign investment in China's high-tech fields and further improve the quality of foreign investment. Promote the upgrading of the overall industrial structure. On the other hand, we should improve the law enforcement level of intellectual property protection, train professionals engaged in intellectual property protection, intensify publicity on intellectual property protection, and enhance the awareness of intellectual property protection in the whole society. We should strengthen the professional training of relevant law enforcement personnel in a planned way, and constantly improve the effectiveness and transparency of law enforcement. There are laws to be followed and laws to be followed, so that China's intellectual property protection legislation and law enforcement are in line with international standards, thus promoting the quality of foreign capital introduction.

Although this study uses the provincial level data of China to study the impact of foreign direct investment on carbon emissions, it still has some limitations, which we hope to solve in our future research. First, we can use microdata to study the relationship between them in the future. Second, the instrumental variable estimation may be a good method to solve potential endogenous problems.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YX: conceived the idea and contribute to the writing of the manuscript. KG: performed the data collection and statistical analysis. RS: proofread the manuscript and gave guidance throughout the process of this study. All authors have read and agreed to the published version of the manuscript.

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How Multi-Dimensional Local Government Competition Impacts Green Economic Growth? A Case Study of 272 Chinese Cities

Xufeng Su[1,2], Guangliang Liu[1†], Yang Xu[1†], Wenfeng Ge[1†], Bing Shen[1†], Qiying Ran[3,4] and Hui Zhou[5]**

[1]School of Economics and Management, Xinjiang University, Urumqi, China, [2]School of Economics and Management, Tarim University, Alar, China, [3]Shanghai Business School, Shanghai, China, [4]Center for Innovation Management, Xinjiang University, Urumqi, China, [5]Tianjin Industry and Information Technology Institute, Tianjin, China

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****Correspondence:***
Qiying Ran
ranqyxjedu@126.com
Hui Zhou
zhouhvi@163.com

†These authors have contributed equally to this work and share first authorship

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Green economic growth is an unavoidable choice for China's development model, while the government-led Chinese economic development system determines that local government competition may have an essential impact on green economic growth. For this purpose, this study employs data on Chinese 272 prefecture-level cities and the system generalized method of moments (SYS-GMM) model to investigate the impact of multi-dimensional local government competition (ecological competition, service competition, economic competition, and comprehensive competition) on green economic growth. The empirical results reveal that local government competition significantly influences green economic growth, in which economic competition significantly inhibits green economic growth, and ecological competition, service competition, and comprehensive competition positively influences green economic growth. The influence mechanism indicates that economic competition, ecological competition, service competition, and comprehensive competition significantly affect green economic growth through economic agglomeration and industrial structure upgrading, respectively. Moreover, the impact of multi-dimensional local government competition on green economic growth shows significant temporal and regional heterogeneity. Therefore, policymakers should further develop a multi-dimensional local government competition target system for local government officials and moderately enhance both ecological competition and service competition that is oriented to green economic growth.

Keywords: local government competition, green economic growth, mediating effects, heterogeneity, China

1 INTRODUCTION

China's economy has experienced significant growth for many years since the reform and opening up of the economy (Irfan et al., 2021), which demonstrates the "Chinese miracle" of economic development (Li et al., 2018; Wu et al., 2021b; Ren et al., 2021). In particular, local government has a significant function in attracting factors such as capital, labor, and land (Boyne, 1996; Hao et al., 2021; Wu et al., 2020). China's unique decentralized structure of both central and local governments has driven internal competition among local governments, rendering it the most direct factor in promoting high economic growth

(Abbasi et al., 2022; Fang et al., 2022; Hao et., 2021). Fiscal decentralization and related competitive institutions have contributed to the accelerated development of the economy (Wu et al., 2021a; Rauf et al., 2021; Tang et al., 2022), while competition in attracting capital (Jinru et al., 2021; Irfan and Ahmad 2022; Qiu et al., 2022), represented by foreign direct investment (FDI), has increased China's economic growth (Clegg et al., 2004; Yang et al., 2021a).

However, under administrative and resource flow constraints, local government competition may accelerate local protectionism (Chandio et al., 2021; Shi et al., 2022), which may bring about increased market transaction costs and inhibits economic growth (Zhang et al., 2020; Ahmad et al., 2021). Moreover, the development model that leans on investment to drive GDP has been responsible for numerous problems in China's economy, such as rapid consumption of resources, serious environmental pollution and ecological damage, and low economic efficiency (Ran et al., 2020; Zhang et al., 2021). As reported in the 2020 Bulletin on the State of China's Ecological Environment, up to 40.1% of 337 cities have ambient air quality exceedances, of which the annual average concentration of $PM_{2.5}$ is even three times higher than the 10 μg/m^3 standard set by the World Health Organization's Air Quality Guidelines Values.[1] Therefore, under the situation mentioned above, how to comprehensively strengthen green economic growth has emerged as one of the urgent strategic issues for China's economic transformation (Song et al., 2019; Ren et al., 2022a; Shen et al., 2022). Since 2012, the Chinese government has elevated green development to a national strategy, while the concept of green development, represented by "green mountains and clear water are equal to mountains of gold and silver," has become the consensus of society (Ren et al., 2022b). Only green economic growth can effectively fulfill economic transformation, alleviate resource and environmental constraints, and bridge the gap between the "green mountains and clear water" and the "mountains of gold and silver" (Wang J. et al., 2021; Ren et al., 2022c).

In the context of green development, can local government competition drive China's green economy to continue its high growth? On the one hand, economic competition among local governments, competition in productive fiscal spending, competition in FDI attraction, fiscal competition, and competition in tax burden may not be conducive to green economic growth (Hao et al., 2020; Irfan and Ahmad 2021; Tanveer et al., 2021). Fiscal and economic competition strategies have local emission reduction effects, while investment attraction and regulation competition strategies will aggravate local pollution with the "pollution paradise" effect and "regulation paradox" phenomenon. On the other hand, as the environmental responsibility system is implemented and the environmental performance evaluation system is established, the new promotion champion theory, which focuses on environmental protection, pushes local governments' financial expenditures toward environmental protection and simultaneously strengthens regional environmental governance to contribute to the overall improvement of environmental quality. However, a diversified performance appraisal system can effectively correct the distortion of resource allocation caused by competition among local governments and reduce the loss of city production efficiency (Zhang et al., 2021). Meanwhile, competition among local governments in moderation facilitates green economic growth, and conversely, excessive local government competition is detrimental to green economic growth. Moreover, in terms of institutional competition, environmental regulation will also improve the green economic growth level (Wu et al., 2020b; Hao et al., 2022; Qiu et al., 2022). Local government competition is comprehensive, multi-dimensional, and dynamic. So, how does multi-dimensional local government competition affect green economic growth? Are there significant heterogeneous effects of multi-dimensional local government competition on green economic growth at different time points and regions? Can multi-dimensional local government competition contribute to green economic growth by influencing economic agglomeration and industrial structure upgrading? The answers to the above questions are significant for promoting green economic growth and achieving reasonable competition among local governments in China. Therefore, this paper investigates the influence mechanism of multi-dimension of local government competition (ecological competition, service competition, economic competition, and comprehensive competition) on green economic growth, to provide an empirical basis and factual reference for optimizing local government competition and promoting green economic growth.

Compared with the existing studies, the potential contributions of this paper are primarily reflected in the following several aspects. Firstly, this paper constructs a multi-dimensional local government competition system from four dimensions: economic competition, ecological competition, service competition, and comprehensive competition, and employs the SYS-GMM method to evaluate the influence of local government competition on green economic growth from a multi-dimensional perspective. Secondly, this paper verifies the influence mechanism of local government competition on green economic growth considering economic agglomeration and industrial structure upgrading as mediating variables. Finally, the heterogeneous characteristics of local government competition on green economic growth are further investigated in terms of temporal and regional heterogeneity, which facilitates the enrichment of relevant studies on local government competition and green economic growth.

The remainder of the paper is organized as follows. **Section 2** gives the literature review. **Section 3** gives the model setting, variables selection, and data description; **Section 4** provides the empirical results and discussion in detail; **Section 5** shows the research conclusions and policy implications.

2 LITERATURE REVIEW

Local government competition denotes cross-regional competition among local officials regarding investment environment, legal system, and government efficiency to catch production factors

[1]See more detail: https://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/202105/P020210526572756184785.pdf

such as capital, technology, and talent (Eberts and Gronberg, 1988; Li et al., 2021; Jiang et al., 2022). Government competition has been studied for ages, starting with Adam Smith's argument that capitalists determine capital flows in response to taxation (Edwards and Keen, 1996; Lyytikäinen, 2012; Claveres, 2022). Following Smith, the American economist Tiebout studied "local government competition," a theory of "voting with one's feet" that suggests that residents will migrate to regions that provide better satisfaction of their requirements for public goods (Tiebout, 1956). Breton (1998) provides a more comprehensive overview of "local government competition," arguing that government competition is inevitable and exists not only between different levels of government but also between government and non-government agencies. Allers and Elhorst (2005) argue that local governments compete in terms of resources, policies, performance, and institutions, but they essentially compete in terms of resources and capabilities. Local governments are individuals with relatively independent interests and needs, while various mobile resources for regional development are scarce, thus they need to compete with each other (Wang K.-L. et al., 2021; Trojanek et al., 2021; Li, 2022).

Local government competition is a multi-dimensional competition that includes economic competition, ecological competition, and service competition (Oates and Schwab, 1988). Competition in the local government economy is essentially about catching up with developed economies and overtaking homogeneous economies (Tang et al., 2021; Tang and Qin, 2022). Economic competition is a prominent competitive situation in terms of performance, both in terms of pressure for economic growth targets and economic growth rates and in terms of motivation for investment and tax competition (Mintz and Smart, 2004; Jiang et al., 2022). Local governments' economic growth targets are derived from the central government's economic growth target setting, while local governments will cascade and enhance their economic growth targets (Xu and Gao, 2015; Su et al., 2021). The country's urgent need for economic growth drives local governments to generate GDP growth preferences, and choosing the GDP growth rate as a measure of the economic competition dimension is a frequent practice of researchers (Mohammad et al., 2021). Hong et al. (2020) suggest that increased investment by local governments can not only directly boost local economic growth but also play the role of "attracting phoenixes to the nest." In addition, local governments are active in attracting foreign capital, while FDI is characterized by significant economic efficiency and liquidity, reflecting the "voting power" feature for local governments (Zhang et al., 2021). Capital attraction competition is a more used variable in local government competition studies, which portrays the strength and ability of local governments in attracting capital through FDI (Fan and Zhou, 2019). Fiscal competition, as the most directly controlled competitive tool for local governments, captures the economic spending propensity of local governments through the ratio of fiscal expenditure to fiscal revenue (Jiang et al., 2022; Liu et al., 2022).

Government investment in environmental management and pollutant treatment rates are the primary symptoms of ecological competition. To promote ecological improvement and build a livable environment, local governments invest more in environmental management and improve environmental regulations (Yang et al., 2018; Ren et al., 2022). The local governments have shown different forms of competition in fiscal environmental protection spending due to the "free-rider" mentality and concern for enhancing environmental quality (Keyu, 2021). Yang et al. (2018) choose three representative indicators to characterize environmental regulation, namely COD reduction task, wastewater discharge compliance rate, and private wastewater reduction cost, to examine the Pollution Haven Hypothesis (PHH) effect of environmental regulation in Jiangsu province. Some scholars have also used wage level, human capital, and population density as basic indicators of informal environmental regulation (Wang and Tan, 2017; Hao et al., 2021). Moreover, according to Hicks' theory of induced innovation, stricter regulation will lead to changes in input factor prices and increased environmental costs, forcing firms to adopt green technology innovations to cope with the problem (Cai et al., 2020).

The ability of the government to provide basic services to businesses and residents is the key factor in service competition. Freret (2005) analyzes the spatial interaction of social services and health care expenditures, economic construction expenditures, highway expenditures, and education expenditures and argues that there are differentiated competitive strategies for different public expenditures. Heng and Hong (2012) point out that the decentralized model of local government decision-makers in China, who are primarily accountable to their superiors, leads local governments to pursue the highest possible economic growth rate. Wu et al. (2017) find that increasing the proportion of government expenditure can increase total factor productivity after dividing fiscal expenditure into government administrative service expenditure, investment and development expenditure, and protection and governance expenditure. Petrusha et al. (2019) propose a framework for human resource attraction and retention and intellectual capital creation for sustainable low-carbon economic transition based on micro-and macro-level changes.

The influence of local government competition on green economic growth is multi-dimensional, which not only responds to the impact of local government competition on environmental quality such as haze and carbon emissions but also on energy efficiency and green economic efficiency. Some scholars believe that local government competition has deteriorated environmental quality (Deng et al., 2019; Li et al., 2021; Shen et al., 2022). Bai et al. (2019) reveal that tax competition is one of the strategies of local governments to cope with fiscal pressure, inter-regional tax competition not only brings about a local environmental negative impact but also deteriorates the environmental quality of spatially related regions. Moreover, local governments exert control over the effective tax rate via several factors including tax enforcement and regulation, both of which are major contributors to the distorted implementation of environmental regulatory policies and the effectiveness of environmental regulation (Deng et al., 2021). Ma et al. (2020) find that formal environmental regulation can influence water

pollutant discharges through formal environmental regulation in local government competition, however, there is no clear role mechanism for informal environmental regulation. With the increase in formal environmental regulations, local government competition played a greater role in curbing water pollutant discharges (Ma et al., 2020; Pan et al., 2020; Nie et al., 2021). As an essential tool for environmental management, government environmental spending can not only induce social capital and corporate environmental behavior but can also impinge on economic growth and environmental quality (Ruffing, 2010). Galdeano et al. (2008) and Zhang and Wang (2022) verify that local governments' emission reduction targets lead to more emission reduction efforts, implying that local governments increase competition in environmental protection and reduce local governments' competition in economic growth, which ultimately improves environmental performance effectively (Yang et al., 2020). However, under the concept of functional finance, additional fiscal spending on public goods is likely to spur economic growth, which consequently creates more pressure on the environment (Lin and Zhu, 2019). The government's environmental livability policy expands urban green space and facilitates green economic growth (Bush, 2020; Irfan et al., 2022). In addition, the government's subsidy policy for enterprises can promote enterprises to improve production technology and reduce energy consumption, thus contributing to a higher level of green economic growth (Yang et al., 2021b).

However, some scholars have also measured green economic growth from multiple dimensions and analyzed the role of local governments on green economic growth based on different perspectives. Li and Xu (2020), for example, identify local government competition as one of the primary causes of the regional "green paradox." Wang (2020) employs a super-efficient DEA model to measure green economy efficiency and reveals that the use of environmental regulation competition from local governments has a "U" shaped relationship with green economy efficiency. Chai et al. (2021) find that the overall level of competition in investment promotion significantly inhibits the increase of green total factor productivity, and the interaction between institutional quality and competition in investment promotion shifts green total factor productivity from inhibition to promotion. Tang and Qin (2022) reveal that local government competition not only distorts factor prices across regions but these factor distortions are also transmitted to green total factor productivity. Zhang et al. (2020) unveil that growth competition, fiscal competition, and investment competition among local governments significantly dampen green development efficiency.

To sum up, most scholars focus on single competition such as economic competition, ecological competition, and service competition, and less on multi-dimensional and dynamic local government competition. In addition, the study on the impact of local government competition on environmental quality and green economic growth is also mainly based on economic competition and environmental regulation. Most scholars support local government competition to inhibit environmental quality and green economic growth. Meanwhile, less attention has been paid to the mechanisms by which local government competition affects green economic growth. As such, Based on the panel data of 272 prefecture-level cities in China from 2004 to 2019, this paper studies the impact of multi-dimensional local government competition (economic competition, ecological competition, service competition, and comprehensive competition) on green economic growth using the dynamic panel system generalized method of moments estimation model (SYS-GMM), explores its impact mechanism in the context of economic agglomeration and industrial structure upgrading, to make some contributions to the relevant fields of local government competition and green economic growth.

3 METHODOLOGY

3.1 Economic Strategies

Most scholars have confirmed the existence of time-lagged characteristics of green economic growth (Zhao et al., 2021a; Cao et al., 2021). Therefore, this paper utilizes a generalized method of moments (GMM) to perform optimal estimation of the correlation coefficient parameters. GMM are generally subdivided into differential GMM (DIFF-GMM) and the system GMM (SYS-GMM). Panel data in DIFF-GMM estimation advances over time, inevitably triggering more instrumental variables. In contrast, the SYS-GMM is developed based on the DIFF-GMM approach, which effectively overcomes the endogeneity problem that arises within the model. Following Arellano and bond (1991) and Yang et al. (2021b), this paper incorporates a one-period lag of the green economic growth into the benchmark regression model, while using SYS-GMM to evaluate the impact of multidimensional local government competition (service competition, economic competition, ecological competition, and comprehensive competition) on green economic growth from the perspective of economic agglomeration and industrial structure upgrading. The set form of **Eq. 1** is given as follows.

$$GEG_{it} = \alpha \cdot GEG_{it-1} + \beta_0 + \beta_1 \cdot COM_{it} + \beta_2 \cdot X_{it} + \varepsilon_{it} \quad (1)$$

where i and t respectively denote the year t of prefecture-level city i. β represents the coefficient vector. ε is a random disturbance term that matches the orthogonal characteristics. The explained variable is green economic growth (GEG). The core explanatory variable is local government competition (COM), which is an index system, including economic competition, ecological competition, service competition, and comprehensive competition. The control variables are denoted by X which mainly include marketization (MAR), urbanization (URB), financial development (FIN), informatization (INF), human capital (HUM), internet development (INT), economic development (PGD), natural population growth rate (NAT).

Economic agglomeration, industrial structure upgrading, and may have had a significant impact on multi-dimensional local government competition for green economic growth. So what role do economic agglomeration, industrial structure and technological innovation as key factors influencing green economic growth perform in multi-dimensional local

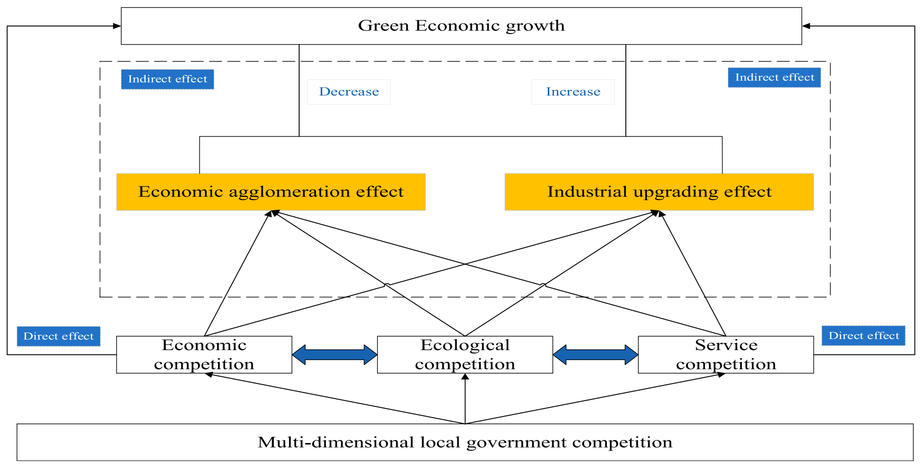

FIGURE 1 | Influences mechanism.

government competition to influence green economic growth? This paper uses **Figure 1** to briefly describe the impact of multi-dimensional local government competition on green economic growth in the context of economic agglomeration, technological innovation, and industrial upgrading.

Therefore, referring to Yang et al. (2021c) and Baron and Kenny (1986), this paper employs the stepwise regression method proposed to test the mediating effect of economic agglomeration and industrial structure. To intuitively describe the verification procedure of mediating effect, the mediation effect model is simplified into **Eqs 2–4**.

$$GEG_{it} = \alpha \cdot GEG_{it-1} + c \cdot COM_{it} + \beta \cdot X_{it} + \varepsilon_1 \quad (2)$$

$$MED_{it} = \alpha \cdot MED_{it} + a \cdot COM_{it} + \beta \cdot X_{it} + \varepsilon_2 \quad (3)$$

$$GEG_{it} = \alpha \cdot GEG_{it-1} + c' \cdot COM_{it} + b \cdot COM_{it} + \beta \cdot X_{it} + \varepsilon_3 \quad (4)$$

where *Mediator* represents the mediating variable, c represents the total effect, $c = ab + c'$. $a{\cdot}b$ means mediating effect, that is indirect effect, and c' means direct effect. X denotes the same variables as in **Eq. 1**. For the measure of mediating effects, we examine them using a stepwise regression method. The first step is to investigate the total effect of local government competition on green economic growth in **Eq. 2** and measure whether the coefficient c is significant. The second and third steps are to examine the effect of local government competition on the mediating variables in **Eq. 3** and the effect of the mediating variables on green economic growth in **Eq. 4**, respectively while estimating the significance of the coefficients a and b.

3.2 Variables Selection

3.2.1 Explained Variable

Green economic growth (*GEG*). Based on the calculation method of Yang et al. (2021d) and Liu et al. (2021), we apply the research framework of non-radial SBM including unexpected output to characterize *GEG*. GDP at the prefecture-level, which is discounted using 2004 as the base period, is employed as the desired output. Industrial wastewater emissions from prefecture-level cities, industrial soot emissions from prefecture-level cities, and industrial sulfur dioxide emissions from prefecture-level cities were employed as the undesired outputs. There are three indicators of input variables, namely, unit employment from prefecture-level cities, capital stock, and energy consumption. In the case of capital stock, we characterize the depreciation rate of fixed assets at 9.6% and assume that the capital stock in the base period is expressed as 10 times the investment in fixed assets in the base period (Young, 2003). Energy consumption is replaced by per capita electricity consumption from prefecture-level cities. Green economic growth is calculated by MAX-DEA software and super efficiency SBM model of undesired output, which is expressed by SBM-GML. Additionally, we apply the DDF-GML model to perform robustness checks on green economic growth (Su et al., 2021). **Table 1** reports the green economic growth indicator construction system.

3.2.2 Core Explanatory Variable

Local government competition (*COM*). Local government competition is a multi-dimensional comprehensive competition. Under this idea, this paper constructs a local government competition index system, covering economic competition (*JJJZ*), ecological competition (*STZJ*), service competition (*FWZJ*), and comprehensive competition (*ZHJZ*). **Table 2** characterizes the construction of indicators specific to local government competition and the interpretation of the indicators.

In this paper, local government competition is a multi-dimensional government competition, including three sub-index competition and comprehensive competition: economic competition, ecological competition, and service competition. This paper adopts the full permutation polygon synthesis illustration method to calculate the multi-dimensional local government competition (Wang et al., 2015; Kosajan et al., 2018). The fully arranged polygon graphic method can be used for multi-index evaluation. Taking the upper limit value of n evaluation indexes as the radius to form a central regular N-sided shape, the connecting line of index values forms an

TABLE 1 | Green economic growth indicator construction system.

Variables	Definition	Specific Indicators	References
Output	Desired outputs	Discounted real GDP using 2004 as the base period	Lin and Zhu (2019)
	Undesired outputs	Industrial wastewater emissions	Wang et al. (2021a)
		Industrial soot emissions	Yang et al. (2021)
		Industrial sulfur dioxide emissions	Wang et al. (2021a)
Input	Labor	Employment in units from prefecture-level cities	Su et al. (2021)
	Capital	Calculated using the perpetual inventory method	Lin and Zhu (2019)
	Energy	Electricity consumption per capita from prefecture-level cities	Liu et al. (2021)

TABLE 2 | Local government competition index system.

Level-I	Level-II	Level-III	References
Economic competition (*JJJZ*)	Growth competition	GDP growth rate	Liu et al. (2021)
	Capital attraction competition	Foreign direct investment divided by GDP	Fan and Zhou. (2019)
	Tax competition	$\frac{tax_t/GDP_t}{tax_{it}/GDP_{it}}$	Hong et al. (2020)
	Investment competition	Fixed asset investment in prefecture-level cities divided by national fixed asset investment	Zhang et al. (2020)
Ecological competition (*STZJ*)	Overall greening competition	The green coverage rate of the built-up areas	Gao and Hua (2015)
	Per capita greening competition	Per capita green space level in prefecture-level cities	Lu and Xiang (2020)
	Environmental regulation competition	The proportion of environmental employees in employed persons	Gao et al. (2020)
	Pollutant treatment competition	Wastewater treatment rate in prefecture-level cities	Wu et al. (2020)
Service competition (*FWZJ*)	Basic conditions competition	Road area per capita	Meng et al. (2021)
	Medical service competition	Number of beds in medical and health institutions	Qiu et al. (2022)
	Commuter competition	Public transport vehicles per 10,000 people	Feng and Liu (2016)
	Income competition	The average wage of employees	

irregular central N-sided shape, and the vertex is a full arrangement of N indexes connected head to tail.

First, a hyperbolic standardization was performed for each index:

$$F(x_i) = \frac{(U_i - L_i)(x_i - T_i)}{(U_i + L_i - 2T_i)x + U_iT_i + L_iT_i - 2U_iL_i} \tag{5}$$

Among them, the number of indicators is denoted using i. The standardized value of the ith indicator is characterized by $F(x_i)$. The lower limit value of the upper limit level of the i_{th} the indicator is characterized by U_i and L_i, respectively. The critical value of the i_{th} the indicator is characterized by using T_i, and the value of the i_{th} the indicator is characterized by using x_i.

$$S = \sum\nolimits_{i \neq j}^{i,j} \frac{(S_i + 1)(S_j + 1)}{2N(N-1)} \tag{6}$$

$$F(x_i) = \frac{(U_i - L_i)(x_i - T_i)}{(U_i + L_i - 2T_i)x + U_iT_i + L_iT_i - 2U_iL_i} \tag{7}$$

Then, a regular polygon with n sides in the center is composed of the upper limit values of N indicators, while the overall arrangement and combination of irregular n-shaped areas are composed of the standardized values of each indicator. The calculation method of polygon comprehensive index is the ratio of the area of arrangement and combination to the corresponding area of the central n-side regular polygon. The calculation formula is as follows.

$$S = \sum_{i \neq j}^{i,j} \frac{(S_i + 1)(S_j + 1)}{2N(N-1)}$$

The value range of the comprehensive index is [0, 1]. The larger the composite index, the higher the level of local government competition.

3.2.3 Mediating Variables

This paper selects three indicators of economic agglomeration (EAG) and industrial upgrading (IND) as mediating variables to examine the role mechanism of local government competition in green economic growth. Among them, the total output value of secondary and tertiary industries divided by the area of the regional jurisdiction is used to characterize EAG. According to Pan et al. (2019), the value of tertiary sector output divided by the ratio of secondary sector is employed to estimate the industrial structure upgrading (IND).

3.2.4 Control Variables

Considering the impact of other unobservable factors on green economic growth, this paper mainly employs market (MAR),

TABLE 3 | Variables description.

Variables	Obs	Mean	Std. Dev	Min	Max
GEG	4352	0.985	0.2451	0.135	6.570
JJJZ	4352	−1.852	0.527	−5.125	−0.587
STJZ	4352	−1.590	0.550	−4.659	−0.554
FWJZ	4352	−1.566	0.527	−3.519	−0.386
ZHJZ	4352	−1.003	0.121	−1.307	−0.620
EAG	4352	1.807	1.318	−3.140	5.508
IND	4352	4.399	0.463	2.390	9.010
HUM	4352	4.525	1.109	−0.450	7.180
INF	4352	1.942	1.167	−0.810	23.750
INT	4352	6.720	1.141	−0.500	9.900
NAT	4352	5.668	5.447	−16.640	113
MAR	4352	3.794	0.348	1.600	4.690
FIN	4352	0.816	0.807	−1.010	21.300
PGD	4352	10.337	0.789	4.600	13.130

urbanization (URB), financial development level (FIN), information level (INF), internet development (INT), economic development (PGD), natural population growth rate (NAT), and human capital level (HUM) to control green economic growth. Among them, following Lin and Du (2015), the ratio of private and solopreneur employees to the resident population is used as the quantitative indicator for the marketization of each prefecture-level city. Referring to Pan et al. (2019), the non-agricultural population divided by the total population is employed to calculate urbanization. Referring to Wang J. et al. (2021), the ratio of deposit and loan balance to GDP is used to express the financial development level. Referring to Shen and Du (2018), the informatization level is expressed by regional electricity business volume. Drawing on Wang J. et al. (2021), human capital levels (HUM) are denoted by the number of college students in school, and GDP per capita is chosen to measure economic development (PGD). Following Yang et al. (2021b), the number of Internet users is utilized to measure internet development (INT). The natural population growth rate (NAT) is chosen to examine the extent to which population growth affects green economic growth.

3.3 Data Sources

This paper investigates the panel data of 272 prefecture-level cities from 2004 to 2019. The source data for all variables in this paper are captured from the China City Statistical Yearbook, EPS database, and the National Research Network. Missing values for a few variables were supplemented by interpolation (Yuan et al., 2020). **Table 3** reports the descriptive statistics of the variables.

4 RESULTS AND DISCUSSION

4.1 Benchmark Regression Results

Table 4 reports the direct impact of multi-dimensional local government competition on green economic growth estimated employing the SYS-GMM method [columns (1)–(4) exhibit the estimation results without control variables, while columns (5)–(8) exhibit the estimation results with the inclusion of control variables]. The insignificant value of AR (2) suggests that there is no second-order autocorrelation. Hansen tests confirms that the benchmark regression model does not suffer from an excess of this instrumental variable. To conclude, the result of estimating the impact of local government multi-dimensional competition on green economic growth employing the SYS-GMM method is valid. **Table 4** reveals that the coefficient of $JJJZ$ is negative ($p < 0.05$), implying that economic competition significantly dampens green economic growth. Besides, the coefficients of $STJZ$, $FUJZ$, and $ZHJZ$ ($p < 0.01$) are positive ($p < 0.05$), implying that the multi-dimensional local government competition, ecological competition, service competition, and comprehensive competition significantly contributes to green economic growth. This result is in line with the conclusions reached by Zhang et al. (2021), Hong et al. (2020), and Wu et al. (2020). We may explain the above results for the following reasons.

The focus of the economic competition is to pursue GDP performance. Aiming to enhance economic competitiveness, local governments favor productive expenditures in fiscal spending and make great efforts to attract FDI and increase investment in fixed assets, resulting in the investment of funds for economic competition mainly in productive fields (Zhang et al., 2021). At the same time, to further improve economic catch-up, it is the consistent practice of local governments to reduce taxes and transfer profits (Wu et al., 2021). Through policies such as tax reduction and tax rebates, enterprises are attracted to invest and improve economic performance (Rauscher, 2005). Although economic competition has promoted rapid economic growth, the accompanying negative effects such as environmental pollution and ecological damage have increasingly become a threat to sustainable development (Zhang et al., 2020). The economic competitiveness of local governments has strengthened local protectionism, appeared the behavior of sacrificing long-term development potential in exchange for the growth of short-term economic assessment level, exacerbated the externality of environmental pollution, brought difficulties to regional collaborative governance, and triggered “bottom-by-bottom competition” in the environment and “adverse selection” in the market, to strengthen the path dependence of the regional economy on extensive growth and curb green economic growth (Tang and Qin, 2022).

The ecological competition includes overall greening competition, per capita greening competition, environmental practitioners competition, solid waste treatment competition, and sewage treatment competition. These five indicators measure the green and ecological level of regional development, reflect the green investment ability and environmental regulation level of local governments. Along with the launch of the “Evaluation and Assessment Measures for the Construction of Ecological Civilization” and other relevant policies, the Chinese government has included green development as a crucial assessment indicator for local governments. Under the context of ecological competition, environmental regulation of top-by-top competition and

TABLE 4 | Benchmark regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.GEG	−0.118***	−0.120***	−0.118***	−0.118***	−0.085***	−0.098***	−0.100***	−0.097***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)	(0.002)	(0.002)	(0.002)
JJJZ	−0.002***				−0.004**			
	(0.001)				(0.002)			
STJZ		0.018***				0.035***		
		(0.000)				(0.003)		
FWJZ			0.014***				0.046***	
			(0.001)				(0.003)	
ZHJZ				0.071***				0.227***
				(0.004)				(0.019)
Control variables	NO	NO	NO	NO	YES	YES	YES	YES
Constant	1.099***	1.133***	1.125***	1.174***	0.887***	1.108***	1.209***	1.429***
	(0.001)	(0.001)	(0.001)	(0.004)	(0.031)	(0.031)	(0.027)	(0.071)
AR (2)	−0.51	−0.55	−0.54	−0.54	0.03	−0.26	−0.31	−0.25
	[0.608]	[0.580]	[0.589]	[0.597]	[0.976]	[0.795]	[0.755]	[0.801]
Hansen test	267.87	271.19	269.41	269.20	265.11	263.80	266.98	263.17
	[0.999]	[0.999]	[0.999]	[0.999]	[0.993]	[1.000]	[0.999]	[1.000]
N	272	272	272	272	272	272	272	272

Note: Standard errors in parentheses and p-value *in brackets; ***p < 0.01, **p < 0.05, *p < 0.1.*

governmental environmental governance behaviors which will improve resource use efficiency and reduce pollution emissions will positively reflect on green economic growth (Zhuo and Minjie, 2018; Neves et al., 2020). In addition, the porter effect of environmental regulation (Acemoglu et al., 2012; Peng, 2020) shows that enterprises will improve the level of technological innovation, use the increased income to increase pollution control, and bring the "technological progress effect" of enterprises (Li et al., 2021). Increased government environmental expenditure and environmental personnel as important instruments of environmental governance in China will not only guide the direction of social investment and the environmental behavior of enterprises but also play an essential catalytic role in green economic growth through informal environmental regulations such as public oversight (Langpap and Shimshack, 2010; Ruffing, 2010; Cole et al., 2013).

Service competition includes five dimensions: basic condition competition, medical service competition, commuting competition, income competition, and employment competition. "People's yearning for a better life" is one of the goals of Chinese local governments in the new era (Lin, 2021). In terms of service competition, through the comprehensive promotion of early childhood education, education, labor, medical care, elderly care, housing, and support for the weak, local governments can gain an advantage in this field (Llena-Nozal et al., 2019). Under the guidance of macro policies, regional governments vigorously develop high-tech industries, and local governments gradually transition their development strategy from attracting investment to building nests and attracting Phoenix and implementing the war of robbing people. The competition for talents reflects the important content of service competition (Luna-Arocas and Lara, 2020). The transformation of local governments from production-based to service-based governments will not only strengthen the effective supply of public services but also facilitate human capital and technological innovation, thus promoting green economic growth.

Local government competition is multidimensional, dynamic, and comprehensive. Comprehensive competition promotes green economic growth. During the early phase of economic development, the "competition for growth" model of governance was able to maximize social effects, while as external conditions changed, "competition for ecology" emerged. Such a paradigm shift can give institutional assurance to fulfill the transformation of the economic development model. "The fact that" competition for growth" has contributed to China's rapid economic development has also introduced a gradual deterioration of environmental pollution, which resulted in a shift in competition among local governments to "competition for environmental protection" along with changes in assessment rules (Wang et al., 2021). Under the background of fully implementing the innovation-driven strategy, indicators such as technological innovation performance have been incorporated into the assessment system, while the "competition for innovation" has gradually emerged. To further improve innovation ability, "competition for talents" has become a new phenomenon of local government competition (Zhao et al., 2021b). During the current stage, local governments have switched from high-speed competition to high-quality development competition, and local government competition is becoming more and more diversified and integrated. Under the comprehensive effect of economic competition, ecological competition, and service competition, the comprehensive competition to promote green development and high-quality development will also effectively promote green economic growth.

4.2 Role Mechanism Results and Discussion

Table 4 implies that multi-dimensional local government competition significantly affects green economic growth. To further explore the intrinsic mechanism of multidimensional

TABLE 5 | Role mechanism of economic agglomeration results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	GEG	EAG	GEG	GEG	EAG	GEG	GEG	EAG	GEG	GEG	EAG	GEG
L. GEG/EAG	−0.085***	0.959***	−0.081***	−0.077***	0.966***	−0.081***	−0.085***	0.963***	−0.086***	−0.091***	0.967***	−0.091***
	(0.002)	(0.001)	(0.004)	(0.003)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
EAG			−0.007***			−0.008***			−0.004***			−0.008***
			(0.001)			(0.001)			(0.001)			(0.001)
JJJZ	−0.013***	0.055***	−0.005**									
	(0.002)	(0.002)	(0.002)									
STJZ				0.023***	−0.045***	0.020***						
				(0.002)	(0.003)	(0.003)						
FWJZ							0.066***	−0.085***	0.063***			
							(0.003)	(0.004)	(0.005)			
ZHJZ										0.210***	−0.064***	0.195***
										(0.018)	(0.015)	(0.021)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Constant	1.237***	0.508***	1.191***	1.418***	0.097***	1.335***	1.692***	−0.189***	1.653***	1.711***	0.270***	1.635***
	(0.010)	(0.012)	(0.018)	(0.021)	(0.029)	(0.022)	(0.034)	(0.024)	(0.032)	(0.043)	(0.036)	(0.050)
AR (2)	0.08	−0.11	0.11	0.24	−0.10	0.10	−0.01	−0.10	−0.05	−0.11	−0.10	−0.13
	[0.933]	[0.912]	[0.908]	[0.814]	[0.918]	[0.920]	[0.991]	[0.924]	[0.958]	[0.914]	[0.919]	[0.900]
Hansen test	266.50	267.84	265.02	263.65	266.86	265.27	267.85	266.33	267.57	268.19	269.45	266.67
	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]
N	272	272	272	272	272	272	272	272	272	272	272	272

Note: Standard errors in parentheses and p-value *in brackets;* ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

local government competition on green economic growth, this paper examines its mechanism using SYS-GMM model.

Table 5 reports the estimation results of multi-dimensional local government competition on green economy growth under the economic agglomeration perspective. Among them, columns (1)–(3) of **Table 5** indicate that economic competition can inhibit green economic growth by facilitating economic agglomeration. Columns (4)–(12) of **Table 5** suggest that ecological competition, service competition, and comprehensive competition can promote green economic growth by dampening economic agglomeration. Local governments in pursuit of economic growth have manifested great enthusiasm in investment, taxation, and attracting foreign investment (Zhang et al., 2021). The economic competitiveness of local governments motivated by the economic growth goals is beneficial to economic agglomeration. The direct consequence of economic agglomeration carries with it the expansion of production capacity and the increase of production and consumption, which in turn has a dampening effect on environmental quality (Hong et al., 2020). Ecological competition is more reflected in environmental regulation, and economic agglomeration exists in the scale effect of pollution emissions resulting in increased pollutant emissions is the primary reason for the lower level of green economic growth (Deng et al., 2019). Under the influence of ecological competition, the increase of the environmental level of regulation will heighten the production cost for enterprises, increase the environmental tax burden, and inhibit economic agglomeration. Service competition is more reflected in public infrastructure construction and talent attraction. Service competition provides public infrastructure and talent support for industrial agglomeration, promotes the development of new industries and tertiary industries, and inhibits economic agglomeration (Hong et al., 2020). However, local government competition is prone to local protection, which favors subsidizing mobility factors while increasing essential public services to attract investment, thus economic agglomeration of local protection causes a decrease in resource allocation efficiency (Brakman et al., 2002; Irfan et al., 2021a). Moreover, excessive clustering in the same industry generates congestion effects of agglomeration, contributing to market rigidity and distorted factor allocation. Simultaneously, economic agglomeration usually coexists with pollution agglomeration and the two promote each other, resulting in a realistic situation where economic agglomeration inhibits green economic growth.

Table 6 reports the estimation results of multi-dimensional local government competition on green economy growth under the industrial structural upgrading perspective. Columns (1)–(3) results of **Table 6** reflect that the coefficients of $JJJZ$ and IND are one-negative and one-positive ($p < 0.01$), suggesting that economic competition can significantly inhibit green economic growth through inhibiting industrial structural upgrading. Columns (4)–(12) results of **Table 6** show that the coefficients of $STJZ$, $FWJZ$, and $ZJJZ$ are negative and the coefficient of IND is positive ($p < 0.01$), pointing to the fact that ecological competition, service competition, and comprehensive competition can significantly contribute to green economic growth through facilitating industrial structure upgrading. One potential interpretation is that industrial upgrading requires inputs of key factors of production, while government competition is crucial to influence industrial structural upgrading (Wu, 2015). Although economic competition stimulates industrial structure rationalization, it inhibits industrial structure advancement, which can be complemented by fiscal spending policies that intervene in market mechanisms and industrial structure upgrading (Li and Mao, 2019). In terms

TABLE 6 | Role mechanism of industrial structural upgrading results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	GEG	IND	GEG	GEG	IND	GEG	GEG	IND	GEG	GEG	IND	GEG
L. GEG/IND	−0.085***	0.675***	−0.083***	−0.077***	0.671***	−0.082***	−0.085***	0.673***	−0.087***	−0.091***	0.619***	−0.090***
	(0.002)	(0.142)	(0.002)	(0.003)	(0.139)	(0.003)	(0.002)	(0.142)	(0.002)	(0.002)	(0.145)	(0.001)
IND			0.047***			0.040***			0.039***			0.037***
			(0.002)			(0.002)			(0.002)			(0.002)
JJJZ	−0.013***	−0.029***	−0.023***									
	(0.002)	(0.011)	(0.002)									
STJZ				0.023***	0.035***	0.020***						
				(0.002)	(0.009)	(0.002)						
FWJZ							0.066***	0.054***	0.067***			
							(0.003)	(0.019)	(0.005)			
ZHJZ										0.210***	0.243**	0.126***
										(0.018)	(0.107)	(0.027)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Constant	1.237***	−0.566***	0.983***	1.418***	−0.169	1.217***	1.692***	−0.086	1.515***	1.711***	0.490	1.363***
	(0.010)	(0.118)	(0.016)	(0.021)	(0.110)	(0.026)	(0.034)	(0.139)	(0.037)	(0.043)	(0.313)	(0.061)
AR (2)	0.08	0.64	0.10	0.24	0.73	0.12	-0.01	0.68	−0.05	−0.11	0.69	−0.05
	[0.933]	[0.524]	[0.992]	[0.814]	[0.467]	[0.906]	[0.991]	[0.496]	[0.956]	[0.914]	[0.487]	[0.916]
Hansen test	266.50	269.10	264.81	263.65	267.46	264.26	267.85	267.18	268.96	268.19	267.94	269.40
	[1.000]	[1.000]	[1.000]	[1.000]	[0.999]	[1.000]	[1.000]	[0.988]	[1.000]	[1.000]	[1.000]	[1.000]
N	272	272	272	272	272	272	272	272	272	272	272	272

Note: Standard errors in parentheses and p-value *in brackets;* ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

of service competition, for example, competition in science, education, culture, and health expenditures is beneficial to industrial structure upgrading, while competition in economic construction expenditures hampers industrial structure upgrading. Meanwhile, ecological competition and service competition are mainly reflected in the competition of local governments for ecological environment-related construction and infrastructure construction in public service areas, which provides an excellent business environment for industrial development and thus facilitates industrial upgrading. Under the combined effect of economic competition, ecological competition, and service competition, the comprehensive competition reveals the positive effect of industrial structure upgrading. In addition, according to the law of industrial evolution, the secondary industry gradually evolves into the tertiary industry, the structure within each industry is also constantly optimized and upgraded, and various production factors gradually shift to high value-added industries (Irfan et al., 2021b). During the process, resource-based industries and high-energy-consuming industries will strengthen intensive production efficiency, facilitate energy conservation and emission reduction, as well as push forward environmental management and ecological protection, and thereby stimulate green economic growth.

4.3 Heterogeneity Results and Discussion

4.3.1 Time Heterogeneity Results and Discussion

The year 2012 is an extremely crucial juncture in China's economic development, with the 18th Congress of the Communist Party of China, the change of the President and the introduction of ecological civilization, all of which have had a significant influence on the direction and goals of multi-dimensional local government competition. Therefore, this paper separates the research sample from 2004–2019 into two groups (one for 2004–2011 and the other for 2012–2019) to heterogeneously analyze the impact of multi-dimensional local government competition on green economic growth, using 2012 as the time point (**Table 7**).

Table 7 shows the significant temporal heterogeneity of the effect of multidimensional local government competition on green economic growth, i.e., the effect of multidimensional local government competition on green economic growth diminishes after 2012 compared to before 2012. Judging from the economic competition, China's economic growth rate is progressively shifting from high-speed growth to medium-high growth, and the economic competition pressure on local governments is gradually decreasing, thus reducing the inhibitory effect on green economic growth (Su et al., 2021). Moreover, the Chinese government further advances market-oriented reforms after 2012, which highlight "a greater and broader role of the market in resource allocation," thus the status of the market in resource allocation is enhanced and the economic competition from local governments is relatively reduced, resulting in a relatively lower impact of economic competition on negative green economic growth (Tang and Qin, 2022). Judging from the perspective of ecological competition and service competition, environmental regulation strengthens after 2012, investment in environmental pollution control rises year by year, which contradicts the increase in environmental infrastructure and contributes to the increase in the number of environmental practitioners (Liu et al., 2022). Moreover, local governments' ecological competition intensified in line with the yearly reinforcement of their environmental governance capacity and guided by the eco-performance assessment. Nevertheless, the degree of influence of local governments' ecological competition on green economic

TABLE 7 | Time heterogeneity results.

Variables	Year 2004–2011				Year 2012–2019			
L.GEG	−0.113***	−0.109***	−0.125***	−0.116***	−0.226***	−0.068***	−0.067***	−0.067***
	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
JJJZ	−0.012***				-0.005**			
	(0.002)				(0.003)			
STJZ		0.005*				0.048***		
		(0.003)				(0.006)		
FWJZ			0.116***				0.016***	
			(0.005)				(0.006)	
ZHJZ				0.280***				0.172***
				(0.025)				(0.021)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.078***	1.068***	1.851***	1.735***	0.902***	1.033***	0.871***	1.158***
	(0.041)	(0.041)	(0.052)	(0.058)	(0.039)	(0.063)	(0.057)	(0.057)
AR(2)	−0.38	−0.31	−0.60	−0.45	−1.48	0.51	0.56	0.57
	[0.702]	[0.756]	[0.548]	[0.656]	[0.139]	[0.614]	[0.576]	[0.569]
Hansen test	262.29	261.27	257.71	259.77	266.62	264.20	265.75	266.61
	[0.993]	[0.975]	[0.983]	[0.979]	[0.997]	[0.994]	[0.992]	[0.991]
N	272	272	272	272	272	272	272	272

Note: Standard errors in parentheses and p-value *in brackets;****p < 0.01, ***p < 0.05, **p < 0.1.*

growth decreases after 2012 in the context of increasing environmental pollution emissions and slowing GDP growth. Judging from the service competition, local governments step up the construction of public service infrastructure to elevate their human capital level and continuously improve its livability and basic education capacity. However, a demographic dividend gradually vanished after 2012, the competition for talent among local governments intensified, the operating costs of enterprises gradually escalated, while the service competition among local governments exhibited a decreasing degree of impact on green economic growth. Eventually, the comprehensive competition of local governments also characterizes a decrease in the degree of influence on green economic growth.

4.3.2 Regional Heterogeneity Results and Discussion

Chinese mainland lies high in the western part of the land and low in the eastern part, with a stepped distribution of high mountains and plateaus in the western part and hills and plains on the eastern coast, and a stepped slope descending from west to east, thus resulting in an unbalanced development of each region and significant regional differences (Zeng et al., 2020). Therefore, referring to Wang (2020), this paper divides the research samples into three parts: the eastern, the central, and the western for regional heterogeneity analysis (**Tables 8**, **9**). **Table 8** reports the regional heterogeneity results of economic competition and ecological competition, suggesting that the impact of economic competition on green economic growth demonstrates the strongest feature of central (insignificant), followed by western and the weakest eastern, and the degree of impact of ecological competition on green economic growth exhibits the strongest in the eastern, followed by the western, and the weakest in the central (insignificant). **Table 9** reports the regional heterogeneity results of service competition and comprehensive competition, which demonstrates that the influence of both service competition and comprehensive competition on the green economic growth presents the strongest degree in the eastern region, followed by the western region, and the weakest in the central region (insignificant).

The remarkably different regional natural conditions and economic bases in China, provide a potential explanatory foundation for the regional heterogeneity effect of multidimensional local government competition. Judging from the characteristics of physical geographic distribution and natural conditions, the natural conditions of China gradually deteriorate from eastern to western, precipitation decreases, and its weak ecological and environmental endowment determines that the economic and social development of the western region lags behind that of the eastern and central regions (Zhang et al., 2021; Tang and Qin, 2022). In addition, judging from the economic foundations, the eastern region owns better basic conditions for economic development. Taking the Aihui-Tengchong Line as the boundary, the eastern and central regions are mainly located east of the Aihui-Tengchong Line, which is densely populated and provides sufficient labor for economic development while the western region is mainly located west of the Aihui-Tengchong Line and has a relatively small population. Meanwhile, the capital stock in the eastern region is higher than that in the central and western regions, and the investment reveals a decreasing trend from eastern to western, which supplies a differential capital foundation for economic development. As such, the economic development degree is strongest in the eastern region, followed by the central region, and weakest in the western region, and conversely, the impact of local government competition on green economic growth shows the characteristics strongest in the central region, followed by the western region, and weakest in the eastern region (Jiang et al., 2022). Judging from the ecological competition, the fragile ecological environment has higher requirements for environmental regulation, while the

TABLE 8 | Regional heterogeneity results under economic and ecological competition.

Variables	(1) Eastern	(2) Eastern	(3) Central	(4) Central	(5) Western	(6) Western
L.GEG	−0.049*	−0.078***	−0.149***	−0.149***	−0.054	−0.070*
	(0.026)	(0.011)	(0.012)	(0.010)	(0.034)	(0.040)
JJJZ	−0.037***		0.014*		−0.028*	
	(0.007)		(0.008)		(0.016)	
STJZ		0.066***		−0.005		0.036*
		(0.010)		(0.012)		(0.021)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.788***	1.306***	0.193**	0.012	1.179***	1.587***
	(0.092)	(0.091)	(0.081)	(0.068)	(0.119)	(0.203)
AR(1)	−2.26	−2.33	−5.48	−5.41	−5.49	−5.00
	[0.024]	[0.020]	[0.000]	[0.000]	[0.000]	[0.000]
Hansen test	89.21	89.22	92.04	94.16	70.57	68.14
	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]
N	98	98	98	98	76	76

*Note: Standard errors in parentheses and p-value in brackets; ***p < 0.01, **p < 0.05, *p < 0.1.*

TABLE 9 | Regional heterogeneity results under service competition and comprehensive competition.

Variables	(1) East	(2) East	(3) MID	(4) MID	(5) West	(6) West
L.GEG	−0.062***	−0.089***	−0.153***	−0.146***	−0.092***	−0.071***
	(0.018)	(0.009)	(0.012)	(0.012)	(0.030)	(0.021)
FWJZ	0.088***		0.021		0.073***	
	(0.013)		(0.016)		(0.024)	
ZHJZ		0.363***		0.073		0.215**
		(0.040)		(0.055)		(0.094)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.299***	1.677***	0.271*	0.305**	1.782***	1.760***
	(0.139)	(0.092)	(0.159)	(0.152)	(0.164)	(0.244)
AR(2)	−1.18	−1.61	0.63	0.73	−1.56	−1.35
	[0.237]	[0.108]	[0.528]	[0.463]	[0.120]	[0.177]
Hansen test	88.15	90.22	94.96	92.51	60.59	70.72
	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]	[1.000]
N	98	98	98	98	76	76

*Note: Standard errors in parentheses and p-value in brackets; ***p < 0.01, **p < 0.05, *p < 0.1.*

western region has relatively lagging economic development and relatively less environmental management investment (Wu et al., 2020). Under this background, local governments, as suppliers of public goods, are bound to strengthen their influence on the ecological environment, ultimately producing the result that the degree of influence of ecological competition on green economic growth is higher in the eastern region than in the western region, and higher in the western region than in the central region.

Judging from the service competition, talents as the source of innovation have been the key resources for economic and social development. The eastern region had more advanced facilities in both basic education and higher education than the central and western regions, while the western region lacked talents and educational resources. To further elevate the human capital level, local governments undertake considerable efforts, which eventually yield the result that service competition has the strongest influence on green economic growth in the eastern region, followed by the western region and the weakest in the central region (Hong et al., 2020). Ultimately, the comprehensive competition for green economic growth is characterized as the strongest in the eastern region, followed by the western region, and the weakest in the central region under the comprehensive effect of economic competition, ecological competition, and service competition.

4.4 Robustness Checks

To confirm whether the above findings are reliable, methods such as replacing the explanatory variables and excluding special years are applied to perform robustness checks on the effect of local government competition on green economic growth.

4.4.1 Replace the Explained Variable Results and Discussion

Following Su et al. (2021), this paper re-measures green economic growth using the DDF-GML model and then re-validates the effect of local government competition on green economic growth (**Table 10**). Columns (1)–(4) of **Table 10** suggest that

TABLE 10 | Robustness tests for replacing the explanatory variables.

Variables	(1)	(2)	(3)	(4)
L.GEG	−0.056***	−0.073***	−0.068***	−0.077***
	(0.006)	(0.008)	(0.006)	(0.006)
JJJZ	−0.003***			
	(0.001)			
STJZ		0.016***		
		(0.001)		
FWJZ			0.027***	
			(0.003)	
ZHJZ				0.079***
				(0.009)
Control variables	Yes	Yes	Yes	Yes
Constant	1.071***	1.171***	1.269***	1.264***
	(0.012)	(0.021)	(0.020)	(0.023)
AR (2)	0.36	0.00	0.10	−0.10
	[0.717]	[0.997]	[0.921]	[0.100]
Hansen test	265.25	265.46	264.47	267.37
	[0.993]	[1.000]	[1.000]	[0.999]
N	272	272	272	272

Note: Standard errors in parentheses and p-value *in brackets; ****p *< 0.01,* **p *< 0.05,* *p *< 0.1.*

TABLE 11 | Remove special year's result.

Variables	(1)	(2)	(3)	(4)
L.GEG	−0.089***	−0.089***	−0.093***	−0.088***
	(0.003)	(0.003)	(0.002)	(0.004)
JJJZ	−0.016***			
	(0.004)			
STJZ		0.030***		
		(0.003)		
FWJZ			0.049***	
			(0.004)	
ZHJZ				0.216***
				(0.016)
Control variables	Yes	Yes	Yes	Yes
Constant	0.857***	1.139***	1.234***	1.379***
	(0.030)	(0.047)	(0.048)	(0.057)
AR (2)	0.15	0.14	0.03	0.08
	[0.785]	[0.757]	[0.683]	[0.757]
Hansen test	266.7	267.47	268	261.66
	[1.000]	[0.999]	[0.999]	[0.999]
Ob	3,791	3,791	3,791	3,791
N	272	272	272	272

Note: Standard errors in parentheses and p-value *in brackets; ****p *< 0.01,* **p *< 0.05,* *p *< 0.1.*

economic competition still significantly $(p < 0.01)$ inhibits green economic growth, while the ecological competition, service competition, and comprehensive competition significantly $(p < 0.01)$ contribute to green economic growth.

4.4.2 Remove Special Years Results and Discussion

Because of the global recession induced by the US subprime mortgage crisis in 2008, FDI and international trade in many parts of China were severely affected, the competition forms of local governments in China in terms of preserving employment, economic growth and safeguarding people's livelihood as well as environmental management were also severely impacted (Chor and Manova, 2012). Following Li et al. (2021), robustness checks on the effect of local government competition on green economic growth are carried out by excluding the special year 2008. The test results are shown in **Table 11**. After excluding special years, economic competition still presents a significantly dampening effect on green economic growth, while it is significantly stimulated by ecological competition, service competition and integrated competition.

5 CONCLUSION AND POLICY IMPLICATIONS

This paper employs the EBM-GML model to calculate the green economic growth and then investigates the impact of multidimensional local government competition (ecological competition, service competition, economic competition, and comprehensive competition) on green economic growth in terms of economic agglomeration and industrial structure upgrading, and technological innovation using SYS–GMM and mediating effect models on the basis of 272 prefecture-level cities in China from 2004 to 2019. The main research conclusions are: First, the green economic growth of China's prefecture-level cities shows an upward trend. Second, multi-dimensional local government competition has a significant impact on green economic growth, in which economic competition significantly inhibits green economic growth, while ecological competition, service competition, and comprehensive competition significantly contribute to green economic growth. Third, the role mechanism shows that economic competition, ecological competition, service competition, and comprehensive competition significantly affect green economic growth from the perspective of economic agglomeration and industrial upgrading. Finally, temporal and regional heterogeneity reports that the ability of multi-dimensional local government competition to influence green economic growth diminishes after 2012. The impact of economic competition on green economic growth shows a significant characteristic of heterogeneity (central > western > eastern), while the impact of ecological competition, service competition, and comprehensive competition on green economic growth show the characteristics of the eastern > western > central. Based on the above findings, some necessary policy implications should be provided.

(1) The effect of multidimensional local government competition on green economic growth shows that effective and multidimensional local government competition is beneficial to green economic growth. Therefore, policymakers should continue to moderate local government competition, reasonably construct a multidimensional local government competition goal system and improve the ecological goal and service goal level of local governments.
(2) Policymakers should optimize the competition system of local governments, weaken economic competition and enhance ecological and service competition under the goal of green economic growth. For example, policymakers

should strengthen the quality of services, create a livable environment, and increase the rational allocation of talents and other resources. Moreover, policymakers should develop economic growth targets according to local conditions and facilitate the harmonization of economic growth and environmental governance.

(3) To eliminate conflicts between local interests and regional common interests, policymakers must establish cross-administrative organizational coordination bodies and strengthen local government cooperation to further enhance inter-regional environmental governance. Furthermore, policymakers should develop regional competition programs specifically based on local realities. From regional characteristics, industrial competitiveness should be improved, industrial upgrading should be increased, environmental regulation should be improved, and service competitiveness should be enhanced.

Although this paper provides an analysis of the impact of multidimensional local government competition (ecological competition, service competition, economic competition, and comprehensive competition) on green economic growth in terms of economic agglomeration, industrial upgrading, and technological innovation, some crucial factors that need to be considered urgently in the future are still ignored. For example, some studies confirm the existence of spatial spillover characteristics of green economic growth, so future researchers can use spatial econometric models to perform an extended analysis of the impact of local government competition on green economic growth (Lei et al., 2021). Moreover, local government competition is also likely to influence green economic growth through, foreign direct investment, and resource misallocation. Therefore, scholars can evaluate the perspective of local government competition affecting green economic growth from several perspectives.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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An Empirical Study on the Impact of Energy Poverty on Carbon Intensity of the Construction Industry: Moderating Role of Technological Innovation

Jianhua Zhang[1], Yushan Liu[1], Najia Saqib[2] and Hafiz Waqas Kamran[3]*

[1]School of Economics and Management, Northeast Petroleum University, Daqing, China, [2]Department of Finance, College of Business Administration, Prince Sultan University, Riyadh, Saudi Arabia, [3]Department of Business Adminstration, Iqra University, Karachi, Pakistan

As a national pillar industry, the carbon emissions generated by the construction industry have received significant attention. As a large developing country, China has unbalanced regional development and imperfect modern energy infrastructure in some regions, leading to a prominent problem of energy poverty in China. Therefore, this study constructs the index system of energy poverty using panel data of 30 provinces and cities from 2004 to 2016. This article analyzes the influence of energy poverty on carbon intensity of the construction industry and constructs the influence model of carbon intensity of the construction industry. The results show that 1) the carbon intensity of the construction industry increases by 1.683 units per unit increase of energy poverty, showing a positive impact. 2) Energy consumption structure has a mediating effect on the impact of energy poverty on carbon intensity of the construction industry. 3) The technological level plays a moderating role in the main effect of energy poverty and carbon intensity in the construction industry; the degree of marketization plays a moderating role in the indirect effect of energy consumption structure and carbon intensity of the construction industry. These results offered valuable policy recommendations for sustainable industrial growth.

Keywords: carbon intensity, energy poverty, energy structure, technical level, marketization degree

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****Correspondence:***
Yushan Liu
13946210301@163.com

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1 INTRODUCTION

As the world's second largest economy and largest energy consumer, China is the world's largest carbon emitter. At the seventy-fifth Session of the United Nations General Assembly in 2020, it was proposed to enhance the "nationally determined contribution" and strive to reach the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. China is still in a medium-high speed of economic development, and the pace of industrialization cannot be slowed down. Weighing economic development and carbon emissions is worth thinking about. As the largest developing country in the world, China has a large population, uneven resources, and economic development among regions, leading to energy poverty as some people cannot fairly obtain and safely consume adequate, affordable, high-quality, environmentally friendly, and potential energy. Regional energy poverty will lead people to prefer cheaper but environmentally unfriendly energy production activities such as firewood and coal when making energy consumption choices. In the long run, air pollutants such as smog, dust, and inhalable particles will increase, and the environmental

carrying capacity will reach the red line. In addition, the excessive use of non-clean energy will also lead to the rise of greenhouse gas emissions, such as climate change caused by excessive carbon dioxide emissions. According to the fifth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2013), the national average surface temperature has increased by 0.89°C (IPCC, 2013). Climate change is closely related to energy consumption. Acaroğlu (2022) explored the causal relationship between climate change, economic growth, and energy consumption in Turkey and found that the use of renewable energy can help reduce temperature (Acaroğlu and Güllü, 2022). The global spread of COVID-19 also affects the relationship between carbon dioxide and energy consumption. Adebayo (2022) takes the United Kingdom as the background to explore the impact of renewable energy, non-renewable energy, and COVID-19 on carbon dioxide emissions and finds that the positive transformation of the development of renewable energy reduces CO_2 emissions, and the positive impact of fossil fuel energy has increased CO_2 emissions (Adebayo et al., 2022). Global warming has become a serious environmental problem so far. Countries around the world have reached a consensus on "curbing temperature rise and reducing carbon emissions" and taken effective measures. The United Nations Framework Convention on Climate Change (UNFCCC), adopted by the Intergovernmental Negotiating Committee of the United Nations in 1992, became the first international convention for international cooperation to deal with the control of greenhouse gases such as carbon dioxide and global warming. The UNEP study concludes that the building sector accounts for a similar proportion of total energy consumption to carbon emissions. Therefore, the study of carbon emissions is closely related to energy consumption and emissions in the construction industry.

With the advancement of urbanization in China, the consumption of building materials and new floor space in China has become the first in the world. The construction industry accounts for about 35–50% of total emissions (Zhou et al., 2018). In recent years, with the strong support of the government and the promotion of low-carbon economic development, energy conservation, and emission reduction work, the construction industry has made good progress, and the carbon emission intensity of the construction industry has been declining year-by-year. On 22 April 2020, the World Meteorological Organization (WMO) said that the reduction in global carbon dioxide emissions this year due to the pandemic will be the largest annual decrease since World War II, but this is not enough to curb global warming, and the building sector still has great potential for energy conservation and emission reduction. China's vast territory and uneven distribution of abundant energy reserves have led to irrational energy consumption structure in some regions, resulting in huge waste and resulting in energy poverty. What is the impact of energy poverty on energy consumption and carbon emissions of local construction industries? What are the effects of marketization and technological level? Based on this, this article uses the panel data regression model to analyze the mechanism of energy poverty, carbon emissions of the construction industry, and energy consumption structure in 30 provinces and cities (autonomous regions and municipalities directly under the Central Government) from 2004 to 2016 and discusses the mechanism and relationship of energy consumption structure, marketization degree, and technological level. The evolution mechanism of carbon emissions in the construction industry is deeply analyzed in order to provide practical reference suggestions for the future energy conservation and emission reduction and sustainable development of the country and region.

Existing studies focus on the relationship between carbon emissions and climate change, energy relationship and climate change, but there are few studies on the logical relationship between energy poverty and carbon intensity and their impact paths. Compared with the existing articles, the contribution of this article is as follows: 1) based on the existing research, we measured and calculated the energy poverty at provincial level in China, and found that the energy poverty will increase the carbon intensity of the construction industry. 2) This article will start with the logical relationship between energy poverty, energy consumption structure, and carbon emissions, and elaborate the path of energy consumption structure that energy poverty affects the carbon intensity of the construction industry. This article theoretically explores the influence path of energy relationship and carbon emission, strengthens the logical chain of energy relationship, carbon emission and climate change, and provides new ideas for regional governments to formulate energy conservation and emission reduction policies.

The structure of the article is as follows: 1) to sort out the research on energy poverty and carbon emissions by domestic and foreign scholars and determine the theoretical basis of the research. 2) Calculate the energy poverty index of 30 provinces and cities in China and build the influence model of carbon intensity of the construction industry to analyze the impact of energy poverty on carbon emissions of the construction industry. 3) Test the empirical results to ensure the accuracy of the results. 4) Conclusion and revelation.

2 LITERATURE REVIEW AND RESEARCH HYPOTHESIS

2.1 Literature Review

Energy has brought convenience to human production and life. However, the traditional energy development model also brings energy exhaustion, climate change, and other problems. Therefore, most scholars at home and abroad have carried out relevant studies on energy poverty, mainly focusing on the definition, measurement, and influencing factors of energy poverty. Martina (2019) created a Structural Energy Poverty Vulnerability Index (SEPV) and explored the association between SEPV and EP morbidity, as well as excess winter mortality. Finally, the energy poverty vulnerability index was established by principal component analysis, and the correlation between the index and excess winter mortality was analyzed. The results found that the most vulnerable countries showed statistically higher rates of energy poverty and excess risk of winter mortality (Recalde et al., 2019). Raúl (2020) found that

many people in Southern European countries live in cold and inefficient environments, unable to meet their energy needs for comfort and warmth, and are therefore at risk of cold-related diseases (Castaño -Rosa et al., 2020). Abidah (2020) found that the deployment of renewable energy in many remote areas could provide opportunities for significant and rare complementarities between energy security, energy access, and climate change mitigation (Setyowati, 2020). In order to assess the impact of the economic crisis on energy poverty in Europe, Halkos (2021) uses consensus methods and comprehensive measures to calculate energy poverty and identifies the price of electricity as the main driver of energy poverty (Halkos and Gkampoura, 2021). According to the current situation of China's rural energy poverty, Zhao (2018) constructed an index system of China's rural energy poverty, used Theil index and spatial autocorrelation analysis to describe the spatial-temporal evolution characteristics of China's rural energy poverty, and analyzed the influencing factors (Zhao et al., 2018). There are significant differences not only between urban and rural areas but also between regions in energy poverty. Cai (2021) studied the spatio-temporal evolution pattern and influencing factors of energy poverty in 30 provinces of China and found that energy poverty improved significantly during the research period, with huge differences among provinces. Energy poverty was the most serious in the western region, followed by the central region. Energy poverty has significant spatial correlation characteristics, and the spatial development pattern shows a trend of rising first and then falling (Cai et al., 2021). In this study, the definition of energy poverty in China is based on the concept of Nussbaumer (2012) and Li et al. (2014): energy poverty is defined as the difficulty in equitable access and safe consumption of adequate, affordable, high-quality energy with development potential (Nussbaumer et al., 2012; Li et al., 2014).

The international community has been struggling to reach a consensus on tackling global warming and reducing carbon emissions. At present, studies on carbon emissions at home and abroad focus on the influencing factors of carbon emissions and the relationship between carbon emissions and climate change. Research on the influencing factors of carbon emissions focuses on energy intensity (Greening et al., 1998; Tang et al., 2021), energy structure (Li et al., 2022;2021), per capita GDP (Hatzigeorgiou et al., 2011; Işık, 2013; Azam et al., 2021), and green tech innovation (Razzaq et al., 2021; Sun and Razzaq, 2022; Sun et al., 2022a). Işık (2017) examined the dynamic causal relationship between economic growth, financial development, international trade, tourism expenditure, and carbon dioxide emissions in Greece from 1970 to 2014 and found that tourism as the leading sector of the Greek economy has a serious negative impact on the Greek environment (Işik et al., 2017). Alisa (2020) analyzed the feasibility of using carbon tax revenue to finance energy efficiency and renewable energy projects based on the case of Switzerland. The study showed that such policy could not only reduce carbon emissions but also help reduce the cost of home heating (Freyre et al., 2020). Rehman (2021) explored the interaction between carbon dioxide emissions and industrialization, energy imports, carbon intensity, economic development, and total capital by using data from 1971 to 2019 in Pakistan (Rehman et al., 2021). Nguyen (2021) made use of the data from 1978 to 2014 of the group of six countries and found that there was insufficient evidence for the environmental Kuznets curve, while economic growth, capital market expansion, and trade opening were the main drivers of carbon emissions (Nguyen et al., 2021). Solomon (2009) believes that climate change due to increased Co_2 concentration is basically irreversible within 1,000 years after cessation of emissions; After emissions stop, the removal of carbon dioxide from the atmosphere reduces radiative forcing, but is largely compensated for by a slow loss of heat to the ocean, so atmospheric temperatures will not drop significantly for at least 1,000 years (Solomon et al., 2009). Since then, the relationship between carbon emissions and climate change has also become the focus of research, and it is found that energy poverty will also affect climate change through carbon emissions. Ürge-Vorsatz (2012) suggested that alleviating energy poverty and slowing down climate change are difficult goals, or both can be coordinated, if the internalization of external costs for carbon emissions cannot be offset by efficiency gains, so a strong action on climate change could lead to higher energy poverty levels, the most significant synergies deep found in building energy efficiency (Ürge-Vorsatz and Tirado Herrero, 2012). Shoibal (2013) found that policies to eliminate energy poverty would increase global end-use energy consumption by 7%, while generating a large amount of carbon emissions, and the additional energy facilities needed to eliminate energy poverty would increase global temperature by 0.13°C at most (Chakravarty and Tavoni, 2013). Hassan (2022) estimated the impact of energy poverty, education, income inequality, and globalization on carbon emissions in BRICS countries from 1989 to 2016, looking at carbon emissions and climate change from the relationship between energy security and energy poverty (Hassan et al., 2022). Wang (2014) discussed the impact of climate change by sorting out policies related to energy poverty. It found that improving household energy efficiency and promoting the development and utilization of renewable energy or other energy policies could help alleviate energy poverty and reduce carbon emissions (Wang et al., 2014). Liu (2022) analyzed the effect of an individual carbon trading mechanism on improving energy poverty by constructing an individual carbon trading model and using the latest public data of China's household energy consumption survey, and designed the core parameters of the individual carbon trading mechanism such as quota and price (Liu et al., 2022). The research on energy poverty and carbon intensity of the construction industry, which is directly related to the core issue of this article, needs to be further studied. At present, the research on energy poverty and carbon emissions focuses on the causal relationship between renewable energy and non-renewable energy, climate change, and carbon emissions (Sun et al., 2022b). Işik (2019) examined the environmental Kuznet curve hypothesis for the ten states with the highest carbon dioxide emissions in the United States, using independent variables such as real GDP, population, and renewable and fossil energy consumption (Işik et al., 2019). Montoya (2021) found that renewable and non-renewable energy in Brazil would have an impact on global

climate change through international trade (Montoya et al., 2021). Gernaat (2021) uses climate and integrated assessment models to estimate the impact of climate change on key renewable energy sources, with the availability of bioenergy increasing under the baseline warming scenario (Gernaat et al., 2021). Therefore, in order to clarify the energy relationship and the impact path of climate change, this article explores the relationship between potential energy poverty and carbon emissions, so as to make the path and relationship of energy, carbon emission, and climate change clearer.

2.2 Research Hypothesis

2.2.1 Impact of Energy Poverty on Carbon Intensity of the Construction Industry

With the rapid development of China's economy, while rapidly promoting urbanization and increasing infrastructure construction, China also faces the problem of increasing carbon emissions from the construction industry caused by excessive energy consumption and low efficiency of energy use. Ürge-Vorsatz (2012) found that improving building energy efficiency could reduce carbon emissions while alleviating energy poverty (Ürge-Vorsatz and Tirado Herrero, 2012). Energy poverty is a unique form of poverty. The unbalanced economic development between provinces in China, on the one hand, shows that people in some areas of China cannot afford the living energy, which makes people prefer to use traditional biomass coal, which directly leads to the increase of carbon emissions. On the other hand, inadequate access to electricity is manifested, which is more serious in developing countries. The lack of electricity service means the lack of access to clean energy, which leads to the characteristics of high carbonization and non-clean energy consumption of residents. By constructing an energy poverty index and comparing the energy poverty in China and Germany, Bonatz (2018) found that the development of China's low-carbon strategy can improve energy efficiency and alleviate energy poverty. At this time, we will find that energy poverty and carbon emissions will affect each other, and most low-carbon development policies are consistent with energy poverty policies, which will reduce carbon emissions while alleviating energy poverty (Bonatz et al., 2019). McGee (2019) finds through research that renewable energy can alleviate energy poverty to a certain extent and has significant energy saving and emission reduction effects. But further study found that the correlation between renewable energy consumption and carbon emissions fell sharply as the income share of the top 20 percent of earners grew (McGee and Greiner, 2019). Therefore, the research hypothesis is proposed.

H1: Energy poverty increases construction intensity.

2.2.2 Mediating Effect of Energy Consumption Structure

The energy consumption structure is the ratio of individual energy consumption to the total energy consumption. From the perspective of energy consumption structure, traditional biomass energy and electricity are two main types of energy consumption. With the national emphasis on energy conservation and emission reduction and the implementation of relevant policies, Hao and Yin (2014) found that during the decade from 1998 to 2007, the proportion of traditional biomass energy in residential energy consumption continued to decline, while the proportion of electricity consumption kept rising, effectively alleviating the energy poverty in China (Hao et al., 2014). But some parts of China suffer from severe energy poverty due to its vast territory. Chen (2019) made an empirical analysis of the dynamic cross-sectional data of 30 provinces in China and found that technological innovation, economic growth, and energy consumption structure would have a significant positive effect on the increment of carbon emissions (Chen, 2019). Xu (2020) made scenario prediction of carbon peak and found that carbon emissions would not reach the peak under normal circumstances, but after reasonable planning of energy structure, carbon emissions would reach the peak in 2030, and under low-carbon energy structure, it would reach the peak in 2025 (Xu et al., 2020). Zhao (2021) reestimated the impact of energy poverty on CO_2 emissions by using the systematic generalized moment method, and found that there is a two-way causal relationship between energy poverty and CO_2 emissions in regions with high energy poverty in China, while there is a one-way causal relationship between energy poverty and CO_2 emissions in regions with low energy poverty (Zhao et al., 2021). Therefore, it is speculated that energy consumption structure also has a certain influence mechanism on energy poverty and carbon emissions of the construction industry, and the hypothesis is proposed as follows:

H2: Energy consumption structure has a mediating effect on the impact of energy poverty on carbon intensity of the construction industry.

2.2.3 The Moderating Effect of Marketization Degree and Technological Level

Technological progress will bring about the improvement of labor productivity, making the production of products of the same value consume fewer resources, and reduce carbon emissions from the perspective of reducing energy consumption. Wei (2010) analyzed the influencing factors of China's interprovincial carbon emissions from 1997 to 2007 and proposed that technological progress played a significant role in promoting China's carbon emissions, showing obvious regional differences (Wei and Yang, 2010). Li (2019) uses the IPCC calculation method to calculate China's carbon emissions, and the STIRPAT model to analyze the impact of factors such as total population, technological level, and industrial structure on carbon emissions, and finds that improving the technological level can effectively control carbon emissions (Li et al., 2019). Li (2020) constructed the super-era total factor carbon emission performance index of the construction industry in 30 provinces, and concluded that the growth of NMTCPI was mainly caused by technological progress, but the regional technological gap gradually widened after 2011 (Li et al., 2020a). Zhao (2022) investigated the mediating effect of technological innovation on the relationship between energy poverty and green growth,

and found that eliminating energy poverty and increasing technological innovation can effectively promote national green growth, and the interaction between energy poverty and technological innovation has a positive impact on green growth (Zhao et al., 2022). Technological innovation plays an important role in the process of energy saving and emission reduction and promoting green growth.

H3a: The technology level plays a moderating role in the relationship between energy poverty and carbon intensity of the construction industry.

Marketization degree refers to the sensitivity of the market to the changes of supply and demand. According to the relevant theories of Western economics, the higher the marketization degree of enterprises, the more efficient the allocation of market resources. At the same time, relevant literature has also studied the influence of marketization degree on carbon emission of the construction industry. Hu (2015) found that the increase of marketization degree would have a negative impact on carbon emissions, and found that in areas with high marketization degree, the marketization degree had a more obvious impact on carbon emissions. However, in places with low degree of marketization, the impact of marketization on carbon emissions was not obvious (Hu and Wang, 2015). For a long time, in China's construction industry, compared with other industries, the degree of marketization has been low. However, since the establishment of the market economy system in 1992, the rapid development of the market economy has made the resource allocation of the construction industry optimized. Therefore, the improvement of marketization degree will accelerate the optimization of energy consumption structure and reduce the carbon emission of the construction industry. Hence the hypothesis is proposed.

H3b: The marketization degree plays a moderating role in the relationship between energy consumption structure and carbon intensity of the construction industry.

3 DATA SOURCES, VARIABLE DESCRIPTION, AND MODEL ESTABLISHMENT

3.1 Data Sources

Limited by the availability of data, annual data of 30 Chinese provinces from 2004 to 2016 were selected. The carbon emission data and energy consumption of the construction industry are from the China Carbon Emission database. The total output value of the construction industry from the Statistical Yearbook of the construction industry. The original data of energy consumption structure came from the energy balance sheet of the China Carbon Emission database. The degree of marketization data comes from the marketization composite index in The Report of Marketization Indexes by Provinces in China. R&D expenditure comes from the official website of the National Bureau of Statistics, Statistical Bulletin and China Statistical Yearbook. The total population and GNP come from China Statistical Yearbook, and the GDP of the construction industry comes from the Statistical Yearbook of China Construction Industry.

3.2 Variable Description

1) Dependent variable: The dependent variable in this article is carbon intensity (CI) of the construction industry. In this article, the carbon emission intensity of the construction industry is expressed by the ratio of carbon emission to the total output value of the construction industry (Feng et al., 2017).
2) Independent variable: Energy poverty (EP) based on the Multidimensional Energy Poverty Index and the energy poverty assessment system is constructed by Li et al. (2014); this article builds China's regional energy poverty system from two aspects of energy access and energy service. Energy access refers to the provision of modern energy services, such as electricity, to all people. Modern energy services specifically refer to access to electricity and clean kitchen appliances in homes. For regional energy poverty, urban and rural areas should be considered at the same time, so indicators representing urban and rural areas are selected in terms of energy access and energy services.

The aforementioned indicators are standardized, and the calculation formula is as follows:

$$y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}. \quad (1)$$

In **Eq. 1**, y_{ij} is the standardized value of item j of province i; x_{ij} is the actual value of the j item in province i. Through standardization, each index can be expressed as a value between 0 and 1. A simple arithmetic average method was used to calculate the energy poverty index of different provinces. The basic formula is as follows:

$$EP_{ij} = \sum_{j=1}^{J} y_{ij} \times w_{ij}. \quad (2)$$

In **Eq. 2**, EP_{ij} is the energy poverty index of item j in province i. y_{ij} is the standardized value of the j item in province i; Take 0.125 as w_{ij}. The higher the energy poverty index, the more serious the energy poverty in the region.

3) Intermediate variable: Energy consumption structure (ES). In the research of energy consumption structure in recent years, most scholars use the proportion of electricity consumption in total energy consumption or coal consumption in total energy consumption to express energy consumption structure (Gao et al., 2020; Wang, 2020; Zhang et al., 2021). Since carbon emissions are studied in this article, all the energies in the energy consumption structure will be considered comprehensively. Therefore, all energies are multiplied by correlation coefficients and converted into standard coal for subsequent research.
4) Moderating variables: Technical level (Tec) and marketization degree (Mar). Nowadays, it is not enough to control carbon emissions only by optimizing the energy structure and

TABLE 1 | Variable definition table.

Variable	Abbreviation	Description
Carbon intensity in the construction industry	CI	Construction industry carbon intensity = construction industry carbon emissions/total output value of the construction industry
Energy poverty	EP	$EP_{ij} = \sum_{j=1}^{J} y_{ij} \times w_{ij}$
Energy consumption structure	ES	Energy consumption structure = (raw coal *0.7143 + washed coal *0.9 + other washed coal *0.2857 + bridle coal *0.6 + coke *0.9714 + coke oven gas *6.143 + Other gas *3.5701)/total energy consumption
Technological level	Tec	R&D expenditure input intensity = R&D expenditure/GNP
Marketization degree	Mar	Fan Gang marketization index
Population density	TP	Population density = LN (total population)
Industrial structure	IS	Industrial structure = LN (total output value of construction/GROSS national product)
Energy intensity	EI	Energy intensity = LN (total energy consumption in the construction industry/GROSS national product)

Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China.

optimizing the allocation of market resources. Technology will also play a certain role. Through the introduction of advanced processes to improve the energy efficiency of equipment and reduce pollution emissions, carbon emissions can be directly reduced. This article adopts R&D/GDP (Li et al., 2020b). The index of marketization degree can be expressed by the ratio of the total output value of non-state–owned construction enterprises and the total output value of the construction industry in the region (Zhang et al., 2019). You can also use Fan Gang et al.'s China Marketization Index: Report on the Relative Progress of Marketization in Different Regions in 2009 (Fan et al., 2010). Considering the authority and universality of application, this article chooses the latter.

5) Control variables: Total population, energy intensity, and industrial structure. In order to exclude the influence of other influencing factors on carbon emissions of the construction industry, this study controls the total population, energy intensity, and industrial structure of the region, so as to measure the impact of energy poverty on carbon emissions of the construction industry more accurately (Jiang et al., 2016; Song et al., 2018; Cheng et al., 2019).

The variable definitions are shown in **Table 1**.

3.3 Model Establishment

This section uses panel data to analyze the impact of energy poverty on carbon intensity of China's construction industry. **Eq. 3** is a regression model of the impact of energy poverty on carbon intensity of the construction industry, which is used to verify hypothesis H1.

$$CI_{it} = \alpha_0 + \alpha_1 EP_{it} + \sum_{j=1}^{J} \alpha_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it}. \tag{3}$$

Equation 4 is the regression model of the impact of energy poverty on energy consumption structure, and **Eq. 5** is the regression model of the impact of energy poverty on carbon intensity of the construction industry after the addition of energy consumption structure, used to test hypothesis H2.

$$ES_{it} = \beta_0 + \beta_1 EP_{it} + \sum_{j=1}^{J} \beta_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it} \tag{4}$$

$$CI_{it} = \gamma_0 + \gamma_1 EP_{it} + \gamma_2 ES_{it} + \sum_{j=1}^{J} \gamma_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it}. \tag{5}$$

Eqs 6–8 is the regression model of the moderating effect of technology level on energy poverty and carbon intensity of the construction industry, which is used to verify hypothesis H3a.

$$CI_{it} = \lambda_0 + \lambda_1 EP_{it} + \lambda_2 Tec_{it} + \lambda_3 EP{*}Tec_{it} + \sum_{j=1}^{J} \lambda_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it}, \tag{6}$$

$$ES_{it} = \varphi_0 + \varphi_1 EP_{it} + \varphi_2 Tec_{it} + \varphi_3 EP{*}Tec_{it} + \sum_{j=1}^{J} \varphi_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it}, \tag{7}$$

$$CI_{it} = \phi_0 + \phi_1 EP_{it} + \phi_2 Tec_{it} + \phi_3 EP{*}Tec_{it} + \phi_4 ES_{it} + \phi_5 ES{*}Tec_{it} + \sum_{j=1}^{J} \phi_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it}. \tag{8}$$

Eqs 9–11 is the regression model of the moderating effect of the marketization degree on energy poverty and carbon intensity of the construction industry, which is used to verify hypothesis H3b.

$$CI_{it} = \eta_0 + \eta_1 EP_{it} + \eta_2 Mar_{it} + \eta_3 EP{*}Mar_{it} + \sum_{j=1}^{J} \eta_j Control_{ijt} + \sum_{t=1}^{T} \delta_t Year_t + \varepsilon_{it}, \tag{9}$$

TABLE 2 | Descriptive statistical results.

Variable	Number	Mean	Std	Min	Max
CI	390	0.930	0.876	0	5.153
EP	390	0.661	0.153	0.277	0.935
ES	390	0.180	0.174	0	0.806
Tec	390	1.377	1.057	0.179	6.077
Mar	390	6.413	1.862	2.330	11.71
TP	390	8.167	0.750	6.290	9.306
IS	390	7.568	1.761	3.633	12.21
EI	390	4.716	0.712	2.494	6.020

Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China

$$ES_{it} = \iota_0 + \iota_1 EP_{it} + \iota_2 Mar_{it} + \iota_3 EP{*}Mar_{it} + \sum_{j=1}^{J}\iota_j Control_{ijt} + \sum_{t=1}^{T}\delta_t Year_t + \varepsilon_{it}, \quad (10)$$

$$CI_{it} = \kappa_0 + \kappa_1 EP_{it} + \kappa_2 Mar_{it} + \kappa_3 ES_{it} + \kappa_4 ES{*}Mar_{it} + \sum_{j=1}^{J}\kappa_j Control_{ijt} + \sum_{t=1}^{T}\delta_t Year_t + \varepsilon_{it}, \quad (11)$$

where ε_{it} is the residual; $\alpha_j, \beta_j, \gamma_j, \lambda_j, \varphi_j, \phi_j, \eta_j, \iota_j, \kappa_j$ are regression coefficients; δ_t is the regression coefficient of dummy variables of year; *i* for province; *j* is the control variable; *t* is the year; *EP* stands for energy poverty; *ES* is energy consumption structure; *CI* stands for carbon emission intensity of construction industry; *Tec* stands for technical level; *Mar* stands for marketization degree; *EP*Tec* represents the cross term of energy poverty and technological level; and *EP*Mar* is the cross term of energy poverty and marketization degree.

4 ANALYSIS OF EMPIRICAL RESULTS

4.1 Descriptive Statistics

After sorting out the data, in order to have a more intuitive understanding of the impact of energy poverty on construction intensity, descriptive statistical analysis of relevant variables of 390 valid samples in 30 provinces and cities from 2004 to 2016 was conducted. The results are shown in **Table 2**.

According to the results of descriptive statistical analysis in **Table 2**, the mean value of CI is 0.93, the minimum value is 0, and the maximum value is 5.15, which indicates that the overall carbon intensity is good during the sample period, but there are still large differences among provinces and cities. The value of carbon intensity is 0 because the carbon emission in some areas is less than 0.001 mt, and the value becomes 0 after two decimal digits are reserved. The reason why the energy consumption structure appears 0 is that in some areas, such as Hainan in 2013, the main energy consumption is electricity and the coal consumption is 0, so the energy consumption structure is 0. The mean value of EP is 0.661, the minimum value is 0.153, and the maximum value is 0.935, indicating that the energy poverty degree is not bad during the sample period. On the whole, the standard deviations of all variables in the sample are less than the mean, indicating that the statistical characteristics of variables are good on the whole.

4.2 Correlation Analysis

The correlation between variables is shown in **Table 3**. **Table 3** shows that there is a correlation between the main variables, and the variance inflation factor (VIF) calculated is significantly less than 10, indicating that there is no serious multicollinearity problem in regression analysis.

4.3 Analysis of Model Estimation Results

The regression results of the impact of energy poverty on carbon intensity of the construction industry are shown in **Table 4**. The OLS method and the 2SLS model were used to test the impact of energy poverty on carbon intensity of the construction industry in this study.

Column 2 shows the regression results made by OLS. There is a positive correlation between energy poverty and carbon intensity of the construction industry, and the carbon intensity of the construction industry increases by 1.683 units for every increase of energy the poverty level by one unit. R2 reflects the explanatory effect of independent variables of the model on dependent variables, while F-statistics represents the overall significance index of the model. R-square is 0.592, indicating that the degree of explanation of the model reaches 59.2%. F-statistic is 13.961 and significant at 1%, indicating that the overall significance of the model is good.

Column 3 is regression using 2SLS. In this study, the existence of endogenous variables is confirmed by the Hausman test, which conforms to the idea of the model. The model reported chi-square statistics, and the comparison *p* value was 0.000, indicating that the model had a good fitting effect.

The regression results of the aforementioned two models are consistent, that is, energy poverty increases the carbon intensity of the construction industry, so the hypothesis H1 is valid. Then the mediating effect model of Wen (2004) is used to analyze the mediating effect of energy consumption structure (Wen et al., 2004). Models (1)–(2) in **Table 4** are regression of the impact of energy poverty on carbon intensity of the construction industry; Model (3)–(4) is the regression of the impact of energy poverty on energy consumption structure; Model (5)–(6) is the regression of the impact of energy poverty on carbon intensity of the construction industry after the addition of energy consumption structure.

As can be seen from Column (3), the regression coefficient of energy poverty on energy consumption structure is significantly positive (β_1 = 0.459, t = 8.41, $p < 0.01$), indicating that the higher the energy poverty index is, the more unbalanced the regional energy consumption structure is, and the more inclined the region is to use coal and other non-clean energy. Column (4) adopts the 2SLS model for testing and presents consistent results. Energy poverty has a positive impact on energy consumption structure, which is significant at the level of 1%. When the energy consumption structure is included in column (5), the impact of energy

TABLE 3 | Pearson correlation coefficients.

Variable	CI	EP	ES	Tec	Mar	TP	IS	EI
CI	1							
EP	0.391***	1						
ES	0.553***	0.429***	1					
Tec	–0.320***	–0.721***	–0.195***	1				
Mar	–0.378***	–0.701***	–0.293***	0.555***	1			
TP	–0.429***	–0.0300	–0.092*	0.0250	0.354***	1		
IS	0.318***	0.359***	0.106**	–0.379***	–0.482***	–0.469***	1	
EI	0.638***	0.197***	0.422***	–0.127**	–0.364***	–0.416***	0.262***	1

, **, and * represent significant at the statistical level of 10, 5, and 1% respectively.*
Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China

TABLE 4 | Main effect and mediation effect test results.

Variable	CI		ES		CI	
	(1) OLS	(2) 2SLS	(3) OLS	(4) 2SLS	(5) OLS	(6) 2SLS
EP	1.683***	1.629***	0.459***	0.457***	1.146***	1.004***
	(7.59)	(7.57)	(8.41)	(8.54)	(4.90)	(4.48)
ES	-	-	-	-	1.172***	1.369***
					(5.57)	(6.58)
TP	–0.302***	–0.302***(–6.29)	0.003	0.011	–0.305***	–0.316***
	(–6.12)		(0.21)	(0.89)	(–6.44)	(–7.00)
IS	–0.052***	–0.066***	–0.019*** (–3.48)	–0.016***	–0.030	–0.044**
	(–2.36)	(-3.07)		(–2.98)	(–1.39)	(–2.16)
EI	0.581***	0.534***	0.096***	0.097***	0.469***	0.402***
	(11.96)	(11.20)	(8.02)	(8.16)	(9.24)	(8.17)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.468	0.211	–0.365**	–0.557***(–3.86)	0.897	0.974*
	(0.76)	(0.36)	(–2.40)		(1.50)	(1.75)
N	360	332	360	332	360	332
R^2	0.592	0.575	0.377	0.375	0.626	0.624
F	31.139***		12.971***	-	33.692***	-
Chi	-	448.249***	-	200.651***	-	550.886***

1) The t values of the regression coefficients are reported in parentheses.
*2) *, **, and *** represent significant at the statistical level of 10%, 5%, and 1%, respectively.*
Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China

poverty on carbon intensity of the construction industry is significantly positive (γ_1 = 1.146, t = 4.90, and $p < 0.01$). Energy consumption structure has a positive influence on carbon intensity of the construction industry (γ_2 = 1.172, t = 5.57, and $p < 0.01$). In Column 6, the 2SLS model is used to test the consistency. After the addition of energy consumption structure, energy poverty still has a positive impact on carbon intensity of the construction industry. γ_1 is 1.146, the coefficient is positive, the coefficient of $\beta_1* \gamma_2$ is positive, and the coefficient direction is consistent, belonging to the partial mediation effect. Therefore, we accept hypothesis H2 that energy consumption structure has a partial intermediary effect on the impact of energy poverty on carbon intensity of the construction industry. Combined with theoretical analysis, it can be seen that energy poverty has a positive impact on energy consumption structure, that is, the more serious the energy poverty is in this province, the more dependent the energy consumption structure is on traditional non-clean energy. The structure of energy consumption has a positive impact on the carbon emissions of the construction industry. The unbalanced structure of energy consumption and the high dependence on coal will lead to the increase of regional carbon emission intensity. Therefore, in order to reduce carbon emissions, it is necessary to reduce regional energy poverty and adjust the energy consumption structure to clean and high energy efficiency energy types.

To test whether the moderating effect of technical level exists, this study applies Wen's (2014) moderated mediation model to test (Wen and Ye, 2014). The first step is to examine whether the direct effect of energy poverty on carbon intensity is moderated by the technology level. The second step is to test whether the mediating effect of energy consumption structure on the impact of energy poverty on carbon intensity is adjusted by the technology level. The results are shown in **Table 5**.

TABLE 5 | Test of moderating effect of the technical level.

Variable	CI		ES		CI	
	(1) OLS	(2) 2SLS	(3) OLS	(4) 2SLS	(5) OLS	(6) 2SLS
EP	2.253***	2.116***	0.602***	0.693***	0.775**	0.653*
	(5.95)	(5.50)	(6.38)	(7.15)	(2.06)	(1.73)
Tec	0.293***	0.266***	0.024	0.054**	0.217**	0.185**
	(2.91)	(2.67)	(0.94)	(2.16)	(2.39)	(2.09)
EP*Tec	−1.031***	−0.980***	−0.038	−0.039	−0.443*	−0.441*
	(−4.19)	(−4.05)	(−0.62)	(−0.64)	(−1.81)	(−1.89)
ES	-	-	-	-	3.204*** (8.77)	3.176*** (8.96)
ES*Tec	-	-	-	-	−1.784*** (−6.03)	−1.624*** (−5.61)
TP	−0.231*** (−4.42)	−0.229*** (−4.46)	0.004 (0.32)	0.019(1.48)	−0.276*** (−5.82)	−0.278*** (−6.10)
IS	−0.069*** (−3.13)	−0.081*** (−3.84)	−0.015*** (−2.67)	−0.012** (−2.19)	−0.030 (−1.49)	−0.046** (−2.40)
EI	0.597*** (12.59)	0.550*** (11.86)	0.096*** (8.13)	0.099*** (8.48)	0.439*** (9.38)	0.385*** (8.50)
Year	Yes		Yes			
Constant	−0.098 (−0.14)	−0.211 (−0.31)	−0.565*** (−3.18)	−0.863***(−5.04)	1.050* (1.61)	1.072* (1.72)
N	360	332	360	332	360	332
R^2	0.617	0.602	0.401	0.399	0.693	0.690
F	30.561***		12.666***		38.261***	
Chi		499.617***		223.957***		739.116***

1) The t values of the regression coefficients are reported in parentheses.
, **, and * represent significant at the statistical level of 10, 5, and 1%, respectively.*
Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China

As can be seen from columns (1)–(2) in **Table 5**, *EP*Tec* is the cross product of adding *Tec* and moderating effect test. Energy poverty had a significant positive effect on carbon intensity in the construction industry, while *EP*Tec* had a significant negative effect on carbon intensity in the construction industry (λ_3 = −1.031, t = −4.19, and $p < 0.01$). The technology level reduces the positive impact of energy poverty on carbon intensity of the construction industry. Then the adjusting mechanism of the technical level in the intermediary role was tested. In columns (3)–(4), energy poverty has a positive and significant effect on energy consumption structure, while *EP*Tec* has no significant effect on energy consumption structure (φ_3 = −0.038, t = −0.62, and $p > 0.1$). Columns (5)–(6), then when we add *ES* and *ES*Tec*, energy poverty has a significant positive effect on carbon intensity of the construction industry, energy consumption structure has a significant positive effect on carbon intensity of the construction industry, and *EP*Tec* has a significant negative effect on carbon intensity of the construction industry (ϕ_3 = −0.443, t = −1.81, and $p < 0.1$). *ES*Tec* negatively affected the carbon intensity of the construction industry (ϕ_5 = −1.784, t = −6.03, and $p < 0.01$). Therefore, the technology level plays a moderating role between the main effect of energy poverty and carbon emissions from the construction industry, and between the indirect effect of energy consumption structure and carbon intensity of the construction industry. The theory of technological innovation explains that technological innovation follows market rules and meets social needs. In order to reduce the cost of resource waste and pollution emission, enterprises will improve energy efficiency and reduce carbon emission through technological progress. The excessive use of non-clean energy and pollution emissions caused by energy poverty can be improved through technological innovation, and the positive effect of energy poverty on carbon intensity of the construction industry can be indirectly weakened.

Similarly, to test whether the moderating effect of the degree of marketization exists, the first step is to test whether the direct effect of energy poverty on carbon intensity is regulated by the degree of marketization. The second step is to test whether the mediating effect of energy consumption structure on energy poverty on carbon intensity of the construction industry is regulated by the degree of marketization. The test results are shown in **Table 6**.

In columns (1)–2) of **Table 6**, after adding EP*Mar, the cross product of Mar and moderating effect test, energy poverty has a positive and significant effect on carbon intensity of the construction industry, while EP*Mar has no significant effect on carbon intensity of the construction industry (η_3 = −0.094, t = −0.72, and $p > 0.1$). It can be seen that marketization degree has no moderating effect on the main effect of energy poverty and carbon intensity of the construction industry and then the degree of marketization in the intermediary role of the adjustment mechanism test. It can be seen from columns (3)–(4) that energy poverty has a positive and significant effect on energy consumption structure. The effect of EP*Mar on energy consumption structure is not significant in the OLS model, but is significant in the 2SLS model (ι_3 = −0.069, T = −1.76, and $p < 0.1$). In columns (5)–(6), we add *ES* and *ES*Mar*, and energy poverty has a significant positive effect on carbon intensity of the construction industry, energy consumption structure has a significant positive effect on carbon intensity of the construction industry, and *ES*Mar* has a significant negative effect on carbon intensity of the construction industry (κ_4 = −0.624, t = −5.46, and $p < 0.01$). Therefore, the degree of marketization plays a negative moderating role in the indirect effect of energy consumption structure and carbon intensity of the construction industry.

TABLE 6 | Test of the moderating effect of the marketization degree.

Variable	CI		ES		CI	
	OLS (1)	2SLS (2)	OLS (3)	2SLS (4)	OLS (5)	2SLS (6)
EP	2.452** (2.55)	2.487** (2.07)	0.565** (2.39)	0.845*** (2.85)	1.280*** (3.48)	1.239*** (3.48)
Mar	0.070 (0.84)	0.074 (0.72)	0.007 (0.32)	0.030 (1.17)	0.103*** (2.68)	0.096*** (2.61)
EP*Mar	−0.094 (−0.72)	−0.117 (−0.74)	−0.025 (−0.79)	−0.069* (−1.76)	-	-
ES	-	-	-	-	5.147*** (6.83)	4.877*** (6.67)
ES*Mar	-	-	-	-	−0.624*** (−5.46)	−0.559*** (−5.00)
TP	−0.299*** (−5.35)	−0.291*** (−5.35)	0.010 (0.71)	0.024* (1.79)	−0.337*** (−6.84)	−0.344*** (−7.29)
IS	−0.050** (-2.11)	−0.066*** (−2.90)	−0.021*** (−3.61)	−0.019*** (−3.34)	−0.018 (−0.83)	−0.034* (−1.62)
EI	0.583*** (11.59)	0.532*** (10.80)	0.093*** (7.48)	0.091*** (7.49)	0.424*** (8.36)	0.369*** (7.53)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−0.171 (−0.17)	−0.430 (−0.40)	−0.399* (−1.65)	−0.791***(−2.97)	0.460 (0.66)	0.459 (0.71)
N	360	332	360	332	360	332
R^2	0.593	0.574	0.379	0.380	0.657	0.651
F	27.613***	-	11.578***	-	34.248***	-
Chi2	-	448.098***	-	204.850***	-	619.795***

1) The t values of the regression coefficients are reported in parentheses.
, **, and * represent significant at the statistical level of 10, 5, and 1%, respectively.*
Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China

TABLE 7 | Robustness test results of the LIML replacement method.

Variable	Main effect	Mediating effect A	Mediating effect B	Moderating effect Tec	Moderating effect Mar
EP	1.629*** (7.57)	0.457*** (8.54)	1.004*** (4.48)	0.653* (1.73)	1.239*** (3.48)
ES	-	-	1.369*** (6.58)	-	-
EP*Tec	-	-	-	−0.441* (−1.89)	-
ES*Mar	-	-	-	-	−0.559*** (−5.00)
Others	Yes	Yes	Yes	Yes	Yes
R^2	0.575	0.375	0.624	0.690	0.651
Chi2	448.249***	200.651***	550.886***	739.116***	619.795***

1) The t values of the regression coefficients are reported in parentheses.
, **, and * represent significant at the statistical level of 10, 5, and 1%, respectively.*
Original data sources: China Carbon Emission database, Statistical Yearbook of the Construction Industry, Market Index Report by Provinces in China, Statistical Yearbook of China, and Statistical Yearbook of the Construction Industry in China

Therefore, hypothesis H3b is accepted, indicating that the degree of marketization weakens the mediating role of energy consumption structure in the relationship between energy poverty and carbon emissions from the construction industry.

4.4 Robustness Test

To ensure the robustness of the empirical results, this study tested the validity of the "weak instrumental variable," and the result showed that the F-statistic was greater than 10, so there was no "weak instrumental variable." Using the finite information maximum likelihood method (LIML) regression, the positive impact of energy poverty on carbon intensity of the construction industry still exists. The regression coefficient between LIML and 2SLS did not change significantly. Based on this, it can be considered that the conclusion of this study is robust. The test results are shown in **Table 7**.

4.5 DISCUSSIONS

Based on the interprovincial panel data of China from 2004 to 2016, this article conducts an empirical analysis on the impact of energy poverty and energy consumption structure on carbon emissions of the construction industry and finds that energy poverty has a significant positive impact on carbon intensity. The viewpoint of Ürge-Vorsatz (2012) that improving building energy efficiency can alleviate energy poverty and reduce carbon emissions also confirms this point (Ürge-Vorsatz and Tirado Herrero, 2012). At the same time, the path of energy poverty affecting carbon intensity of the construction industry was explored, and it was found that energy poverty has an impact on carbon intensity of the construction industry through energy consumption structure, and energy consumption institutions play an intermediary role. Furthermore, the moderating effect

of the external market environment and the industrial technology level on the influencing path was considered. It was found that the technology level has a moderating effect on the energy consumption structure and building carbon intensity. The market degree has a moderating effect on the relationship between energy consumption structure and carbon intensity of the construction industry.

The limitations of this study are also the focus of future research in two aspects 1) this article explores the impact of energy poverty on carbon intensity of the construction industry, and the research object was limited to the construction industry. This may restrict the impact path between energy relationship and carbon emissions by the construction industry, and the industrial heterogeneity path will be studied in the future. 2) This article studied the relationship between energy poverty and carbon emissions, and may further extend the research chain in the future to explore the impact pathways of energy poverty, carbon emissions, and climate change.

5 RESULTS AND POLICY IMPLICATIONS

5.1 Results

This article analyzes the influencing mechanism of carbon intensity in the construction industry. First, the energy poverty index of each province in China is measured in **Section 3.3**. Second, in **Section 4.3**, the regression model is used to test the mediating effect and the moderating effect of the technology level and the marketization degree on the influence mechanism of energy poverty on carbon emissions from the construction industry through energy consumption structure. The main research conclusions are as follows: 1) energy poverty has a positive impact on carbon intensity of the construction industry, and the carbon intensity of the construction industry increases by 1.683 units per unit increase of energy poverty. Regression analysis shows that energy poverty has a positive impact on carbon intensity of the construction industry. Energy poverty is severe in the region, and access to clean, safe, and consumable energy is difficult. This situation leads to the construction industry and other industries tend to use coal and other primary energy. However, the extensive use of energy will lead to low energy efficiency and a large number of carbon emissions. 2) Energy consumption structure plays a mediating role in the influence of energy poverty on carbon intensity of the construction industry. 3) The moderating effect of the technology level and the marketization degree exists. The technology level will reduce the positive impact of energy poverty on carbon intensity of the construction industry, that is, technologically advanced areas where carbon dioxide emissions are reduced through carbon capture, sequestration, and advances in production technology. The improvement of marketization degree of the construction industry enables construction enterprises to strive to improve their core competitiveness in the market close to perfect competition, including but not limited to the use of green technology innovation to improve energy utilization efficiency, development of carbon capture, carbon sequestration, carbon secondary utilization, and other technologies to reduce carbon dioxide emissions.

5.2 Policy Implications

From the outbreak of COVID-19 in 2019 to the current pandemic, social and economic uncertainties have increased, which in turn affects the macro economy (Işık et al., 2020; Ahmad et al., 2021). Macroeconomic fluctuation makes the economic parameters of the construction industry fluctuate as well, which affects the production cost of the construction industry. This will theoretically affect the choice of energy sources and energy efficiency in the construction industry. The effective utilization of energy is related to the construction industry energy conservation, and emission reduction target can be achieved smoothly. Based on the analysis of the research results, the following policy recommendations are put forward: 1) industrial low-carbon and clean energy consumption structure transformation in coordination. The normalized development trend of COVID-19 poses severe challenges to energy conservation and emission reduction. The public's requirements for buildings and structures tend to be green, energy saving, and environment friendly, making construction enterprises aware of using cleaner energy in production. However, the difficulty of obtaining clean energy in different regions leads to the difference in energy use cost of construction enterprises. Therefore, local governments should be urged to make full use of their resource endowment and location advantages, focus on project construction according to local conditions, and effectively change the mode of economic development. We will give appropriate subsidies and policy support to enterprises for clean energy, and effectively guide the coordinated development of the low-carbon construction industry and clean energy consumption structure. 2) Introduce and localize carbon reduction technologies. At present, the building materials and energy used in China's construction industry are highly carbonized. In order to achieve the goal of reducing carbon dioxide in the context of the COVID-19 pandemic, it is suggested that the construction sector take the lead in introducing foreign advanced carbon emission reduction technologies and clean energy acquisition technologies. At the same time, increase investment in green technology, research low-carbon, or carbon-free building materials. Use BIM technology to simulate construction, encourage the recycling of building materials, and promote the use of recycled cement, recycled concrete, and other recycled building materials. 3) Accelerate the establishment of a national carbon emission trading market. With the carbon market as the starting point, the construction enterprises with high emissions and high pollution will be forced to retire or transform their development, the transformation of energy structure will be accelerated, the innovation of low-carbon technology will be promoted, and

the market will play an effective role in the allocation of resources, so as to effectively reduce carbon emissions.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here 1) the carbon emission data and energy consumption of the construction industry are from the China Carbon Emission database (CEADS) https://www.ceads.net.cn/. 2) The rest of the variables come from the official website of the National Bureau of Statistics, Statistical Bulletin, China Statistical Yearbook, and Statistical Yearbook of China Construction Industry. http://www.stats.gov.cn/.

AUTHOR CONTRIBUTIONS

JZ was responsible for determining the theme of energy poverty and carbon intensity in the construction industry and reviewing the revised draft of the paper at various stages and making suggestions. YL was responsible for the design of the study, data collection, collation and analysis, and paper drafting and revision. In the revision of the paper, NS made innovative suggestions on the structure and content of the paper, and made contributions to the improvement of the quality of the paper. HWK made substantial contributions to the revision of the article, including the revision of the article language, the search for new materials to be added to the article, analysis, classification and enrichment of the article, and made contributions to the improvement of the quality of the article.

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Green Supply Chain Coordination During the COVID-19 Pandemic Based on Consignment Contract

Yi Wang[1]*, *Geovanny Genaro Reivan Ortiz*[2], *William Dextre-Martinez*[3†] *and Liandi Zhang*[1]

[1]College of Science, Tianjin University of Commerce, Tianjin, China, [2]Laboratory of Basic Psychology, Behavioral Analysis and Programmatic Development PAD-LAB, Catholic University of Cuenca, Cuenca, Ecuador, [3]School of Management and Tourism, Universidad Nacional Santiago Antúnez de Mayolo, Huaraz, Peru

COVID-19 has further strengthened consumers' online consumption habits and brought a new boom in which enterprises can use online transactions and green products to avoid risk and gain profits in the pandemic. A green supply chain model is established containing one e-commerce platform and one manufacturer. The Nash bargaining contract and Rubinstein bargaining contract are applied to mitigate conflicts of profits in the model. From the coordination analysis, we show that both Nash and Rubinstein bargaining contracts can achieve coordination and mitigate conflict of profits through the adjustment of platform usage rates. According to each member's bargaining power and patience, the optimal platform usage rate is determined, the supply chain profits of both sides are allocated, the green production's research and development are promoted, and a win-win situation is realized. Specifically, in the Nash bargaining contract, the excess profit of each member depends on their bargaining power. The stronger the bargaining power, the more excess profits will go to the e-commerce platform, and the less excess profits will go to the manufacturer. In the Rubinstein bargaining contract, the excess profit of each member depends on the lowest profit bound and bargaining patience. The higher the manufacturer's (or e-commerce platform's) patience, the higher his profit. When the patience of both is high (or low), the e-commerce platform (or the manufacturer) plays a leading role and obtains more profits.

Keywords: COVID-19, green supply chain, consignment contract, sustainable development, environmental sustainability

Edited by:
Asif Razzaq,
Dalian University of Technology, China

Reviewed by:
Tayyaba Rani,
Xi'an Jiaotong University, China
Mohsin Shahzad,
Dalian University of Technology, China

***Correspondence:**
Yi Wang
lxywangyi@tjcu.edu.cn

†ORCID:
William Dextre-Martinez
orcid.org/0000-0003-1481-0584

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INTRODUCTION

With population growth, the contradiction among economic development, resource utilization, and environmental protection has become increasingly prominent. A great deal of enterprises are only concerned about economic interests and ignore ecological protection, resulting in the increasingly severe problem of environmental pollution. According to the current population growth trend, the world population will reach 9.8 billion by 2050. The continuous growth of the population has brought a great burden to the Earth, while the energy crisis and environmental pollution will in turn affect human survival. How can awareness be raised to protect the Earth and the environment? In 1970, the United States first proposed "World Earth Day," which was the first large-scale environmental protection movement in human history. World Earth Day has been held 52 times with different topics until 2021. The purpose is to raise public awareness of environmental

protection and advocate for sustainable development. Environmental protection needs everyone to participate. Whether individuals, enterprises, or governments, all can become green concept advocates and practitioners in promoting green action to protect the Earth on which we live. At present, the development of production and living favors are mostly integrated into environmental protection. Because of the outbreak of COVID-19, the economies of all countries and the lives of all people are affected. To reduce exposure, slow down the spread, and minimize the impact of COVID-19, consumers prefer to use online shopping platforms instead of physical stores, which indirectly affects the competition among enterprises. Amid the COVID-19 pandemic, everyone has realized the convenience of the era of the network period and the importance of online communication, especially online shopping. It not only changed people's lifestyle, but also brought uncertainty to the world's economic development. Deeply affected by COVID-19, more and more people worldwide have to use online shopping platforms to meet their daily needs, such as, Amazon, eBay, Wish, Alibaba, etc. Since it is difficult for physical stores to maintain economic profits, many manufacturers choose to sell through online platforms to combat COVID-19.

To investigate the performance of online shopping, the usual method is to establish an economic model containing all participants. To mitigate conflicts of interests in an established model, coordination under consignment contracts appears particularly important. The Nash bargaining contract and Rubinstein bargaining contract are two favorite cooperation contracts in characterizing the problem. In 1950, the Nash equilibrium was first proposed by John Forbes Nash in his doctoral thesis (Nash, 1950a). This is an equilibrium analysis theory of non-cooperative game, which reveals the internal relationship between game equilibrium and economic equilibrium. It has a significant impact on game theory and economics, and the 1994 Nobel Memorial Prize in Economic Sciences was awarded to Nash (Nash, 1950b; Nash, 1951; Nash, 1953). In 1982, Ariel Rubinstein simulated the basic and indefinite complete information bargaining process with the method of complete information dynamic game, and established a complete information alternating bidding bargaining model, which is called the Rubinstein bargaining model (Rubinstein, 1982). Enterprises sell their green products *via* e-commerce platforms, sharing profits with e-commerce platforms through Nash or Rubinstein consignment contracts. In the contract, e-commerce platforms will gain profits from manufacturers in using his platform.

Benefitted from the Nash and Rubinstein bargaining contracts, partners will make joint efforts to cooperate in a model to reach a win-win state, which will promote sustainable development of the global economy. For sustainable development, countries have strengthened the management and restriction on enterprises' environmental problems. Therefore, environmental issues have also become a problem for the development of enterprises. Only enterprises that comply with the green era can have sustainable competitiveness in the face of fierce competition. To deal with the effect of a competitive environment and technological innovation, enterprises have to explore cooperative opportunities to survive in a competitive market. The supply and demand relationship between enterprises constitutes a supply chain, and their cooperation between enterprises generates the mode named supply chain management. How to get the optimal decisions of the sharing ratio among each member be achieved through Nash and Rubinstein bargaining contracts? This can be solved by green supply chain management, which is a very practical issue worth studying.

The supply chain combined with "environmental protection" and "green" is called a green supply chain, which aims to lower the waste of resources, reduce environmental pollution, and lessen production costs. Governments worldwide have made great efforts in encouraging enterprises to produce green products. For example, China determined to achieve low-carbon life by implementing limitations of carbon dioxide emissions. In 2030, an emission peak will be reached; in 2060, carbon neutrality will be accomplished. Environmental protection not only has attracted increasing attention of enterprises, but also draws the attention of consumers looking to buy green food. The question of how to obtain optimal profits, reduce manufacturing costs, and minimize environmental pollution becomes the critical point of supply chain management.

In this paper, we established a model of green products under consignment contracts in. Comparing to the current results, we have the following contributions. Firstly, we investigated effects under consignment contracts on green supply chain performance, greenness, and prices of green products. Secondly, by using Nash and Rubinstein bargaining contracts, we coordinated the supply chain. Thirdly, through a coordination mechanism, we redistributed profits of supply chain members to promote the sustainable development of green products and a win-win situation for two parties.

LITERATURE REVIEW

We reviewed the related literature in three topics: the game model based on consignment contracts, the green supply chain model, and the coordination of the green supply chain.

Game Model Based on Consignment Contracts

The development trend of economic globalization and the trade scale of the global economy urgently need a new economic operation mode and business operation mode. In the background of economic globalization, how can a global strategy be implemented to improve one's viability and competitiveness, and overcome constraints of space and time? Organizations such as modern enterprises, merchants, and state machines must seek and adopt new development models. This brings the development of e-commerce platforms. A consignment contract, as a legal provision, standardizes the consumer market, and attracts the attention of researchers. Researchers have made great

efforts in coordinating models by the Nash and Rubinstein bargaining contracts.

Li et al. (2009) used the Nash bargaining model to analyze a chain model containing two members. They researched conditions to coordinate their supply chain, and gave optimal decisions of their members and whole channel. Yildiz (2011) studied a final-offer arbitration model under the Nash and Rubinstein bargaining game. Adida and Ratisoontorn (2011) set a model of three members under consignment contracts. They found that the contract which most benefits the manufacturer will not be fixed, but for the retailer, the consignment price contract is better than the other two contracts. Hu et al. (2014) investigated an inventory control model on consignment contracts. They gave optimal control strategies and analyzed the vendor's return policy. Avinadav et al. (2015) focused on a model influenced by risk sensitivity corresponding to mobile applications. They obtained optimal decisions by different risk attitudes, such as averse, neutral, seeking. Guha (2019) searched the performance of malice and patience in the Rubinstein bargaining model. De Giovanni et al. (2019) issued the supply chain management of a marketing-operations interface under a consignment contract. They found that a cooperative program will be beneficial to a retailer, but not good for manufacturers. Zhao et al. (2020) developed a supply chain shelf model on a consignment contract. They presented each member's optimal decisions in horizontal scenarios, and investigated strategies under horizontal collusion. Zhou et al. (2022) described a competitive model with third-party platform-integration under Nash bargaining. Shi et al. (2021) established a platform supply chain. By Nash game theory, they found that the usage of a platform only benefits partners with low competition, occurring in different four different channels. Xu et al. (2021) constructed a sea-cargo supply chain, and analyzed the impact on their model through the Stackelberg-Nash game. Ye et al. (2021) built a model containing a platform. By Nash game theory, they examined competition between partners, and examined performance in a long-run or short-run. Hasiloglu and Kaya (2021) considered a model containing e-commerce platforms and analyzed the influence of each factor by game theory. Zhang and Wang (2021) (Zhang and Wang, 2021) investigated a sustainable supply chain under the Rubinstein game model. Caparr o′ s and Pereau (2021) (Caparrós and Pereau, 2021) showed different results in two cooperation negotiating procedures under Rubinstein game theory. Tang et al. (2021a) studied a model under credit term-based contracts. They obtained optimal decisions, and a win-win state was proposed. Ouyang et al. (2021) issued a framework to warn for COVID-19 by some contracts. They found that their framework is beneficial in decentralized decision-making channels. Avinadav et al. (2022) searched a model of an app developer and a distributer, and analyzed their revenue sharing by a consignment contract.

Green Supply Chain Model

For application in actual production, various models have been built to investigate optimal decisions. For example, Ghosh and Shah (2015) researched the optimal solutions in a model under different contracts. Xu et al. (2016) investigated the optimal strategy for each link in a three-tier chain model when the green level of upstream suppliers affects the carbon emissions of the core manufacturer. Cao and Liu (2017) investigated the feasibility of proactive implementation in a supply chain model without government incentives under information asymmetry. They demonstrated the superiority of cooperative decision-making under information asymmetry by comparing games of whether or not to cooperate. Zhang et al. (2017) established a model due to consumer strategy behavior for three cases: no government subsidy, a government subsidy to the green product manufacturer, or to the green consumer, and the study showed that government subsidy to the green product manufacturer is more beneficial to the development of green products. Sinayi and Rasti-Barzoki (2018) studied optimal product price, greenness, and social welfare strategies for green supply chains under government intervention. Wen et al. (2018) constructed a model considering consumers' green preferences and intervention by governments.

Coordination of Green Supply Chain

To seek maximization in a decentralized channel's overall profits, as well as the maximization of members' profits, the channel's cooperation is the standard method to achieve this goal. Researchers have made great efforts in coordinating different models.

Seifert et al. (2012) established a model of three parties: supplier, manufacturer, and retailer. They analyzed coordination of the supply chain in price-contracts. They found that distinguishing between two sub-supply chains equals the transfer of the channel's shortage cost. Huo et al. (2015) studied a model and tested it with 617 manufacturers. They researched the effect of IT and inter-organizational relationship on coordination capability. Hu et al. (2018) investigated whether different contracts can coordinate their supply chain. Results showed that a conventional option contract will not coordinate the model. Xu et al. (2020) issued a supply chain coordination corresponding of online platforms by cost-sharing contracts. Whether or not the model can be coordinated depends on the factors, such as contracts, delivery time sensitivity, and platform power. Chandra and Vipin (2021) researched a vaccine supply chain by coordinating contracts. The results showed that their supply chain cannot be coordinated by a wholesale price contract. Tang et al. (2021b) researched a coordination of carbon taxation among enterprises and consumers. Song et al. (2022) explored a model containing two different products. They analyzed optimal decisions, and showed contracts in coordinating their model. Qiu et al. (2022) investigated O2O supply chain coordination. A comparison showed among three kinds of contracts in coordinating their model. Overall a large extent of literature considers different attributes of COVID-19, such as socio-economic impacts (Irfan et al., 2021; Ahmad et al., 2022), environmental consequences (Razzaq et al., 2020; Irfan et al., 2022; Razzaq et al., 2022), and logistics operations (Khan et al., 2021a; Yu et al., 2021), and few studies generally discuss industry 4.0 practices at the firm level (Khan et al., 2021b), and other

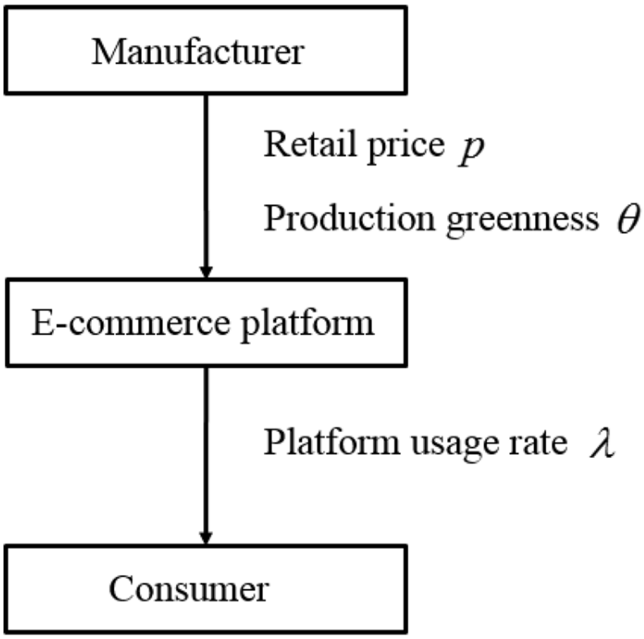

FIGURE 1 | Structure of the supply chain model.

investment factors (Razzaq et al., 2021). However, little is known regarding the proposed relationship.

Under the pandemic, the online transaction has become a mainstream consumption mode. Compared to the reviewed literature streams, we extended the research area of the green supply chain in combining the e-commerce platform and green product manufacturer. We described two partners' decisions in two structures (centralized and decentralized channel), and introduced Nash and Rubinstein bargaining consignment contracts in coordinating the decentralized chain.

DESCRIPTION OF THE PROBLEM

The model in our paper contains a green product manufacturer and an e-commerce platform. Referring to Savaskan et al. (2004), this paper assumes market demand $q(q>0)$ as a linear function of product price p and greenness θ. Let $q(p,\theta)=a-bp+\alpha\theta$, where $\alpha(\alpha>0)$ is the potential market demand, implying that consumers prefer cheaper production with high greenness. Referring to the study of Zhu and Dou (2011), this paper assumes that research and development investment is a quadratic function of its greenness $I\theta^2$, with $I(I>0)$ the green investment parameter. The manufacturer undertakes research and development costs. Referring to Luo et al. (2017), a significant difference of the e-commerce platform consignment model and the traditional wholesale and retail model shows that the manufacturer decides productions' price and greenness, and e-commerce platform charges the manufacturer a certain platform usage fee, i.e., a certain percentage λ $(0<\lambda<1)$ of the revenue from the sale of the green product. The marketing cost of an e-commerce platform denotes as $c(a>bc>0)$. **Figure 1** is the structure of our model.

GAME MODEL UNDER CONSIGNMENT CONTRACTS

Channel Performance With Centralized Decision-Making

Under a centralized channel, two members perform as one form in deciding optimal decisions to maximize the channel's total profits. The whole channel's profit is:

$$\Pi^C(p,\theta)=(p-c)(a-bp+\alpha\theta)-I\theta^2. \quad (1)$$

By optimizing **Eq. 1**, the following Theorem 1 is obtained.

THEOREM 1. When $\alpha^2<4bI$, the optimal greenness, price, and total channel's profit under the centralized decision are, respectively:

$$p_c^*=\frac{2I(a-bc)}{4bI-\alpha^2}+c,\ \theta_c^*=\frac{\alpha(a-bc)}{4bI-\alpha^2},\ \Pi^{C*}=\frac{I(a-bc)^2}{4bI-\alpha^2}.$$

Proof By the first-order optimality conditions,

$$\frac{\partial\Pi^C}{\partial p}=a-2bp+\alpha\theta+bc=0,\ \frac{\partial\Pi^C}{\partial\theta}=p\alpha-c\alpha-2I\theta=0.$$

We have

$$p_c^*=\frac{2I(a-bc)}{4bI-\alpha^2}+c,\ \theta_c^*=\frac{\alpha(a-bc)}{4bI-\alpha^2}. \quad (2)$$

Let $A_1=\frac{\partial^2\Pi^C}{\partial p^2}=-2b$, $B_1=\frac{\partial^2\Pi^C}{\partial\theta\partial p}=\alpha$, $C_1=\frac{\partial^2\Pi^C}{\partial\theta^2}=-2I$. Since $A_1<0$ and $A_1B_1-C_1^2=4bI-\alpha^2>0$, so **Eq. 2** is the optimal solution. Finally, substituting p_c^* and θ_c^* into **Eq. 1**, we get the optimal channel's profit Π_c^*.

Next, we aim to investigate the optimal decisions in the decentralized channel.

Channel Performance With Decentralized Decision-Making

In a decentralized model, partners all aim to maximize self-interest. The leadership of the model is an e-commerce platform, and followership is the manufacturer. Firstly, this e-commerce platform determines the usage rate; Secondly, the manufacturer decides the production's price and greenness after being informed of the usage rate determined by the platform.

For given platform usage rate λ, the manufacturer has profit:

$$\Pi_d^M(p,\theta;\lambda)=(1-\lambda)p(a-bp+\alpha\theta)-I\theta^2. \quad (3)$$

Meanwhile, for any given price p and greenness θ, e-commerce platform holds profit:

$$\Pi_d^R(\lambda;p,\theta)=\lambda p(a-bp+\alpha\theta)-c(a-bp+\alpha\theta). \quad (4)$$

In the framework of the Stackelberg game, maximizing **Eqs 3**, **4**, Theorem 2 is obtained.

THEOREM 2. When $\alpha^2<4bI$, the optimal price and greenness of the product under the decentralized channel are:

TABLE 1 | Optimal profit and optimal solutions under different models.

Model		Profit of manufacturer	Profit of e-commerce platform	Total profit of supply chain	Price	Greenness	Platform usage rate
Centralized channel				12250	41	70	
Decentralized channel		1875	2112.5	3987.5	13	7.5	0.7115
Nash bargaining	μ						
	0	10137.5	2112.5	12250	41	70	0.1758
	0.25	8071.875	4178.125	12250	41	70	0.2046
	0.5	6006.25	6243.75	12250	41	70	0.2334
	0.75	3940.625	8309.375	12250	41	70	0.2622
	1	1875	10375	12250	41	70	0.2909
Rubinstein bargaining	(δ_M, δ_R)						
	(1, 0.8)	10137.5	2112.5	12250	41	70	0.3848
	(1, 0.5)	10137.5	2112.5	12250	41	70	0.3848
	(1, 0.2)	10137.5	2112.5	12250	41	70	0.3848
	(0.8, 1)	1875	10375	12250	41	70	0.3537
	(0.5, 1)	1875	10375	12250	41	70	0.3537
	(0.2, 1)	1875	10375	12250	41	70	0.3537
	(0.5, 0.5)	8166.7	4083.3	12250	41	70	0.2033
	(0.7, 0.7)	7205.9	5044.1	12250	41	70	0.2166
	(0.9, 0.9)	6447.4	5802.6	12250	41	70	0.2272

$$p_d^* = \frac{2aI - c\alpha^2}{2(4bI - \alpha^2)},\ \theta_d^* = \frac{\alpha^2(a - bc) - 2abI}{\alpha(4bI - \alpha^2)}.$$

The optimal usage rate for the platform is:

$$\lambda_d^* = \frac{(2aI + c\alpha^2)(4bI - \alpha^2)}{\alpha^2(2aI - c\alpha^2)}.$$

Manufacturer's optimal profit is

$$\Pi_d^{M*} = \frac{aI[\alpha^2(a - bc) - 2abI]}{\alpha^2(4bI - \alpha^2)},$$

and e-commerce platform has profit

$$\Pi_d^{R*} = \frac{b(2aI - c\alpha^2)^2}{4\alpha^2(4bI - \alpha^2)}.$$

Proof By reasoning process, we first consider the case that manufacturer first decides price and greenness by maximizing its corporate profit based on the platform usage rate determined by the e-commerce platform, whose optimization problem is:

$$\max_{p,\theta} \Pi_d^M(p, \theta|\lambda).$$

The first-order optimality condition yields:

$$\frac{\partial\Pi_d^M}{\partial p} = (1-\lambda)(a - 2bp + \alpha\theta) = 0, \frac{\partial\Pi_d^M}{\partial\theta} = (1-\lambda)p\alpha - 2I\theta = 0.$$

Let $A_2 = \frac{\partial^2\Pi_d^M}{\partial p^2} = -2b(1-\lambda)$, $B_2 = \frac{\partial^2\Pi_d^M}{\partial p\partial\theta} = (1-\lambda)\alpha$, $C_2 = \frac{\partial^2\Pi_d^M}{\partial\theta^2} = -2I$. It is known that when $4bI - \alpha^2 > 0$, $A_2C_2 - B_2^2 = (1-\lambda)[4bI - (1-\lambda)\alpha^2] > 0$ and $A_2 < 0$, there exists a unique optimal solution:

$$p_d^*(\lambda) = \frac{2aI}{4bI - (1-\lambda)\alpha^2},\ \theta_d^*(\lambda) = \frac{a\alpha(1-\lambda)}{4bI - (1-\lambda)\alpha^2}. \quad (5)$$

Substituting **Eq. 5** into **Eqs 3**, **4**, the optimal profit for two members is respectively:

$$\Pi_d^M = \frac{a^2 I(1-\lambda)}{4bI - (1-\lambda)\alpha^2},$$
$$\Pi_d^R(\lambda) = \frac{2abI\{2aI\lambda - c[4bI - (1-\lambda)\alpha^2]\}}{[4bI - (1-\lambda)\alpha^2]^2}.$$

Second, consider the first stage of the Stackelberg game, when the e-commerce platform aims to maximize its profit, and its optimization problem is

$$\max_{\lambda} \Pi_d^R(\lambda).$$

According to the first-order condition in optimizing λ:

$$\frac{d\Pi_d^R}{d\lambda} = \frac{A - B\lambda}{[4bI - (1-\lambda)\alpha^2]^3} = 0,$$

with $A = 2abI[(2aI + c\alpha^2)(4bI - \alpha^2)]$, $B = 2abI\alpha^2(2aI - c\alpha^2)$, we have

$$\lambda_d^* = \frac{(2aI + c\alpha^2)(4bI - \alpha^2)}{\alpha^2(2aI - c\alpha^2)}.$$

By second-order condition,

$$\frac{d^2\Pi_d^R}{d\lambda^2} = -\frac{8a^2bI^2\alpha^2}{[4bI - (1-\lambda)\alpha^2]^4} < 0.$$

Therefore, λ_d^* is the unique optimal solution, which leads to Theorem 2.

The following proposition is easy to follow.

PROPOSITION 1. $p_c^* > p_d^*$, $\theta_c^* > \theta_d^*$, $\Pi^{C*} > \Pi_b^{M*} + \Pi_b^{R*}$.

Proof: Because $p_c^* - p_d^* = \frac{4bcI + 2aI - c\alpha^2}{2(4bI - \alpha^2)} > 0$, so $p_c^* > p_d^*$. Because $\theta_c^* - \theta_d^* = \frac{2abI}{\alpha(4bI - \alpha^2)} > 0$, so $\theta_c^* > \theta_d^*$. Because $\Pi^{C*} - (\Pi_d^{M*} + \Pi_d^{R*}) = \frac{bc^2\alpha^2(4bI - \alpha^2) + 4a^2bI^2}{4\alpha^2(4bI - \alpha^2)} > 0$, so $\Pi^{C*} > \Pi_d^{M*} + \Pi_d^{R*}$.

By Proposition 1, selling price, greenness, and total profits are all higher in the centralized channel than the decentralized one. Since the two parties all pursue the maximization of their profit, it

will inevitably create a conflict of interest between them, and goes against the interest of the research and development of green production, so it is essential to establish a coordination contract to raise the partners' profits.

COORDINATION BASED ON CONSIGNMENT CONTRACTS

Decision-making in a decentralized channel reduces total profit compared with the centralized channel. To mitigate conflicts between partners, it is crucial to establish coordination contracts to optimize the performance of the entire supply chain.

Nash Bargaining Contract

To win more profits for supply chain members, we first take the Nash bargaining contract. Let $\boldsymbol{x}$ be the portion received in total profits by the e-commerce platform. Thus, the manufacturer undertakes the remaining $(1-\boldsymbol{x})$ portion $(0 \le \boldsymbol{x} \le 1)$. Then the profit of the total channel should be

$$\max_{x\epsilon[0,1]} f(x) = \left(x\Pi^{C*} - \Pi_d^{R*}\right)^{\mu}\left[(1-x)\Pi^{C*} - \Pi_d^{M*}\right]^{1-\mu},$$

with $\boldsymbol{\mu}\epsilon[0,1]$ as the bargaining power of platforms. If $\boldsymbol{\mu} = 0$, then the manufacturer has absolute bargaining power; if $\boldsymbol{\mu} = 1$, then platforms have absolute bargaining power; if $\boldsymbol{\mu} = 0.5$, then both two members have equal bargaining power. Through bargaining, both manufacturer and e-commerce platforms aim to get more profits than the decentralized situation. Note that the optimal solution is

$$x^* = \frac{\mu\left(\Pi^C - \Pi_d^M - \Pi_d^R\right) + \Pi_d^R}{\Pi^C},$$

and we will get the following result.

PROPOSITION 2. By the Nash bargaining contract, the optimal profits of each member are:

$$\Pi_n^{M*} = \frac{aI\left[\alpha^2(a-bc) - 2abI\right]}{\alpha^2(4bI-\alpha^2)} + \frac{(1-\mu)b\left[c^2\alpha^2(4bI-\alpha^2) + 4a^2I^2\right]}{4\alpha^2(4bI-\alpha^2)}, \quad (6)$$

$$\Pi_n^{R*} = \frac{b\left(2aI - c\alpha^2\right)^2}{4\alpha^2(4bI-\alpha^2)} + \frac{\mu b\left[c^2\alpha^2(4bI-\alpha^2) + 4a^2I^2\right]}{4\alpha^2(4bI-\alpha^2)}. \quad (7)$$

THEOREM 3. By the Nash bargaining contract, when $\boldsymbol{a} > 2\boldsymbol{bc}$, the optimal platform usage rate is:

$$\lambda_n^* = \frac{(4bI-\alpha^2)\left\{\left(2aI + c\alpha^2\right)^2 - 8bc^2I\alpha^2 + \mu\left[c^2\alpha^2(4bI-\alpha^2) + 4a^2I^2\right]\right\}}{8I\alpha^2(a-bc)(2aI - c\alpha^2 + 2bcI)}. \quad (8)$$

Proof: Substitute $\boldsymbol{p}_n^* = \boldsymbol{p}_c^*$ and $\boldsymbol{\theta}_n^* = \boldsymbol{\theta}_c^*$ into **Eq. 3**. When it equals **Eq. 6**, we get the optimal platform usage rate as **Eq. 8** in the case $\boldsymbol{a} > 2\boldsymbol{bc}$.

Under certain conditions, the Nash bargaining contract can raise both members' profit, which coordinates better than the decentralized channel. Since $\boldsymbol{\lambda}_n^*$ is the optimal decision, this ensures a win-win situation. Regarding the excess profit, it will depend on the members' bargaining power.

Rubinstein Bargaining Contract

Nash bargaining ends in negotiations between manufacturers and e-commerce platforms in one stage. However, in practice, every member can make a bargain by rejecting a previous idea and creating a new offer. Therefore, Rubinstein bargaining contracts come to this stage. More specifically, the manufacturer and e-commerce platforms take turns quoting the channel profit of the centralized decision. They will not reach an agreement until a mutually satisfactory distribution plan is obtained.

Suppose the manufacturer first proposes a distribution scheme $(\Pi^{C*} - \boldsymbol{y}, \boldsymbol{y})$, and then the e-commerce platform decides to accept or reject it. If he accepts it, this process ends; if the platform rejects the plan, he will propose a new distribution scheme in stage 2, and the manufacturer makes a decision. If he accepts, the negotiation process ends; if he refuses, he will propose a new distribution scheme plan in the third period, and so on, until the two parties reach a consensus distribution scheme. Since patience is limited in the negotiation process, it is assumed that the discount factor of the manufacturer is $\boldsymbol{\delta_M}$, and the platform is $\boldsymbol{\delta_R}$, which is determined by patience of negotiating parties. Under the decentralized channel, each member can obtain at least profits Π_d^{M*} and Π_d^{R*}, which is the lowest bound of the bargaining scheme. The following starts from the finite-term situation (the game is played in 1, 2, and 3 stages):

If the negotiation process ends in stage 1, by the optimal principle, then the manufacturer will propose the distribution scheme as $(\Pi^{C*} - \Pi_d^{R*}, \Pi_d^{R*})$, implying that the manufacturer's optimal profit is $\Pi^{C*} - \Pi_d^{R*}$, and the e-commerce platform undertakes Π_d^{R*}.

If the negotiation is carried out in stage 2, after the first negotiation in stage 1, the manufacturer can no longer propose a distribution scheme. Meanwhile, the e-commerce platform will propose $(\Pi_d^{M*}, \Pi^{C*} - \Pi_d^{M*})$ in stage 2. The e-commerce platform's profit is equivalent to $\boldsymbol{\delta_R}(\Pi^{C*} - \Pi_d^{M*})$ in stage 1. In stage 1, the e-commerce platform can get profit distributed by the manufacturer of no less than $\Pi_R^{(2)} = \boldsymbol{max}\{\Pi_d^{R*}, \boldsymbol{\delta_R}(\Pi^{C*} - \Pi_d^{M*})\}$. This results in the optimal decision in stage 2, that is, $(\Pi^{C*} - \Pi_R^{(2)}, \Pi_R^{(2)})$.

PROPOSITION 3.

1) If $\boldsymbol{\delta_R} \le \frac{\Pi_d^{R*}}{\Pi^{C*} - \Pi_d^{M*}}$, then $\Pi_R^{(2)} = \Pi_d^{R*}$, the optimal results in stage 1 and stage 2 are the same
2) If $\boldsymbol{\delta_R} > \frac{\Pi_d^{R*}}{\Pi^{C*} - \Pi_d^{M*}}$, then $\Pi_R^{(2)} = \boldsymbol{\delta_R}(\Pi^{C*} - \Pi_d^{M*}) > \Pi_d^{R*}$. Compared to the results of stage 1, the manufacturer will obtain less profit, but the e-commerce platform will get more;

If the negotiation is carried out in stage 3, then we will deduce the result reversely. First, in stage 3, the manufacturer will provide the scheme $(\Pi^{C*} - \Pi_d^{R*}, \Pi_d^{R*})$, which is equal to the profit in stage 2, say $\boldsymbol{\delta_M}(\Pi^{C*} - \Pi_d^{R*})$. Since the e-commerce platform in stage 2 set the distribution scheme as $\boldsymbol{max}\{\Pi_d^{M*}, \boldsymbol{\delta_M}(\Pi^{C*} - \Pi_d^{R*})\}$, they will obtain the profit $\Pi^{C*} - \boldsymbol{max}\{\Pi_d^{M*}, \boldsymbol{\delta_M}(\Pi^{C*} - \Pi_d^{R*})\}$. This is equal to the profit $\boldsymbol{\delta_R}(\Pi^{C*} - \boldsymbol{max}\{\Pi_d^{M*}, \boldsymbol{\delta_M}(\Pi^{C*} - \Pi_d^{R*})\})$ in stage 1. Therefore, when in stage 1, the manufacturer will set

e-commerce platform's profit no less than $\Pi_R^{(3)} = \boldsymbol{max}\{\Pi_d^{R*}, \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{max}\{\Pi_d^{M*}, \boldsymbol{\delta}_M(\Pi^{C*} - \Pi_d^{R*})\}\}$. Then in Rubinstein bargaining contract of stage 3, the optimal distribution scheme is $(\Pi^{C*} - \Pi_R^{(3)}, \Pi_R^{(3)})$.

PROPOSITION 4.

1) If $\boldsymbol{\delta}_M \le \frac{\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{R*}}, \boldsymbol{\delta}_R \le \frac{\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{M*}}$ or $\boldsymbol{\delta}_M > \frac{\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{R*}}, \boldsymbol{\delta}_M\boldsymbol{\delta}_R \ge \frac{\boldsymbol{\delta}_R\Pi^{C*}-\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{R*}}$, then $\Pi_R^{(3)} = \Pi_d^{R*}$, implying that the distribution scheme in stage 3 is the same as stage 1
2) If $\boldsymbol{\delta}_M \le \frac{\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{R*}}, \boldsymbol{\delta}_R > \frac{\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{M*}}$, then $\Pi_R^{(3)} = \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*}) > \Pi_d^{R*}$. Compared with scheme in stage 1, the manufacturer gets more profit, but the e-commerce platform gets less profit
3) If $\boldsymbol{\delta}_M > \frac{\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{R*}}, \boldsymbol{\delta}_M\boldsymbol{\delta}_R < \frac{\boldsymbol{\delta}_R\Pi^{C*}-\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{R*}}$, then $\Pi_R^{(3)} = \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{\delta}_M(\Pi^{C*} - \Pi_d^{R*})) > \Pi_d^{R*}$. Compared to results in stage 1, the manufacturer obtains fewer profits, but the e-commerce platforms hold greater profits.

If negotiating indefinitely, then the e-commerce platform has profit $\boldsymbol{y} = \boldsymbol{max}\{\Pi_d^{R*}, \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{max}\{\Pi_d^{M*}, \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y})\}\}$. This is because of the subgame is isomorphic to the whole bargaining game.

THEOREM 4.1) If

$$\boldsymbol{\delta}_M \le \frac{\Pi_d^{M*}}{\Pi^{C*} - \Pi_d^{R*}}, \boldsymbol{\delta}_R \le \frac{\Pi_d^{R*}}{\Pi^{C*} - \Pi_d^{M*}} \text{ or } \boldsymbol{\delta}_M > \frac{\Pi_d^{M*}}{\Pi^{C*} - \Pi_d^{R*}}, \boldsymbol{\delta}_M\boldsymbol{\delta}_R \ge \frac{\boldsymbol{\delta}_R\Pi^{C*} - \Pi_d^{R*}}{\Pi^{C*} - \Pi_d^{R*}}$$

, then the distribution scheme of indefinite Rubinstein bargaining contract is $(\Pi^{C*} - \Pi_d^{R*}, \Pi_d^{R*})$, and the platform usage rate is $\boldsymbol{\lambda}_{RB}^* = \frac{(4\boldsymbol{bI}-\boldsymbol{\alpha}^2)[(2\boldsymbol{aI}+\boldsymbol{c\alpha}^2)^2+8\boldsymbol{cI\alpha}^2(\boldsymbol{a}-\boldsymbol{bc})]}{8\boldsymbol{I\alpha}^2(\boldsymbol{a}-\boldsymbol{bc})(2\boldsymbol{aI}-\boldsymbol{c\alpha}^2+2\boldsymbol{bcI})}$

2) If$\boldsymbol{\delta}_M\boldsymbol{\delta}_R \ge \frac{\boldsymbol{\delta}_M\Pi^{C*}-\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{M*}}, \boldsymbol{\delta}_R > \frac{\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{M*}}$, then the distribution scheme of the indefinite Rubinstein bargaining contract is $(\Pi^{C*} - \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*}), \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*}))$, and the platform usage rate is $\boldsymbol{\lambda}_{RB}^* = \frac{\boldsymbol{\delta}_R(4\boldsymbol{bI}-\boldsymbol{\alpha}^2)[\boldsymbol{a}(2\boldsymbol{aI}+\boldsymbol{c\alpha}^2)+\boldsymbol{bc}^2\boldsymbol{\alpha}^2]}{2\boldsymbol{\alpha}^2(\boldsymbol{a}-\boldsymbol{bc})(2\boldsymbol{aI}-\boldsymbol{c\alpha}^2+2\boldsymbol{bcI})}$
3) If $\frac{\boldsymbol{\delta}_M(1-\boldsymbol{\delta}_R)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M} > \frac{\Pi_d^{M*}}{\Pi^{C*}}, \frac{\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M} > \frac{\Pi_d^{R*}}{\Pi^{C*}}$, then the distribution scheme of the indefinite Rubinstein bargaining contract is $(\frac{1-\boldsymbol{\delta}_R}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M}\Pi^{C*}, \frac{\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M}\Pi^{C*})$, and the platform usage rate is $\boldsymbol{\lambda}_{RB}^* = \frac{(4\boldsymbol{bI}-\boldsymbol{\alpha}^2)[\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)(\boldsymbol{a}-\boldsymbol{bc})+2\boldsymbol{bc}(1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M)]}{2\boldsymbol{b}(2\boldsymbol{aI}-\boldsymbol{c\alpha}^2+2\boldsymbol{bcI})(1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M)}$.

Proof: For $\boldsymbol{y} = \boldsymbol{max}\{\Pi_d^{R*}, \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{max}\{\Pi_d^{M*}, \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y})\}\}$, if $\Pi_d^{M*} \ge \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y})$, then $\boldsymbol{y} = \boldsymbol{max}\{\Pi_d^{R*}, \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*})\}$; if $\Pi_d^{R*} \ge \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*})$, then $\boldsymbol{y} = \Pi_d^{R*}$, and hence $\boldsymbol{\delta}_M \le \frac{\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{R*}}$, $\boldsymbol{\delta}_R \le \frac{\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{M*}}$. Set $\boldsymbol{p}_{RB}^* = \boldsymbol{p}_c^*$, $\boldsymbol{\theta}_{RB}^* = \boldsymbol{\theta}_c^*$, the optimal platform usage rate is $\boldsymbol{\lambda}_{RB}^* = \frac{(4\boldsymbol{bI}-\boldsymbol{\alpha}^2)[(2\boldsymbol{aI}+\boldsymbol{c\alpha}^2)^2+8\boldsymbol{cI\alpha}^2(\boldsymbol{a}-\boldsymbol{bc})]}{8\boldsymbol{I\alpha}^2(\boldsymbol{a}-\boldsymbol{bc})(2\boldsymbol{aI}-\boldsymbol{c\alpha}^2+2\boldsymbol{bcI})}$.

If $\Pi_d^{R*} < \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*})$, then $\boldsymbol{y} = \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*})$, and hence $\boldsymbol{\delta}_M\boldsymbol{\delta}_R \ge \frac{\boldsymbol{\delta}_M\Pi^{C*}-\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{M*}}$, $\boldsymbol{\delta}_R > \frac{\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{M*}}$. Set $\boldsymbol{p}_{RB}^* = \boldsymbol{p}_c^*$ and $\boldsymbol{\theta}_{RB}^* = \boldsymbol{\theta}_c^*$, we get the platform usage rate $\boldsymbol{\lambda}_{RB}^* = \frac{\boldsymbol{\delta}_R(4\boldsymbol{bI}-\boldsymbol{\alpha}^2)[\boldsymbol{a}(2\boldsymbol{aI}+\boldsymbol{c\alpha}^2)+\boldsymbol{bc}^2\boldsymbol{\alpha}^2]}{2\boldsymbol{\alpha}^2(\boldsymbol{a}-\boldsymbol{bc})(2\boldsymbol{aI}-\boldsymbol{c\alpha}^2+2\boldsymbol{bcI})}$.

If $\Pi_d^{M*} < \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y})$, then $\boldsymbol{y} = \boldsymbol{max}\{\Pi_d^{R*}, \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y}))\}$; if $\Pi_d^{R*} \ge \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y}))$, then $\boldsymbol{y} = \Pi_d^{R*}$, and hence $\boldsymbol{\delta}_M > \frac{\Pi_d^{M*}}{\Pi^{C*}-\Pi_d^{R*}}$, $\boldsymbol{\delta}_M\boldsymbol{\delta}_R \ge \frac{\boldsymbol{\delta}_R\Pi^{C*}-\Pi_d^{R*}}{\Pi^{C*}-\Pi_d^{R*}}$; if $\Pi_d^{R*} < \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y}))$, then $\boldsymbol{y} = \boldsymbol{\delta}_R(\Pi^{C*} - \boldsymbol{\delta}_M(\Pi^{C*} - \boldsymbol{y}))$, that is, $\boldsymbol{y} = \frac{\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M}\Pi^{C*}$. Then $\frac{\boldsymbol{\delta}_M(1-\boldsymbol{\delta}_R)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M} > \frac{\Pi_d^{M*}}{\Pi^{C*}}, \frac{\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M} > \frac{\Pi_d^{R*}}{\Pi^{C*}}$. Set $\boldsymbol{p}_{RB}^* = \boldsymbol{p}_c^*$ and $\boldsymbol{\theta}_{RB}^* = \boldsymbol{\theta}_c^*$, then the platform usage rate is $\boldsymbol{\lambda}_{RB}^* = \frac{(4\boldsymbol{bI}-\boldsymbol{\alpha}^2)[\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)(\boldsymbol{a}-\boldsymbol{bc})+2\boldsymbol{bc}(1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M)]}{2\boldsymbol{b}(2\boldsymbol{aI}-\boldsymbol{c\alpha}^2+2\boldsymbol{bcI})(1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M)}$.

The Rubinstein bargaining contract can perfectly coordinate our supply chain. The optimal platform usage rate and distribution scheme of channel profits depend on the lower profit limit and patience of each member. In this case, members' profits can be guaranteed. When the patience of each member is weak or the manufacturer's patience performs higher than some threshold, the optimal decision of manufacturer and platform is $(\Pi^{C*} - \Pi_d^{R*}, \Pi_d^{R*})$; when the patience of the manufacturer increases and platform's patience is higher than some threshold, then optimal allocation is $(\Pi^{C*} - \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*}), \boldsymbol{\delta}_R(\Pi^{C*} - \Pi_d^{M*}))$; when the patience of each member is high enough, then the manufacturer and e-commerce platform will press proportional profit distribution, the optimal distribution is $(\frac{1-\boldsymbol{\delta}_R}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M}\Pi^{C*}, \frac{\boldsymbol{\delta}_R(1-\boldsymbol{\delta}_M)}{1-\boldsymbol{\delta}_R\boldsymbol{\delta}_M}\Pi^{C*})$.

CASE STUDY

In this section, the previous theoretical analysis is verified through numerical calculations and managerial insights. Set $\boldsymbol{a} = 1000$, $\boldsymbol{b} = 50$, $\boldsymbol{c} = 6$, $\boldsymbol{I} = 10$, $\boldsymbol{\alpha} = 40$. **Table 1** shows results of optimal profit and optimal solution under different models.

Data in **Table 1** verifies that price, greenness, and total profit in centralized channels are all higher compared to the decentralized one. This is a motivation to find a method to coordinate the decentralized channel in reaching the centralized channel's profit. At the same time, every member obtains more than the lowest profit bound, that is, the profit in the decentralized channel. Under the Nash bargaining coordination contract, the platform usage rate increases in bargaining power $\boldsymbol{\mu}$. Excess profit depends on bargaining power. When the bargaining power increases, profit of the e-commerce platform increases, but the profit of the manufacturer decreases. Although the platform usage rate decreases under the Nash bargaining contract, both members obtained more profits than the decentralized case, achieving a win-win state. Under the Rubinstein bargaining coordination contract, the decentralized channel can also be coordinated. Each member's profit depends on the lowest profit bound and bargaining patience:

1) When the manufacturer is very patient, that is, $\boldsymbol{\delta}_M = 1$, no matter how the e-commerce platform's patience changes, the manufacturer plays a leading role in obtaining the most profit. Still, the e-commerce platform holds the same profit as in the decentralized channel. This is consistent with the first profit distribution scheme of Theorem 4.
2) When the e-commerce platform performs very patiently, i.e., $\boldsymbol{\delta}_R = 1$, they will get the most profit regardless of how

the manufacturer's patience changes. In contrast, the manufacturer obtains the same profit as in the decentralized channel, which is consistent with the second profit distribution scheme of Theorem 4.

3) When the patience of both sides of the game is higher (less than 1), two members will distribute profits proportionally, which is consistent with the third profit distribution scheme of Theorem 4. In this case, as the patience of both sides increases, the e-commerce platform's patience increases, while the manufacturer's profit decreases, showing that the e-commerce platform plays a leading role. This implies that the stronger the patience of the two members, the more profit the e-commerce platform will get.

Under the first distribution scheme of the Rubinstein bargaining contract, the manufacturer has the strongest degree of patience and the largest profit, which is consistent with the profit distribution scheme when $\boldsymbol{\mu} = 0$ under the Nash bargaining coordination contract. Under the second distribution scheme of the Rubinstein bargaining contract, the e-commerce platform has the strongest degree of patience. His profit is also the largest, and it is consistent with the profit distribution plan when $\boldsymbol{\mu} = 1$ under the Nash bargaining coordination contract. Profits of chain members are quite different under the first two distribution plans, but under the third distribution plan, the difference between members is relatively small.

Whether using the Nash or Rubinstein bargaining coordination contract, it all achieved the performance in a centralized channel. Although the platform usage rates of the two bargaining coordination contracts are both lower compared to the decentralized case, they still obtain more profit than the decentralized cases. The platform and the manufacturer get profits shared according to their bargaining power or patience, and their respective profits all come out higher than the decentralized channel. These two contracts coordinate the conflicts well in a decentralized supply chain, which achieves a win-win situation.

RESULT

During the COVID-19 pandemic, the supply chain has entered a new stage of convergence with e-commerce. Consignment contracts based on electronic markets have become the main development trend of corporate marketing in practice. In our paper, a green supply chain model under consignment contracts is studied. We compare and analyze the effects of a centralized channel and decentralized channel under consignment contracts on price, greenness, and total profit. the centralized channel is beneficial to improve the greenness of products and the profitability of the total supply chain. Not only the price, greenness, and profit of manufacturers are reduced, but also the research and development will be promoted.

In the decentralized channel, the competition of partners will lower the total channel's profit, and each member's profit. To improve the profits of chain members, effectively alleviate conflicts of interest between them, and promote the level of research and development, this paper proposes both Nash and Rubinstein bargaining contract of cooperative game to coordinate a chain model. Manufacturers and e-commerce platforms can negotiate prices, enhance coordination awareness, and reallocate overall profits. After determining a new optimal platform usage rate, they can obtain profits that are not lower than those under a decentralized channel, and achieve a win-win situation.

From the coordination analysis, we show that both the Nash and Rubinstein bargaining contracts can achieve coordination through the adjustment of platform usage rates. It can be seen from the numerical calculation that in Nash bargaining, both members in the supply chain will obtain higher profits as their bargaining power improves; in Rubinstein bargaining, the profits shared by both members in the supply chain are closely related to their respective degrees of patience. Compared with the decentralized channel, the e-commerce platform indirectly promotes the manufacturer to increase research and development by reducing platform usage rate, thereby increasing retail price, greenness, and total profits of the channel.

DISCUSSION

This paper discussed green supply chain coordination under bargaining contracts, which contains one e-commerce platform and one manufacturer. The results have practical significance in a socio-economic environment. Partners can obtain profits based on their bargaining power and patience. To get extra profits than the decentralized channel, they can choose a different bargaining contract to benefit themselves. Comparing to Wang et al. (2019), our model added the greenness into discussion, which extended the research area in green supply chain. But there still exist limitations, which will be the topic of future studies.

Limitations and Future Work

1) With regard to the complexity of our model, there are two members: one e-commerce platform and one green manufacturer. But in reality, there may be more participants in the channel. We aim to investigate the optimal decisions in the model, and to coordinate the decentralized channel by consignment contracts.
2) By the assumption of our paper, the model is static, and this can be extended to a dynamic one. Moreover, there exist uncertainty factors in the consumer market, such as product recommendations, credit payment discounts, advertisement, consumer preference, etc., so the demand function can be extended to a stochastic one.

3) In order to encourage the development of the green supply chain, governments across the world have unveiled "Environmental Economic and Policy." It turns out that the participation of government is very necessary. In our future work, we can consider the participation of government, such as subsidy or tax. Under this circumstance, enterprises will take active participation in greening products, protecting the environment, and achieving a win-win situation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YW issued the idea and designed for the research. YW and LZ analyzed the model and drafted the paper. GR and WD-M edited and revised the paper critically.

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Mediating Role of Risk Perception and Environmental Quality on the Relationship Between Risk Knowledge and Traveler's Intention in COVID-19

Dongxu Yang[1], Ning Fang[2], Edwin Ramirez-Asis[3], Yasser Alashker[4,5], Mohammed A. S. Abourehab[6] and Kun Zhang[7]*

[1]Tourism College of Zhejiang, Hangzhou, China, [2]School of Social Development and Management, Hunan Women's College, Changsha, China, [3]Computer Science and Engineering, Universidad Señor de Sipán, Chiclayo, Peru, [4]Civil Engineering Department, King Khalid University, Abha, Saudi Arabia, [5]Structural Engineering Department, Zagazig University, Zagagzig, Egypt, [6]Department of Pharmaceutics Faculty of Pharmacy Umm Al-Qura University, Makkah, Saudi Arabia, [7]School of Economics, Tianjin University of Commerce, Tianjin, China

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***Correspondence:**
Ning Fang
349508218@qq.com

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The recent outbreak of epidemic disease (COVID-19) has dramatically changed the socio-economic and environmental dynamics of the world. In particular, it affects human movement, travel intentions, and ambient air pollution amid rising stringency measures. Therefore, this study examines the influence of tourism knowledge, environmental vulnerability, and risk knowledge on travelers' intentions in China's tourism industry during COVID-19. To address the study objectives, an online survey questionnaire was created, through which a valid sample of 402 respondents was achieved. The direct and indirect relationship between variables was tested through structural equation modeling, the outcomes confirm that both tourism knowledge and risk knowledge in terms of COVID-19 significantly and negatively define the travelers' intention toward tourism. Moreover, environmental vulnerability moderately affected tourism behavior and augmented with COVID-19 stringency disclosures. The mediating effect of risk perception and attitude towards the relationship between exogenous and endogenous constructs was tested. It shows a significant mediating impact of risk perception, environmental hazards and attitude towards risk on the nexus between tourism knowledge and travelers' intention. The study offers valuable recommendations for policymakers to understand tourist intentions and climate vulnerability.

Keywords: social consequences, COVID-19, risk perception, tourism industry, climate vulnerability, China

INTRODUCTION

The year 2020 saw the outbreak of a global pandemic of Coronavirus that severely impacted a variety of work sectors. The collapse of expenditures in the outsourcing sector caused detrimental damage to various services such as tourism, transport, retail, entertainment, and catering (Xuefeng et al., 2021; Irfan et al., 2022). According to the World Tourism and Travel Council (WTTC) survey, a considerable loss of nearly $22 billion will face the global tourism industry due to the spread of COVID-19 (Zhu and Deng, 2020). China faced immediate loss in the tourism sector as the spring

Festival in 2020 was canceled due to the pandemic costing 55 billion Yuan to the economy. As per the reports of the China Tourism Academy, the number of travelers dropped by 15.5% in 2020. The amount generated by the domestic or rural tourism industry also shrank by 20.6% in 2020, causing a considerable reduction in tourism revenue by 1.18 trillion Yuan (Jin and Park, 2019). Survey reports have shown that COVID-19 caused a significant crisis in the tourism sector (Manzoor et al., 2019).

The COVID-19 outbreak first hit China at the start of January 2020, causing most Chinese citizens to go into self-isolation (Irfan et al., 2021a). As per the findings of the Wind database, the favorable ratio of COVID-19 cases in China reduced in late February 2020. Meanwhile, the number of positive COVID-19 cases in foreign countries surpassed that of China in March 2020. The pandemic spread was brought under effective control across China through various isolation measures that also raised many Chinese residents' desire to go escape isolation. At that stage, a rural tourism policy might be the first choice to satisfy the desire of people to come out of isolation. Rural tourism provides several benefits such as short time consumption, low travel cost, low flow density, and the development of rural areas (Rudyanto et al., 2021; Razzaq et al., 2022). Rural tourism could also psychologically fill the requirements of people to enjoy natural beauty in safety while going out for a visit. In addition, people have shifted their concern towards rural tourism, whereas governments have a major focus on controlling the outbreak of COVID-19. Thus, rural tourism can provide a valuable opportunity for the economy to create rapid recovery (Zhu and Deng, 2020).

As stated by Wang et al. (2021), risk perception is the starting point to judge the crisis impact on the tourism sector. The preference and behavior of people become influenced by the perceived risk of pandemic spread in the wake of a public health emergency. Some researchers have proposed that the perceived risk accounted for the behavior of the tourism industry behavior compared to the perceived value (Mitchell and Vassos, 2008). Research in this area is currently exclusively concentrated on the effects of emergencies on the tourist business and general travel intention, ignoring the examination of various types of traveling and people's choices. To begin with, COVID-19 has had a more significant impact than SARS, which first appeared in 2003. Chinese people have attained accurate and mature knowledge of dealing with the spread of the pandemic that can be seen by concrete preventive measures undertaken during COVID-19. Hence, Chinese residents can be taken primarily as the research object for an impact study of the epidemic for better results. In addition, based on the push-pull theory, people have links with traveling from the purpose and needs of travel (Kastenholz et al., 2012; Irfan et al., 2021b; Zhuang et al., 2021). After a long time of isolation, people will take the initiative to get some relaxation from pandemic issues in all sectors. The given research paper mainly focuses on investigating peoples' behavioral intentions. The Chinese government has announced the complete reopening of rural tourist sites. The natural scenery is compelling for relaxation, reducing stress caused by COVID-19, and progressive parent-child relationships through natural tourism. As indicated in the research, the density of tourist flow through rural tourism is very low compared to internal activities such as science, technology, and museums sites (Han et al., 2019; Razzaq et al., 2020; Sun et al., 2021).

This study aims to determine people's willingness to get involved in rural tourism in the wake of an epidemic and the elements they would consider when making that decision. This paper introduces three new concepts. Due to the features of epidemic situations, the aspect of recognized danger was more persuasive in studying tourism intention than the perceived usefulness and quality. Secondly, the research paper has provided "avoidance behavior theory" for rural tourism to analyze tourist intentions regarding traveling and the internal factors that can impact the tourist intentions. Thirdly, the model of knowledge-attitude-behavior (KAB) was proposed in tourism studies (Mowen and Minor, 1998). For the given research study, research was undertaken based on risk perception. Tourism managers must provide careful considerations to risk perception factors and propose a liable plan for tourism development because it is difficult for consumers to accept the risk factors in tourism (Chhay et al., 2015). Research results have provided a reference for the development of tourism in rural areas during the pandemic of COVID-19.

LITERATURE REVIEW

Tourism Risk Perception

The research work of Bauer Pandy and Rogerson (2019) first proposed the theory of perceived risk and raised the concept of risk in marketing to apply it to consumer behavior. Glowka and Zehrer (2019) provided perceived risk as to the likelihood of negative results in a given task. Based on these research studies, tourism risk perception was termed as individual decisions by tourists that can lead to negative consequences in the tourism sector (McCreary et al., 2018). This negative perception by people can increase as a result of crisis events. Different perceived risks have been determined in people with varying personal characteristics (Cater, 2006). According to the research analysis of Cohen et al. (2014), older people regarding travel experiences such as terrorism, health risks, and natural disasters show less awareness of perceived risks. A wide range of perception ideas was taken from older people (Meng et al., 2021), which pointed to a higher need for guiding and consumer support services for senior citizens. Cui et al. (2016) suggested that women can have a higher perception of food and health risks, while foreign visitors with vast traveling experience may have lower perception than seasonal visitors.

Perceived tourism risks may include satisfaction, time, social, psychological, physiological, capital, and security risks (Zaman et al., 2022). Tourism risk perception provides multi-dimensional aspects of risk. Stone and Grønhaug (1993) verified the existence of six risk dimensions and operational and financial risks. Rudyanto et al. (2021) argued that there are various, various risk perceptions have been determined. These perceptions are crisis risks, operational risks, and cultural-conflict risks. As indicated by Zhu and Deng (2020) covers some other factors

entitled as service risks and equipment risks for tourists. Yang and Xia (2020) focused on operational, physical, cost-related, and psychological risks while dealing with the tourism risk perception. Many other research studies have also analyzed risk perception of time, financial, and equipment risk. Time and financial risks can be combined in the form of cost risk; hence, the seven dimensions have been shifted to six dimensions of risk perception: physical, psychological, performance, cost, social, and equipment risk (Zaman et al., 2022).

Impact of Risk Knowledge on Risk Perception

The uncertainty involved in events initiates risk perception within a particular task (Lepp and Gibson, 2003). The research indicates that foreign tourists who have ample experience of traveling and sufficient knowledge of risk factors in tourism face fewer risks. In the case of a sudden or unknown emergency, the crisis risk perception of tourists will increase significantly. Along with the example of earthquake risk, Wang et al. (2021) provided various negative impacts of earthquake risk perception among tourists and suggested that tourist risk perception of any risk can decrease significantly with increased awareness. Jiang et al. (2022) provided a close relationship between risk perception and knowledge based on multiple linear regression models. Wei (2021) studied the impact of interest development and information acceptance on public perceptions of risk in different sectors, finding that mastery of risk-related knowledge has a detrimental impact on public perceptions. They confirmed the “knowledge weakening hypothesis of public risk perception” and found that risk knowledge negatively impacted risk perception using typology methods. A study by the WHO (2021) provided the factors impacting tourists’ risk perception regarding food additives and revealed that consumer awareness of food additives entails a significant negative impact on risk perception. An emergency for public health was declared during the outbreak of the Coronavirus pandemic. Risk knowledge of Pneumonia and tourism risk knowledge have been taken as dependent variables to determine the impact of the COVID-19 pandemic on people’s behavioral intentions regarding rural tourism. The following hypotheses have been generated in the given research report based on the negative relationship between variables:

H1: There is a significant impact of tourism knowledge on the recommended intention.

H2: There is a significant impact of tourism knowledge on travelers’ intentions.

H3: Knowledge about Pneumonia is significantly linked with recommended intention.

H4: Knowledge about Pneumonia is significantly linked with travelers’ intentions.

H5: There is a significant impact of tourism knowledge on risk perception.

H6: There is a significant impact of knowledge about pneumonia/COVID-19 on risk perception.

Risk Knowledge Impact on Risk Aversion Attitude

Various studies have been conducted to determine the influence of scientific knowledge, universality, tactic knowledge, and shared knowledge on acceptance or risk perception (Acheampong et al., 2021). Knowledge was distributed into three factors—social information, major-oriented knowledge, and general knowledge (Browning et al., 2021). For most people, knowledge of risk comes from general and social information. There has been a positive interconnection between aversion attitude and knowledge, similarly to the concept that medical information can eliminate the discrepancy caused by some diseases (WHO, 2021). However, a negative connection is found between risk aversion and risk knowledge in fields other than the medical. In terms of the popularization of nuclear power, the higher the subjective knowledge someone posesses, the more acceptance they have of the hazards of this power source and the less willing they are to avoid them (Levi and Holder, 1998). Knowledge of financial aspects was linked positively with risk choice attitude in financial scenarios, while the attitude of risk preference was positively correlated with finance market engagement. A significant mediating variable was risk preference attitude. The research study found that social interaction between people will enhance the ability of risk knowledge to take risks.

The difference in risk acceptance was caused due to different cost structures and benefits of behavior. In the medical and health sectors, disease risk is directly linked to an individual’s health; hence the cost proportion of the risk becomes higher than the positive outcome. While in the case of outbound tourism and professional investment, the cost of travel/investment risk is less, and benefits are more. This concept states that getting a master of risk knowledge can enhance the acceptance of risks. People are found to be acting rationally when they are affected by risks and try to avoid the risk entirely or partially (Mäser and Weiermair, 1998). To reduce the expected losses, more consumers prefer a partial avoidance based on risk knowledge while entertaining the benefits developed by the behavior as provided in the research of formulation of a response plan, advance confirmation of risk information, and prompt selection of travel time based on risk attributes (Tsaur et al., 1997). Rural tourism has been termed an incomplete risk avoidance in correlation with travel in the research paper.

People will display a responsive attitude toward tourist risk and eliminate the risk avoidance tendency after obtaining more risk information, according to the hypothesis produced in the given paper based on the qualities of risk attitude and risk knowledge towards rural tourism. To match the risk perception in this study work, the attitude of risk aversion was used as a mediating variable. Based on this risk perception, the following hypotheses were proposed:

H7: Tourism knowledge is significantly linked with the attitude towards risk.

H8: Risk of Pneumonia/COVID-19 is significantly linked with the attitude towards risk.

Risk Perception Impacts on Behavioral Intention

Tourists' perceptions of risk may have a significant impact on their decisions. Risk perception in a particular dimension can increase the total degree of tourism risk perception (Roehl and Fesenmaier, 1992). A reduced likelihood of potential visitors can lead to a higher likelihood of tourists limiting risks through risk aversion. The majority of research found was on the impact of quality service on tourism. Tourist intention was positively connected with transportation convenience, safety, tourism information, accommodation convenience, travel providers, rest time, and conforming psychology. The factors mentioned earlier can be converted into a positive relationship with risk perception factors and tourism intentions. (Sönmez and Graefe, 1998) proved in research that geographical damage, safety concerns, damage to equipment, ethical conflicts, psychological taboo, tourism intention, and cost concerns contained a direct negative correlation. Another research paper provided by Sun and Razzaq (2022) determined the negative impacts of political risk, social risk, and cultural risk on the tourism sector of Japan. They analyzed the factors affecting the willingness to utilize balance values. According to the study, consumers will be positively influenced by perceived utility, perceived simplicity of use, subjective norms, benefits, and behavioral control. Economic risk, security risk, and time risk, on the other hand, posed a negative impact on customer willingness. This study investigated the effects of COVID-19 on tourist behavior intention. The following hypothesis is proposed:

H9: Tourism risk perception is significantly linked with the travelers' intentions.

H10: Tourism risk perception is significantly linked with the recommended intentions.

H11: There is a significant relationship between attitude towards risk and recommended intentions.

H12: There is a significant relationship between attitude towards risk and travelers' intention.

H13: There is a significant mediating effect of risk perception on the relationship between tourism knowledge and travelers' intentions.

H14: There is a significant mediating effect of risk perception on the relationship between knowledge about phenomena and recommended intentions.

Risk Knowledge, Risk Aversion Attitude, and Behavioral Intention Model

Risk attitude can be stated as a consumer's compatible choice towards facing the various risk levels or acceptance of consumers to accept risk. This is termed an intrinsic risk selection characteristic (Weber et al., 2002). Individuals' risk attitudes are influenced by their expected outcomes and perceived dangers, with perceived risks negatively linked with risk attitudes. Pennings et al. (2002) identified disparities in risk acceptance among people when accounted for unique consumer behavior. Hence, it is determined that perceived risks alone cannot back the results of the given research study. Furthermore, an increase in risk perseverance can affect their buying behavior in the case of risk-averse consumers. Therefore, risk attitude and risk perception can affect the behavioral perception simultaneously.

Risk-averse and risk-neutral people were found to be choosing their vaccination to avoid the risk presented by the pandemic, compared to risk seekers. The research study of Schroeder et al. (2007) showed that decision-making perception is directly affected by the difference in individual risk attitudes. It states that risk avoiders focus on bad outcomes, while risk seekers focus on good outcomes. Finance information was seen to affect the stock market and retail market positively. At the same time, the consumers with a perception of risk own less market stock as compared to those people who deal with risk aversion and attain higher shares in the market. In the case of rural tourism, avoiders of risk pay more heed to the results of a rural tour, while the risk avoiders will have less desire for the tour. In the case of rural tourism, risk avoidance pays more heed to the results of a rural tour.

This paper established the structure of "risk knowledge-risk perception-behavioral intention" and compared it to the "Knowledge-attitude-behavior" (KAB). This model divides the variations in consumers' behavioral intentions into three processes: developing belief, attaining knowledge, and forming behavior (Maser and Weiermair, 2008). The KAB model primarily works to explore the correlation between attitude, knowledge, and behavior, unlike the other models provided for consumer behavior. Based on other theoretical consumer behavior models given in the literature as the planning behavior model states that knowledge is taken as an outer variable that can influence a consumer's attitude. In the case of consumer behavior, control of subjective norms, attitudes, and perceived behavior can be taken as influencing factors. Knowledge perceptions are not the central focus of this research study. The given research study includes the impacts of risk knowledge on the consumer's behavioral intention through the KAB model.

KAB has found its applications in a wide range of education, public health, and clinical medicine. Based on the model of attitude-related behaviors of Chinese universities' sexual knowledge, Saurabh and Nandan (2019) provided that a neutral attitude puts partial impact on sexual-related behaviors based on adequate knowledge of sexual health. Baron and Herzog, (2020) approved the impact of attitude, actions, and knowledge by applying the structural equation model and termed it as an indirect outcome of knowledge on an individual's thinking in the case of hypertension. Hence, it can be determined that a consumer's attitude can be a mediating variable in the correlation between behavior and knowledge. Therefore, this paper proposed the following hypothesis based on rural tourism and KAB theory characteristics.

H15: There is a significant mediating effect of attitude towards risk on the relationship between tourism knowledge and travelers' intentions.

H16: There is a significant mediating effect of attitude towards risk on the relationship between knowledge about phenomena and recommended intentions.

Many risk perception factors affect the consumer's behavior intention, although there are varying influencing aspects for different tourism scenarios. In the case of overseas and domestic tourism, such influencing factors of perceived risk are natural disasters, political situation, public health, and safety. (Huang and Min, 2002). analyzed the impacts of political risk in overseas tourism. The research study of (Academia 2021) concluded that cultural conflict affects tourists' foreign travel choices. Individual attributes of consumers are also the main factor of differences in consumer behavior. They also investigated the variations in perceived risk under different genders and cultural aspects. The given paper mainly implies rural tourism areas that are close to the residing places of the research interviewees. Hence, cultural conflict and political risk factors are not included in the study. To determine the personal information of tourists, descriptive statistical analysis was implemented.

Government-oriented policies and media aspects are considered sources of risk knowledge that will impact consumer behavior. As stated earlier, the example of Taiwan has been taken as the study of earthquake risk and tourism damage; the survey suggested that media reports were established on the tourism damage that potentially affected the tourism on Taiwan Island (Larsen et al., 2009). Media coverage of a natural disaster can reduce the number of visitors and potential visitors, further complicating the post-disaster recovery of some industries such as tourism (Tasci and Gartner, 2016). Under the direction of the Chinese government, state media reports have taken a significant role in the distribution of information. Residents of China have gained correct and practical knowledge about the associated risks during the time of their isolation. This was possible through participating in and implementing the policies on control and prevention of COVID-19. Hence, media reports were not included in the proposed model as an independent variable for the given study.

TABLE 1 | Demographic factors.

Gender	Frequency	%	Cumulative %
Man	194	48.3	48.3
Woman	208	51.7	100.0
Total	402	100.0	
Marital Status			
Married	326	81.1	81.1
Unmarried	76	18.9	100.0
Total	402	100.0	----
Age			
15–20 Years	101	25.1	25.1
20–23 Years	188	46.8	71.9
23–27 Years	45	11.2	83.1
above 27 Years	68	16.9	100.0
Total	402	100.0	---
Education			
12 Years	3	0.7	0.7
14 Years	142	35.3	36.1
16 Years or Above	257	63.9	100.0
Total	402	100.0	----

RESEARCH METHODS

Questionnaire Design

The questionnaire design under the present research is based on the items from existing literature. For example, the term risk perception was measured through five things under the shadow of risk performance. The sample items include "At rural tourisms [sic] spots, food and entertainment arrangements are not as expected," "The appreciation of natural scenery and landscape are unsatisfactory," and "Travel photography is not good at rural tourist sites," as extracted from the research contribution of (Zhang and Yu, 2017). Furthermore, the term attitude towards risk is measured through three items observed from the researcher's contribution (Liu et al., 2019; Zhang and Yu, 2017). Both the attitude towards risk and risk perception were treated as critical mediators while exploring the relationship between exogenous and endogenous constructs of the study. The sample items for attitude towards risk include "I cannot accept going to travel to the countryside with family and friends" and "I cannot accept that local friends and relatives travel to the countryside". Moreover, the term tourism the intention was measured through two factors entitled as intention of the tourists and recommendations. The questionnaire items for tourism intention and recommendations were extracted from the research contribution of (Lai and Chen, (2011); Zhao et al., (2016), and Xu et al., (2019), respectively. Both of these factors are treated as primary endogenous constructs under the present study. Finally, the terms tourism knowledge and risk knowledge were treated as the main explanatory variables for which related items were taken from the research work (Feng, 2008; Liu, 2019; Wang et al., 2019; Xu et al., 2019).

After extracting the relevant items for the literature, a questionnaire survey was finalized on the measurement scale of strongly disagree = 1, to strongly agree = 5. The structure of the final questionnaire was covered in three sections. The first section covers the study topic, key objective, and list of the study variables with a shorter definition to understand the respondents better. The second section of the questionnaire covers the selected demographic factors entitled gender, age category, level of education, and current occupation. The third section covers the study items for the explanatory, outcome, and key mediators as measured on the stated scales.

Data Collection

During the outbreak of COVID-19, it is impossible to collect the data through face-to-face interaction; therefore, our study mainly considers the online survey approach. In this regard, both accidental and snowball sampling strategies were used to collect the data from different respondents. More specifically, a respondent-driven sampling approach was applied, which helps reduce the sampling biases and requires respondents to recommend some specific number of peer groups as expressed by Jin and Liu (2016). The questionnaire structure in the online survey covers proper checkboxes and options with simple and easy-to-understand items. The whole data collection process took 5 weeks, from January 15 to 21 February 2022. A total valid response of 402 questionnaires was achieved.

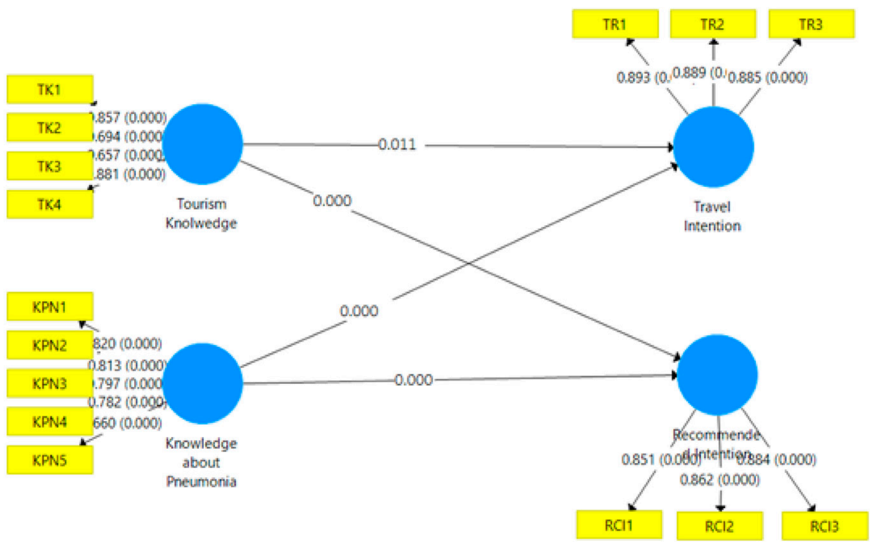

FIGURE 1 | Direct relationship (without mediation).

TABLE 2 | Construct reliability and validity.

Variables	CB.	rho_A	CR.	(AVE)
AT: Attitude towards risk	0.926	0.926	0.953	0.871
TK: Tourism Knowledge	0.799	0.810	0.883	0.718
RI: Recommended Intention	0.879	0.899	0.918	0.739
RP: Risk Perception	0.833	0.850	0.899	0.748
KP: Knowledge about Pneumonia	0.850	0.873	0.899	0.692
TI: Travel Intention	0.868	0.869	0.919	0.791

RESULTS AND DISCUSSION

Demographic Details

Among the targeted respondents, there were 194 men (48.3%), and 208 (51.7%) women, showing that women are dominant in the online questionnaire survey. For the martial status, 81.1% (326) were married, whereas the rest of the respondents were unmarried. For the age distribution, the sample covers all the age groups ranging from 15 to above 27 years where 25.1% of the respondents aged 15.20 years, 46.8% of respondents aged 20–23 years, 11.2% were in the age group of 23–27 years, and finally, 68 or 16.9% were in the age of above 27 years as shown in **Table 1**. Finally, the educational demographics reflect that only 0.7% of respondents were 12 years of education, whereas 35.3 and 63.39% have their 14 and 16 years or above educational level. A better detail of the stated demographic factors has been presented in**Figure 1** below through pie charts and relative % scores.

Measurement Model Assessment

For assessing the outer mode/measurement model, Smart PLS 3.0 software was applied. More specifically, under measurement model assessment, investigation for the individual item reliability, internal item consistency, convergent validity, and discriminant validity was considered. **Table 2** reports the reliability and validity for all latent constructs, where Cronbach's alpha for all the variables is above 0.70. In contrast, composite reliability (CR) also indicates the reliability of the latent constructs through its relative score for the latent constructs above 0.70. Furthermore, the relative scores in terms of average variance extract for the latent constructs are also reported in **Table 2**. AVE measures the amount of variance captured by a construct with the amount of variance due to measurement error. The threshold level of AVE is 0.50, as expressed by Hair et al. (2010). Therefore, it is inferred that all the latent constructs show acceptable reliability.

Discriminant Validity

The existing literature provides three major approaches for examining discriminant validity: Fornell-Larcker Criterion, loadings and cross-loadings, and Heterotrait-Monotrait Ratio (HTMT). The discriminant validity of the latent constructed Through Fornell-Larcker Criterion is presented in **Table 3**. It shows that the square root of AVE of the stated reflective constructs named attitude towards risk, tourism knowledge, recommended intention, risk perception, ability about Pneumonia, and travel intention is higher than its correlation with another construct. This claims the presence of discriminant validity among the latent constructs.

The reporting for the variance inflation factor for the selected items of the explanatory, outcome, and mediating variables have been presented in **Table 4**. It shows that all the items of these variables have reported a VIF score of below five, which is justified as the threshold in the current literature (Marcoulides and Raykov, 2019; O'brien, 2007). Therefore, the study variables have no issue in terms of multicollinearity.

Structural Equation Modelling Output

Finally, the findings through the SEM approach in Smart PLS 3.0 are provided in **Table 5**. It shows that tourism knowledge is

TABLE 3 | Fornell-larcker criterion.

Variables	AT	KP	RI	RP	RK	TI
AT: Attitude towards risk	0.893					
TK: Tourism Knowledge	0.362	0.780				
RI: Recommended Intention	0.420	0.195	0.865			
RP: Risk Perception	0.438	0.263	0.403	0.794		
KP: Knowledge about Pneumonia	0.286	0.752	0.131	0.133	0.793	
TI: Travel Intention	0.477	0.215	0.776	0.475	0.149	0.889

AT, attitude towards risk; TK, tourism knowledge; RI, recommended intention; RP, risk perception; KP, knowledge about pneumonia; TI, travel intention.

TABLE 4 | Variance inflation factor.

Items	VIF	Items	VIF
1. AT1	3.956	RP2	2.624
2. AT2	3.185	RP3	1.635
3. AT3	3.760	RP4	2.520
4. KPN1	4.062	RP5	1.726
5. KPN2	3.902	TK1	2.733
6. KPN3	2.389	TK3	1.336
7. KPN4	1.482	TK4	3.033
8. RCI1	1.797	TR1	2.449
9. RCI2	1.944	TR2	2.150
10. RCI3	2.101	TR3	2.257

AT, attitude towards risk; TK, tourism knowledge; RCI, recommended intention; RP, risk perception; KP, knowledge about pneumonia; TI, Travel Intention.

TABLE 5 | Direct relationship between the variables.

Directions	Original sample (O)	SD	T-VALUE	Remarks
TK -> RI	–0.175	0.029	6.098***	Supported H1
TK -> TI	–0.205	0.080	2.563**	Supported H2
KPN -> RI	–0.440	0.091	4.835***	Supported H3
KPN -> TI	–0.263	0.077	3.416***	Supported H4

negatively and significantly linked with both endogenous constructs (i.e., recommended intention and travel intention). It shows that more the greater knowledge a traveler has about tourism, the more it lowers their tourism intention. This is because the current study has considered the tourism knowledge in terms of risk dynamics for which respondents are deeply considered while traveling to China. On the other side, the Knowledge of Pneumonia/COVID-19 is another significant indicator that determines the lower tourism intention and recommends intention among the tourists while coming to China. It confirms that higher the knowledge about Pneumonia/COVID-19 is negatively and significantly impacts traveler preference (beta = -0.440, -0.263, *p*-value = 0.000). The above findings clear that H1-H4 are empirically tested and accepted under current research. The structural output for the direct relationship between these variables has been depicted in **Figure 1**. The inner model shows the *p*-values and the outer model reflects the loadings and the relative p-scores, respectively.

After analyzing the direct relationship of the variables without adding both of the mediators, it is confirmed that all the direct paths between independent and dependent variables are significant at 5%. The mediation approach is entitled Baron and Kenny's mediation analysis, where an immediate and significant relationship between exogenous and endogenous constructs is initially required (Hayes, 2009; Zhao et al., 2010). More specifically, there is a need to confirm a significant association between the mediator and dependent variable under this approach. Finally, the researcher must examine the direct effect after controlling for the key mediators in the model. If the addition of a mediator in the model rejects the direct association, the stated findings will be entitled to full mediation; otherwise, it is known as partial or absent (Hadi et al., 2016).

- **Table 6** reports the findings after adding the mediating variables (risk perception and attitude towards risk) into the model. The results show that after adding the mediating variables, the association between KP-RI, KP-TI, TK-RI, and TK-TI is statistically insignificant. However, the findings in **Table 6** report the following major output.
- The path coefficient for the association between AT -> RI (M2toDV2) is positively significant at 1%, with a coefficient of 0.301 based on the original sample.
- The path coefficient for the relationship AT -> TI (M2toDV1) is significant, showing that attitude towards is directly associated with the travelers' intentions in China.
- There is a significant and positive relationship between KP -> AT (IV2toM2), which justifies that more knowledge about COVID-19 is directly linked with the attitude towards risk.
- The path analysis for the direct relationship between risk perception and recommended intention is significant at 1% (beta = 0.274, t-value = 4.72).
- **Table 6** also reports a significant relationship between risk perception and travelers' intention, tourism knowledge and risk perception, knowledge about Pneumonia/COVID-19 and risk perception, and tourism knowledge and attitude towards risk.

Based on the above findings, it is inferred that the direct path between mediators and dependent variables is also statistically significant while creating some insignificant findings for the association between independent and dependent variables. Therefore, such findings will be regarded as mediation on the relationship between tourism knowledge, Knowledge about Pneumonia, travelers' intention,

TABLE 6 | Mediation effect.

Directions	Original sample (O)	Sample mean (M)	STD	T-value	Remarks
TK -> RP(IV1toM1)	0.285	0.286	0.056	5.09	Sig, H5
KP -> RP(IV2toM1)	0.165	0.161	0.083	1.99	Sig, H6
TK > AT (IV1toM2)	0.365	0.358	0.078	4.68	Sig, H7
KP -> AT (IV2toM2)	0.246	0.247	−0.099	2.48	Sig, H8
RP -> TI (M1toDV1)	0.198	0.007	0.074	2.68	Sig, H9
RP -> RI (M1toDV2)	0.274	0.279	0.058	4.72	Sig, H10
AT -> RI (M2toDV2)	0.301	0.303	−0.058	5.19	Sig, H11
AT -> TI (M2toDV1)	0.337	0.339	0.059	5.71	Sig, H12
KP -> RI(IV2toDV2)	−0.006	−0.009	−0.083	0.07	**NS**
KP -> TI(IV2toDVI)	−0.018	−0.013	0.071	0.25	**NS**
TK - > RI(IV1toDV2)	−0.004	−0.002	0.061	0.07	**NS**
TK -> TI(IV1toDV1)	−0.341	0.34	0.285	1.2	**NS**

TK, tourism knowledge; KP, knowledge about Pneumonia; RP, risk perception; AT, attitude towards risk; RI, recommended intention; TI, travelers' intention; IV, independent variable; M1, mediating variable; DV, means dependent variable; NS, not significant; Sig, significant.

TABLE 7 | Examining VAF.

Effects	Path	Path Coefficient	Indirect Effect	Standard Deviation	Total Effect	VAF %	T Values	*p* Value	Decision
Direct without mediator	TK > TI(IV1>DV1)	−0.205	Not applicable				2.563	**	Accepted
Indirect with mediator	TK -> TI(IV1toDV1)	0.341	Not applicable		0.824	**58.61**	3.71	***	Sig, H13
	TK -> RP(IV1toM1)	0.285	0.483	0.13					
	RP -> TI (M1toDV1)	0.198							
Direct without mediator	KP -> RI(IV2>DV1)	−0.440	Not applicable				4.83	***	Accepted
Indirect with mediator	KP -> TI(IV2toDVI)	0.018	Not applicable		0.381	**95.27**	2.59	**	Sig, H14
	KP -> RP(IV2toM1)	0.165	0.363	0.14					
	RP -> TI (M1toDV2)	0.198							
Effects	**Path**	**Path coefficient**	**Indirect effect**	**Standard deviation**	**Total effect**	**Decision**	**T values**	***p* value**	**Decision**
Direct without mediator	TK -> RI(IV1toDV2)	−0.175	Not applicable				6.09	***	Accepted
Indirect with mediator	TK -> RI(IV1toDV2)	0.004	Not applicable		0.67	**99.40**	4.89	***	Sig, H15
	TK > AT (IV1toM2)	0.365	0.666	0.136					
	AT - > RI (M2toDV2)	0.301							
Direct without mediator	KP -> RI(IV2toDV1)	−0.44	Not applicable				3.41	***	Accepted
Indirect with mediator	KP- > RI (IV2toDV2)	0.006	Not applicable		0.704	**77.698**	3.48	***	Sig, H16
	KP- > AT (IV2toM2)	0.246	0.547	0.157					
	AT -> RI (M2toDV2)	0.301							

and recommended intention, respectively. However, to justify the mediating effect as determined by risk perception and attitude towards, indirect effect, total effect, VAF, and relative T-values have been calculated through MS-Excel for this finding, **Table 7**.

As stated earlier, the direct paths between independent and dependent variables were significant; therefore, the inclusion of mediating variables was quite meaningful. For this purpose, an indirect path should be considered to verify the mediating effect of risk perception and attitude. Finally, our findings in **Table 7** provide the outlook regarding the strength of the mediating product through variance accounted for (VAF) as suggested by (Hair et al., 2014). The findings in **Table 7** report that 58.61% of the effect of TK in the TI is explained through risk perception. As this value is between 20%–60%; therefore, it is inferred as a partial mediation. At the same time, 95.27% of the effect of KP in the TI is explained through risk perception. It shows that the value of VAF is above 80%; therefore, it is regarded as full mediation.

Furthermore, the findings in **Table 7** also report the mediating effect of attitude towards risk on the relationship between exogenous and endogenous constructs. A score of 99.40% variation also covers the full mediation between KP-RI through AT. Finally, VAF for the mediating effect of AT between KP and RI is 77.69%, which reflects partial mediation.

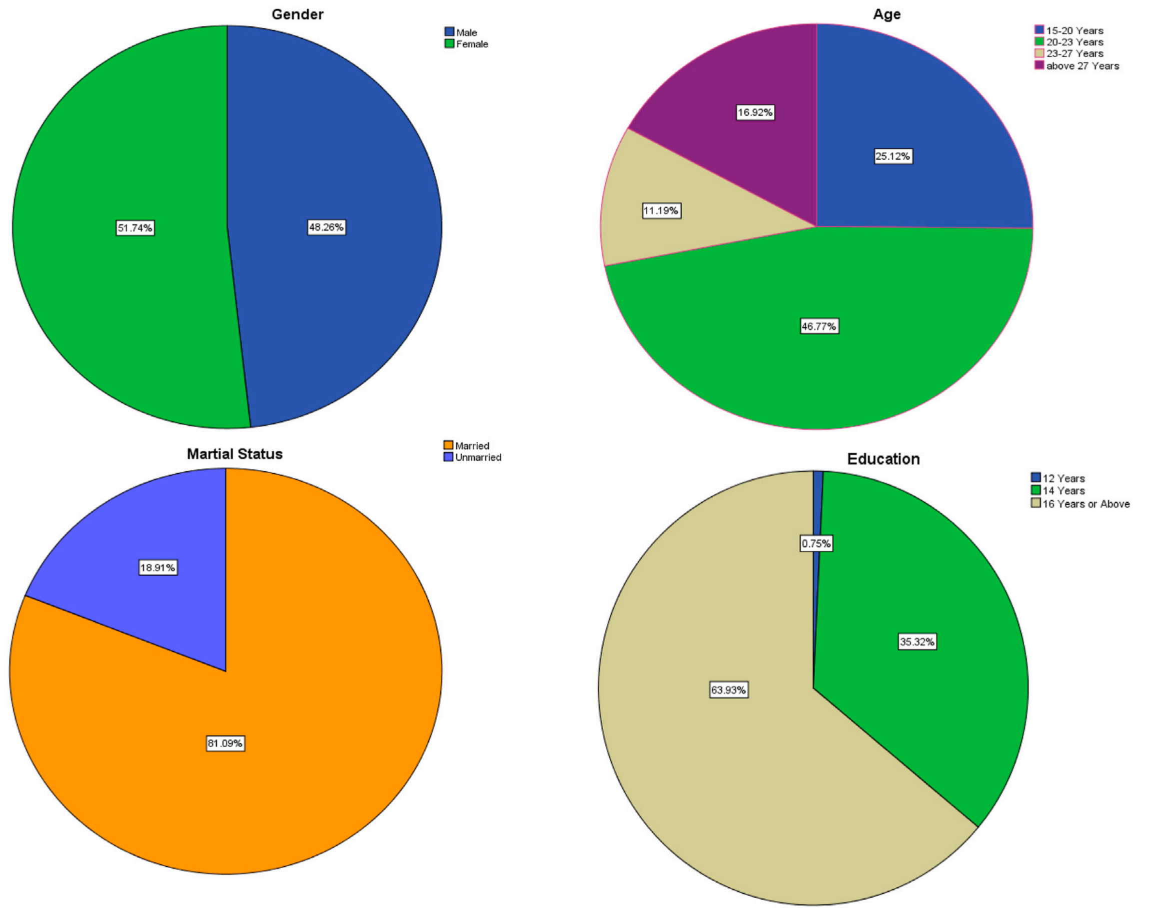

FIGURE 2 | Demographics' Pai charts.

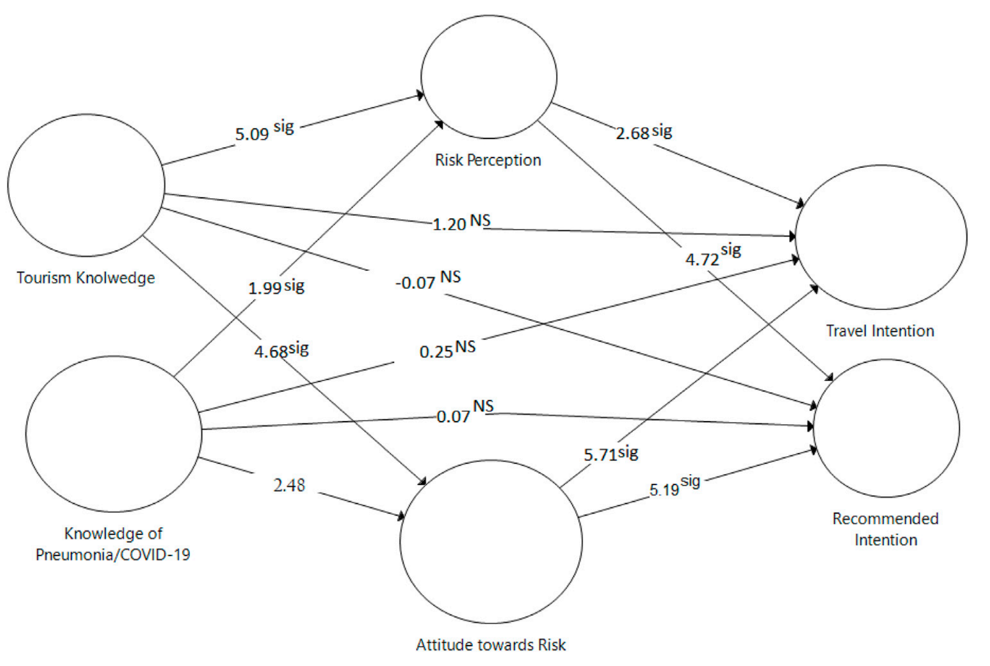

FIGURE 3 | Mediation Analysis SEM output.

CONCLUSION AND RECOMMENDATION

During the recent outbreak of COVID-19, a dramatic change has been observed in the global tourism industry. This study provides a double mediation analysis for investigating the role of risk perception and attitude towards risk in determining the relationship between tourism knowledge, knowledge about Pneumonia/COVID-19 towards travel intention, and recommended intention of the tourists in the Chinese economy. Through a valid sample response of 402 with the help of an online survey questionnaire, data were empirically tested through measurement and structural models. Several direct and indirect hypotheses have been developed and tested. The findings show that without considering risk perception and attitude towards risk, a significant and negative impact of risk knowledge and tourism knowledge on travelers' intention and recommended intention was observed. This would reflect that tourists' choice is adversely affected by the tourism knowledge and risk knowledge factors. However, risk perception and attitude towards risk have provided some interesting results. It is observed that the mediating effect of risk perception between tourism knowledge and travel intention is positively significant with the explanatory power of 58.16, demonstrating a partial mediation. However, 95.27% of the effect of KP in the TI is explained through risk perception, hence regarded as full mediation.

Furthermore, the study findings also report the mediating effect of attitude towards risk on the relationship between exogenous and endogenous constructs. A score of 99.40% variation also covers the full mediation between KP-RI through AT. Finally, VAF for the mediating effect of AT between KP and RI is 77.69%, which reflects partial mediation. This provides one of the major contributions in the literature while filling the direct and indirect relationship between tourism knowledge, risk knowledge, and tourism intention in the region of China.

Finally, it is expressed that current research has several limitations through which future directions would be possible. Firstly, this study takes the residents of China as the sample, while information was collected through an online survey only. This reflects the limited generalizability of the data collection and study findings, specifically in the Chinese economy. Secondly, although the role of risk perception and attitude towards risk is among the major contributions, however, this study is missing the moderating effect of risk communication for which both theoretical and empirical evidence is available. Thirdly, the only quantitative research design was applied in this research, where future studies are highly recommended to use mixed methods to achieve some out-of-the-box findings (**Figure 2**, **Figure 3**) (Roehl and Fesenmaier, 1992).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DY presented the idea and design for the research. KZ analyzed the model and drafted the manuscript. NF, ER-A, YA, and MA revised and edited the manuscript.

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Effects of Environmental Regulation Competition and Public Participation on Enterprise Location Selection Under Climate Change in COVID-19 Pandemic Conditions: An Analysis Based on the Chinese Provincial Spatial Panel Model

Xiuzhen Mu[1], *Qilin Zhan*[1]*, *Waqar Ameer*[1]*, *Muhammad Khalid Anser*[2,3], *Xiaohui Zeng*[1] and *Azka Amin*[4]

[1]Shandong Technology and Business University, Yantai, China, [2]Faculty of Business and Management Sciences, The Superior University, Karachi, Pakistan, [3]School of Public Administration, Xi'an University of Architecture and Technology, Xi'an, China, [4]Department of Business Administration, Sukkur IBA University, Sukkur, Pakistan

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China

***Correspondence:**
Qilin Zhan
201613571@sdtbu.edu.cn
Waqar Ameer
waqar.ameer@yahoo.com

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The deterioration of environmental quality has attracted the attention of the Chinese government and the public. The Chinese government has delegated part of the power of environmental regulation to local governments. To fulfill the KPI, local governments tend to loosen environmental regulations to attract more settlement of enterprises, thus leading to an increasingly fierce local environmental regulation competition. The improvement of people's living standards makes it possible for the public to participate in environmental regulation. This article seeks to carry out the empirical study to interpret the relationship between local environmental regulation competition, public participation, and enterprise location selection through a random effects (RE) spatial Durbin model with 29 provincial panel data in China from 2004 to 2017. The results show that the provincial spatial spillover effect of enterprise location selection is significant. More intensified local environmental regulation competition can attract more investment but may harm sustainable economic development. Active public participation can effectively avoid the excessive investment caused by local environmental regulation competition and sustain economic development. Therefore, we should establish and improve the local environmental prevention and regulation system and establish an information disclosure mechanism to ensure public participation. The local government's environmental regulation and public participation mechanism should be effectively coordinated.

Keywords: environmental regulation competition, public participation, enterprise location selection, panel data, COVID-19

1 INTRODUCTION

China's economy has achieved rapid development in the past 40 years; however, the ecological environment is destroyed rapidly (Hao et al., 2021; Yang et al., 2021; Irfan and Ahmad 2022). The deterioration of environmental quality has attracted the attention of the Chinese government and the public (Jinru et al., 2021; Abbasi et al., 2022; Fang et al., 2022). The government plays an irreplaceable leading role in environmental regulation (Duan et al., 2020; Wu et al., 2020,2021). To reverse the trend of environmental deterioration, the Chinese government has also delegated environmental regulations to the provincial government (Wang et al., 2019; Rauf et al., 2021; Shi et al., 2022). The central government first determines the total emissions of pollutants and then decomposes them in each province (Qiu et al., 2022; Tang et al., 2022). The provincial government has the goal and power to implement environmental regulations. This system promotes the principal–agent relationship between China's central and local governments, whereas the central government cares more about sustainable economic development, but local governments pay more attention to immediate performance. To fulfill the KPI, local governments tend to loosen environmental regulations to attract more enterprises, thus leading to an increasingly fierce local environmental regulation competition (Zhang et al., 2020). Therefore, the intensity of environmental regulation varies significantly in different provinces (Wu et al., 2020).

Enterprise behavior can be decoded in various aspects among which location selection (enterprise location selection) is regarded as one of the most essential reflection, while the decision of location selection is based on the lowest cost principle (Ahmad et al., 2021). Location selection is an important part of enterprise decision-making. The purpose of ideal location selection is to minimize the cost of production (Alfred, 2009). When local governments raise environmental regulation standards, it may lead the outflow of existing enterprises or hinder the inflow of foreign enterprises. However, the location choice of polluting enterprises largely depends on whether the growth of technological innovation income exceeds the cost of environmental regulation (Chandio et al., 2021; Irfan and Ahmad 2021; Tanveer et al., 2021). How does local environmental regulation affect the location choice of enterprises? Does the spatial heterogeneity in environmental regulation affect manufacturers' choice of location? Will manufacturers' location choices have different sensitivity to variation in local environmental stringency? (Wang et al., 2015). Hence, there exists controversial theoretical views about determinants of location selection and thus, it is quite interesting to examine the impact of environmental regulation on enterprise location choice especially in the case of China.

The essential influencing factors of environmental regulation are environmental regulation competition and public participation. Environmental regulation competition refers to the environmental deregulation of local governments to develop the local economy by attracting investment (Hauptmeier et al., 2012). Public participation is the abbreviation of public participation in environmental regulation, which refers to the spontaneous supervision and maintenance of the local environment by social groups based on government environmental regulation. They influence the location choice of enterprises through different paths. There are two controversial views in theory: Porter effect (PE) and pollution haven hypothesis (PHH). The Porter effect (PE) agrees that appropriate environmental regulation can stimulate enterprise innovation as well as reduce enterprise compliance costs and thus attract enterprise's investment. Some scholars believe that stricter environmental regulations can guide enterprises to innovate independently and improve their competitiveness as well as offset the cost of environmental regulations to some extent (Lv et al., 2020). The pollution haven hypothesis (PHH) considers that environmental regulation increases the production cost of enterprises, thus crowding out the investment of enterprises (Dechezlepretre and Sato, 2017). The environmental regulation intensity varies in regions resulting from the fierce competition, which is extensively studied in the literature. It is generally believed that 'pollution heaven' (PH) is a result of an intensified local environmental regulation competition; according to it, enterprises make investment decisions. Commonly, enterprises are located in a region with loosened environmental regulations (Porter and Linde, 1995; Liu et al., 2018; Yang et al., 2018). The main reason is that environmental regulations lead to an increase in the production costs (Li et al., 2019; Zeng et al., 2020), which reduces the competitiveness of enterprises (Hu et al., 2020).

The impact of environmental regulation competition on the location choice of enterprises is also controversial in the empirical aspect. The disputes mainly focus on the following aspects. First, the measurements of environmental regulation competition are controversial due to its complexities and multidimensional characteristics (Kheder and Zugravu, 2012; Antonietti et al., 2017). As different environmental regulations typically involve various pollutants and even the same regulation has different pollution standards across different regions, measuring environmental regulations in any meaningful way is a difficult task (Ben Kheder and Zugravu, 2012). A lot of studies, such as the work of Antonietti et al. (2017), Wu et al. (2017), Zhou et al. (2017), and Dou and Han, (2019), measured environmental regulation competition through a single proxy variable, which led to the risk of measurement error bias (Ben Kheder and Zugravu, 2012; Wang et al., 2019). Nevertheless, there are studies that gauge environmental regulations quite broadly, such as the range of development dimensions, which is clearly beyond the basic meaning of environmental regulation (Wang et al., 2019). Second, disputes on the measurement of enterprise location choice. There are a lot of existing studies, such as the work of List et al. (2003), Mulatu et al. (2010), Mulatu and Wossink (2014), Cai et al. (2016), Chen and Xu (2017), Sarkodie and Strezov (2019), and Wu et al. (2020), which analyzed the effects of variation in environmental regulations on enterprise location selection by using aggregate data on economic activities such as net investment, share of gross output, employment growth, or several new firms (Wang et al., 2019), with the exception of few notable studies (see, for instance, Levinson and Taylor, 2008; Kheder and Zugravu, 2012; Wu et al., 2016).

Third, disputes over sample selection differences. Sample differences lead to controversial conclusions, such as developed or developing samples, pollution-intensive enterprises or not, and spatial heterogeneity differences of pollutants (Zhao, 2014). The data analyses of non-state-owned enterprises in Eastern China, the United States, Canada, Mexico, and Turkey are consistent with PHH (Akbostanci et al., 2007; Quiroga et al., 2007; Zheng et al., 2018) and believe that loose environmental regulations do reduce environmental costs burn by enterprises while are rejected in studies of BRICS and MINT countries (Zhou et al., 2017). Fourth, endogenous disputes. Endogeneity leads to the controversy of empirical results including bidirectional causality (Shi and Xu, 2018) and omitted variables. For instance, a certain case study of the United States rejects PHH (Levinson and Pace, 2008), which might be due to the difference of statistical and research methods (Smarzynska and Wei, 2001; Jeppesen et al., 2010) or the omission of variables such as public participation (Xiao, 2008; Zhao, 2014), transportation convenience, labor availability, and cost (Holl and Mariotti, 2018; Castellani and Lavorati, 2019; Li et al., 2019).

Empirical studies conclude that public participation has a significant impact on the location choice of enterprises (Kostka and Mol, 2013; Zheng et al., 2013; Sun et al., 2016). Public participation is even indirectly involved in enterprise decision-making, but its influential power cannot be overlooked (Su et al., 2018). Current studies on environmental regulations and public participation are concluded into three aspects. First, there are disputes on the effectiveness of public participation. According to supporters, enterprises volunteer to reduce pollution in an affluent region with higher income and education levels (Gamper, 2006), where the government often organizes environmental public hearings and forces the polluting enterprises to relocate. The opponents agree that public participation plays a certain role (Xiao, 2019), but the effectiveness is limited (Xu, 2014; Zhang and Guo, 2015) due to its weak financial and legal restrictions (Carreira et al., 2016; Porter, 2017). Wu et al. (2016) believed that public participation with significant concerns in physical health and quality of life exerts a limited impact on environmental regulations. Second, the influencing factors of public participation are well researched. The popularity of the internet helps to restrict government behavior, improve government's response to public needs, and enhance the public's awareness of environmental protection (Zhang et al., 2022). The openness of government affairs is necessary. It promotes the openness and transparency of government regulation and public accountability (Pérez-Morote et al., 2020) and encourages the public to participate in and supervise environmental regulation. Third, the classification of public participation is well researched. Xiao (2008) classified public participation into three types: citizen-dominated participation (or civil litigation), media-dominated participation, and NGO-dominated participation. Xue and Dong (2010) divided it into *ex ante* participation (for instance, public participation in environmental impact assessment) and *ex post* participation (for example, public tip-offs). Fourth, the interaction between environmental regulation competition and public participation and its impact on the location choice of enterprises is well researched. Public participation or attention can alleviate the intensity of environmental regulation between different regions by affecting the government's environmental regulation behavior, including attracting the government's attention to environmental problems, increasing the government's investment in environmental management, and improving government supervision (Long et al., 2022). The Chinese government should establish an environmental regulation system of "government-led, public, and enterprise collaborative participation" (Tian et al., 2016). The research in this study is based on the understanding that the government and the public jointly constitute China's environmental regulation cooperation model (Chen and Xu, 2017). Last, the impact of public participation on the location choice of enterprises is different in different regions. The public in developed regions of China has a strong awareness of environmental protection, easier to be united to clamp down on enterprises to comply with regional environmental regulations or even force polluting enterprises to relocate.

To sum up, this study improves the existing research. First, there are significant disputes about index measurement and sample selection, which is supplemented in this study. As a large economy and a developing country in the world, China is very representative. This study selects Chinese samples to supplement and demonstrate this topic. This study selects several indicators to supplement and demonstrate environmental regulation competition, public participation, and enterprise location selection. This study also makes an empirical test combined with enterprise heterogeneity. Second, there is less existing research on the interaction between environmental regulation competition and public participation. This study complements the interaction between the two and further demonstrates the mechanism of the two on the location choice of enterprises. Third, the existing research is less focused on the research of the spatial spillover effect. There are 34 provinces and autonomous regions in China, and there are significant spatial spillovers between different provinces. This study introduces a spatial econometric model to demonstrate this combined with China's special samples.

This study comprises five sections. Our first section consists of introduction and literature review. The second section is based on theory analysis and research hypothesis. In the third section, empirical model and data sources are presented. The fourth section shows the findings of the regression and robust test results. The study ends with conclusions and prospects.

2 THEORETICAL ANALYSIS AND RESEARCH HYPOTHESIS

To improve the investment environment and attract foreign investment, local governments tend to loosen environmental policies much more than potential competitors to gain competitive advantages among regions (Deng and Xu, 2013; Deng and Sang, 2015; Wang, 2015). As a result, a "pollution heaven" is formed at the expense of the environment with the

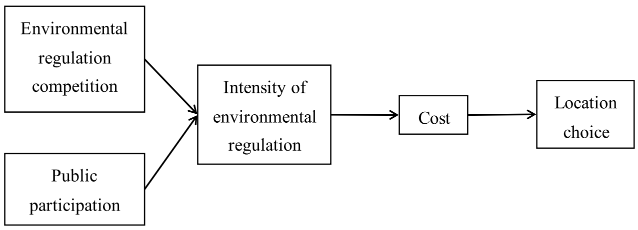

FIGURE 1 | ransmission path of enterprise location choice.

pursuit of political promotion and economic development (Ayadi et al., 2019). However, environmental regulations in developing countries generally suffer supervision and implementation inefficiency, which leads to insufficient environmental regulations (Blondiau and Rousseau, 2010; Han, 2014). Public participation is regarded as the environmental ethics; therefore, it becomes an important supplement to the legal system (Liu et al., 2019). The discussion of the relation between them is categorized into two aspects: well-recognized superimposing relation and crowding out relation. Regional environmental laws and regulations are formed with the participation of the public and the government. China manages them in accordance with formal environmental laws and regulations. Public participation is regarded as a moral supplement to the legal system. Therefore, the superposition relationship between them can be proved (Zheng et al., 2018). However, excessive government regulation has a strong crowding out effect on public participation. Governmental regulations and public participation are relatively independent. When public participation is involved in an environmental issue, it may no longer be a major concern for local governments, indicating the crowding out relationship between them (Wang, 2016; Xiao, 2019). In China, eastern coastal regions are more economically developed where residents concern more on the environment with stronger legal awareness of environmental protection, therefore participating more voluntarily in environmental supervision. As a result, environmental disparities are formed among the regions. The level of local public participation is an important factor that enterprises should consider when making location selections (Xiao, 2008).

2.1 Environmental Regulation Competition and Enterprise Location Selection

Environmental regulation competition and public participation affect the production cost of enterprises through the intensity of regional environmental regulation and then affect the enterprise location choice. The transmission path is shown in **Figure 1**. Local officials may only focus on economic growth during their term of office and tend to unilaterally pursue short-term economic development while ignoring environmental pollution (Zhou et al., 2017). Local governments have incentives to lower local environmental regulations, attract pollution-intensive enterprises with short investment cycles and resource dependence, and adopt extensive economic growth at the cost of environmental damage. There is even a vicious cycle in which local governments compete to lower the level of environmental regulations to attract pollution-intensive enterprises (Wang et al., 2019). Based on the aforementioned analysis, hypothesis 1 is proposed.

Hypothesis 1 (H1): the more intense the environmental regulation competition is, the lower the local environmental regulation intensity will be and more enterprises will be attracted to locate.

2.2 Public Participation and Enterprise Location Selection

According to the public goods supply theory, when residents' marginal willingness to pay for environmental public goods is equal to the marginal cost of environmental public goods supply, residents are willing to sacrifice private consumption to increase the supply of environmental public goods (Fung, 2006). Theoretically, there is the possibility of private provision of environmental public goods. At the same time, the more active the public is in participating in environmental regulation, the higher the cost will be (Sun et al., 2016). Practice shows that residents in developed areas are more sensitive to environmental quality and willing to pay higher costs for environmental regulation. Therefore, there are differences in the degree of public participation in environmental regulation in different regions. The higher the degree of public participation, the higher the level of environmental regulation, and enterprises tend to avoid such areas in location choice. Therefore, hypothesis 2 is proposed.

Hypothesis 2 (H2): the lower the level of public participation is, the lower the environmental costs will be, and more enterprises will be attracted to locate.

2.3 Interaction Between Environmental Regulation Competition and Public Participation

The process of enterprise location selection involves three market players: local government, public, and an enterprise. The local government maps out environmental regulations based on pollution discharge fees. The fiercer the competition of environmental regulation, the lower the environmental regulation intensity will be. Local residents as public participation complement governmental environmental regulation's insufficiency (Fung, 2006). The efforts to shape environmental regulations from local residents depend on the environmental governance level. More specifically, a well-functional environmental regulation system founded by governments reduces the participation from local residents, that is, the participation to optimize environmental regulations is costly in terms of time and money. As long as the government supply is sufficient, the private supply from the public is ignored (Thomas, 2013). Only when the governance is insufficient, the private sector, namely, the residents would contribute (Drazkiewicz et al., 2015). Finally, the enterprise selects its location and optimal output according to the levels of local

environmental regulation competition and public participation (Wang, 2015).

Hypothesis 3 (H3): there is an interaction between environmental regulation competition and public participation.

3 DATA SOURCES AND STATISTICAL DESCRIPTION

The theoretical framework is constructed to investigate the effect of local environmental regulation competition and public participation on enterprise location selection. With different development levels of eastern and western regions in China, enterprises select their locations regarding to local socio-economic indicators and geographical advantages. Thus, the spatial factor should be involved in the theoretical framework. The spatial error model (SEM), spatial lag model (SLM), and spatial Durbin model (SDM) are adopted in the research.

The data are collected from the Chinese Environment Yearbook; China Environment Statistical Yearbook; China Labor Statistical Yearbook; China Statistical Yearbook; Sample Survey of Urban Households; and Survey of Income, Expenditure and Living Conditions of Integrated Urban and Rural Households by the National Bureau of Statistics from 2004–2017. Tibet and Hainan provinces are not included in the research because of missing data. All data are deflated according to corresponding indexes by using the year 2004 as the base year (including GDP deflator, producer price index, fixed investment price index, and consumer price index). Also, some missing data are estimated by using the average over the past 3 years.

3.1 Explained Variable INVE

The local governments attract enterprise investment (mainly fixed assets investment) by loosening environmental regulations to promote economic development. Thus, fixed assets investment can be used to measure enterprise location selection. Considering the heterogeneity of enterprises, investment in China mainly includes state-owned investment; foreign investment; Hong Kong, Macao, and Taiwan investment; and private investment. The data of the first three come from China Fixed Assets Statistical Yearbook. However, private investment lacks effective data, calculated by subtracting state-owned investment; foreign investment; Hong Kong, Macao, and Taiwan investment from fixed assets investment. Because of the statistical measurement changes and errors around 2011, private investment is negative in some year and regarded as zero in our empirical analysis. Therefore, the explained variables in our study include total investment ($INVE_1$); state-owned investment ($INVE_2$); foreign investment ($INVE_3$); Hong Kong, Macao, and Taiwan investment ($INVE_4$); and private investment ($INVE_5$).

3.2 Explaining Variable ER

It is difficult to directly measure the level of local environmental regulation competition. Nevertheless, it is inversely proportional to environmental regulation intensity, that is, the higher the level of competition among regions, the lower the level of environmental regulation intensity. Hence, environmental regulation intensity indicators can be used to reflect the level of local environmental regulation competition. Referring to the calculation method of Xiao (2008) and Zhang et al. (2010), the measurement of environmental regulation intensity can be captured from three indicators in the perspective of production cost: pollution prevention and control investment (PCI), average pollution discharge fees (APC), and total environmental regulation costs faced by enterprises (ERC). The PCI is selected based on the principle of "polluter pays". It is the percentage of industrial pollution prevention and control investment in total local fixed assets investment, which reflects fixed assets investment provided by the government for local environmental pollution remediation. APC is obtained from dividing pollution discharge fees by the number of large-scale local industrial enterprises. All data is collected from the Chinese Environmental Yearbook and China Environmental Statistics Yearbook, and it is deflated to the price index. ERC comprehensively measures total environmental regulation costs per 10,000 RMB of industrial-added value. It is the sum of pollution discharges, industrial pollution prevention, and control investment divided by local industrial-added value.

3.3 Explaining Variable PUB

Since the main force of public participation is well-educated young generations, the study refers to the measurement adopted by Pargal and Wheeler (1996) and Yuan and Xie (2014). Per capita urban disposable income (DPI), proportion of residents with a college education or above (CEA), and urban population density (UPD) are leveraged in the research. Generally, people with higher income prefer better living quality and environment (Pargal and Wheeler, 1996; Antweiler et al., 2001) and vice versa. The income of residents is a key indicator of public participation. The data are obtained from the survey of income, expenditure, and living conditions of integrated urban and rural households by the National Bureau of Statistics. The urban consumer price index is used for deflation. Residents with higher levels of educational backgrounds have more vital environmental awareness and higher public participation willingness. The proportion of residents with college education or above in the total population of the country are selected from the national sample population sampling survey data. The missing data in 2010 is estimated by the average between 2009 and 2011. The more the population density, the more residents are influenced by environmental pollution and consequently, the higher the level of public participation would be. The number of the urban resident population per unit area is taken into consideration at the end of the year. The missing data of the urban areas are approximated with data of the year before and after. The missing data of urban population in 2004 is estimated by the average growth rate over the last 3 years.

3.4 Control Variable Z

The factors affecting enterprise location selection also include the level of local economic development (IND), transportation convenience (TC), and labor cost (LC). The level of local

TABLE 1 | Descriptive statistics of variables.

Variables	Unit	Sample size	Mean	Standard deviation	Min	Max
INVE1	Billion RMB	406	784.5598	692.5307	26.1980	3732.6360
INVE2	Billion RMB	406	190.7038	117.4932	15.1710	594.9390
INVE3	Billion RMB	406	23.8529	30.0070	0.0140	166.2620
INVE4	Billion RMB	406	23.2475	31.2302	0.0000	184.5740
INVE5	Billion RMB	406	546.7672	567.9043	0.0000	3116.6600
PCI	%	406	0.281	0.259	0.020	1.630
APC	Ten thousand RMB	406	5.905	4.769	0.440	39.790
ERC	%	406	0.512	0.394	0.050	2.980
DPI	Ten thousand RMB	406	1.395	0.571	0.670	4.01
CEA	%	406	9.999	6.502	2.500	44.760
UPD	Ten thousand people/km2	406	0.486	0.262	0.090	1.290
IND	%	406	40.090	7.199	15.260	53.040
TC	—	406	38.700	34.553	1.290	133.400
LC	—	406	0.371	0.296	0.140	2.500

economic development affects enterprises' long-term development and products' potential demand. It is usually measured by the level of industrialization and equals the proportion of industrial-added value in GDP. Transportation convenience (TC) affects enterprises' transportation costs, which are divided into the total mileage of railway, highway, and waterway by the total area. Labor cost (LC) is an important part of the production cost and represented by the proportion of total wages of urban employees and industrial-added value. The data of total wages of urban employees in 2004 and 2005 were missing in several provinces, which are obtained by using average growth rate in recent 3 years. Descriptive statistics of variables are shown in **Table 1**.

3.5 Spatial Weight Matrix

The spatial weight matrix is exogenous whose setup is the key to the spatial econometric analysis (Sun and Li, 2008). There are three kinds of spatial competition for enterprise location selection: nationwide competition, inner-regional competition, and interregional economic competition (Zhao, 2014). Correspondingly, the spatial weight matrix should also be selected between the adjacency matrix, geospatial matrix, and economic spatial matrix (Xiao, 2019). To enhance the robustness, all three spatial weight matrices are selected for analysis in our study. The adjacency matrix is set as W^G. $w_{ij}^G = 1$ means two provinces geographically contiguous, otherwise $w_{ij}^G = 0$. The geospatial matrix (also known as the inverse distance matrix) is set as W^D, where $W^D = \frac{1}{d_{ij}}$. Here, d_{ij} is the distance between the capitals of two provinces i and j. The economic spatial matrix is W^E. Referring to the practice of Lin et al. (2006), we selected the reciprocal of the economic development gap between two provinces as the weight. If economic development levels between the two provinces are relatively close, the competition is relatively fierce, and the weight should be greater. The definition of the matrix is as follows:

$W_{ij}^E = \frac{1}{|\overline{Y_i} - \overline{Y_j}|}$, $i \neq j$, $W_{ij}^E = 0$, $i = j$, $\overline{Y_\mathrm{i}} = \sum_{t=T_0}^{T} \frac{Y_{it}}{(T-T_0)}$, where$Y_{it}$ represents GDP and $\bar{Y}_i$ represents the average GDP of province i in year t W^G, W^E, and W^D all need to be unitized.

3.6 Spatial Correlation Test

The spatial effect of enterprise location selection is mainly reflected in spatial correlation and spatial heterogeneity, which can be measured by the global Moran's I. To reduce the data fluctuation and remove the dimensional influence, the test and regression data in our study are treated with a logarithm. We take the adjacency matrix as an example to calculate the global Moran's I from 2014 to 2017, and the estimated results are shown in **Table 2**.

The results show significant positive spatial correlation between enterprise location selection and local environmental regulation competition and public participation, which in general verifies the necessity and feasibility of choosing a spatial measurement model for research.

4 MODELING AND TESTING

4.1 Benchmark Model Setting

Since both SEM and SLM are special forms of SDM, we choose SDM first (Wang, 2019), and LM-error and LM-lag are used to test whether it should be degraded to SEM or SLM. Referring to SDM proposed by Le and Pace (2009), we established a benchmark model as follows:

$$INVE_{it} = \rho W_{ij} \bullet INVE_{jt} + \alpha_1 ER_{it} + \alpha_2 W_{ij} \bullet ER_{jt} + \beta_1 PUB_{it} + \beta_2 W_{ij} \bullet PUB_{jt} + \eta_1 Z_{it} + \eta_2 W_{ij} \bullet Z_{jt} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (1)$$

where $INVE_{it}$ represents enterprise location selection of province i in period t; $W_{ij} \bullet INVE_{jt}$ is the spatial lag term of the explained variable, and ρ is the coefficient; ER_{it} is the level of local environmental regulation competition of province i in period t; PUB_{it} is the level of public participation of province i during period t; Z_{it} are control variables; W_{it} is a non-negative weight and reflects the spatial weight matrix between different provinces; $W_{ij} \bullet ER_{jt}$, $W_{ij} \bullet PUB_{jt}$, and $W_{ij} \bullet Z_{jt}$ are the spatial lag terms of explaining and control variables; α, β, and η are coefficients for explaining and control variables; μ_i and λ_t represent spatial and time fixed effects, respectively; and ε_{it} are error terms.

TABLE 2 | Global Moran's I statistics of enterprise location selection.

Variable	Adjacency matrix W^G				
	2013	2014	2015	2016	2017
INVE1	0.240*** (2.511)	0.230*** (2.412)	0.278*** (2.845)	0.274*** (2.788)	0.279*** (2.804)
INVE2	−−0.07 (−0.322)	−0.056 (−0.186)	0.004 (0.362)	−0.037 (−0.007)	0.023 (0.518)
INVE3	0.336*** (3.349)	0.285*** (2.889)	0.253*** (2.793)	0.361*** (3.558)	0.392*** (3.827)
INVE4	0.448*** (4.330)	0.460*** (4.429)	0.456*** (4.378)	0.523*** (4.997)	0.531*** (5.183)
INVE5	0.302*** (3.056)	0.294*** (2.980)	0.331*** (3.329)	0.354*** (3.503)	0.352*** (3.457)
PCI	0.168** (1.823)	0.284*** (2.907)	0.208** (2.175)	0.323*** (3.243)	0.366*** (3.640)
APC	0.305*** (3.052)	0.352*** (3.438)	0.430*** (4.127)	0.488*** (4.650)	0.418*** (4.038)
ERC	0.197** (2.090)	0.331*** (3.352)	0.143** (1.603)	0.339*** (3.403)	0.433*** (3.557)
DPI	0.366*** (3.652)	0.364*** (3.625)	0.364*** (3.628)	0.359*** (3.585)	0.355*** (4.190)
CEA	0.180** (2.028)	0.186** (2.091)	0.188** (2.109)	0.243*** (2.581)	0.194** (2.124)
UPD	−0.056 (−0.180)	−0.060 (−0.213)	−0.083 (−0.418)	−0.034 (0.013)	−0.043 (−0.070)

*Moran's I is calculated by Stata16.0. Z stands for Z value. ***, **, and * refer to statistically significance at the level of 1, 5, and 10%, respectively. Z value is in the bracket.*

TABLE 3 | Model testing.

Variable	INVE1	INVE2	INVE3	INVE4	INVE5
LM-lag	0.263	0.925	0.173	0.044	0.009
Robust-LMLAG	0.104	0.082	0.635	0.521	0.754
LM-error	0.999	0.929	0.091	0.346	1.061
Robust-LMERR	0.840	0.085	0.553	0.823	1.806
R-squared	0.7054	0.5575	0.8547	0.8677	0.7525
P value	0.0015	0.0348	0.0000	0.0000	0.0003
Hausman test	−30.01	−32.52	2.05	−64.99	−9.92

4.2 Model Selection

On the basis of OLS, the LM test is carried out to check the significance of LM-error and LM-lag. Then, fixed and random effects analyses are carried out by using the Housman test. The results are shown in **Table 3**. The results show that both LM-error and LM-lag tests reject the hypothesis, that is, the spatial model should not degenerate into SEM or SLM, so SDM should be selected. The results of the Housman test cannot reject the hypothesis, and SDM with random effects should be selected.

4.3 Model Expansion

In order to avoid the endogeneity and missing variables, we adopt the actual data of one period lag ($INVE_{it-1}$) into the following model.

$$INVE_{it} = \phi INVE_{it-1} + \rho W_{ij}\bullet INVE_{jt} + \alpha_1 ER_{it} + \alpha_2 W_{ij}\bullet ER_{jt} + \beta_1 PUB_{it} + \beta_2 W_{ij}\bullet PUB_{jt} + \eta_1 Z_{it} + \eta_2 W_{ij}\bullet Z_{jt} + \mu_i + \lambda_t + \varepsilon_{it}. \tag{2}$$

Considering the interaction between local environmental regulation competition and public participation, we introduce an interaction term to measure it. In the interaction item, ERC is selected to represent local environmental regulation competition, and DPI is selected to represent public participation. Formula 10 becomes

$$INVE_{it} = \phi INVE_{it-1} + \rho W_{ij}\bullet INVE_{jt} + \alpha_1 ER_{it} + \alpha_2 W_{ij}\bullet ER_{jt} + \beta_1 PUB_{it} + \beta_2 W_{ij}\bullet PUB_{jt} + \psi_1 ER_{it}\bullet PUB_{it} + \psi_2 W_{ij}\bullet ER_{jt}\bullet PUB_{jt} + \eta_1 Z_{it} + \eta_2 W_{ij}\bullet Z_{jt} + \mu_i + \lambda_t + \varepsilon_{it}. \tag{3}$$

4.4 Empirical Results and Robustness Testing

Under the three spatial weight matrices, we adopt the maximum likelihood method and use random effects SDM to test the data of INVE1, INVE2, INVE3, INVE4, and INVE5.

Table 4 lists statistics of the random effects SDM under the three spatial matrices. **Table 5**, **Table 6**, **Table 7**, **Table 8**, and **Table 9** display the result estimations. According to R-sq., the fitting effect of the economic matrix is the best. Thus, the economic matrix is taken as an example to analyze the regression results of INVE1, INVE2, INVE3, INVE4, and INVE5.

ρ is greater than zero at 1% significance level, indicating that enterprise location selection has a significant spatial spillover effect. It further verifies that there is a strong spatial correlation in the choice of enterprise location. Because spatial lag and explained variables are added into SDM, the regression coefficient is biased and it cannot directly explain the relationship between the explaining and the explained variables. Thus, it needs to be decomposed by a partial differential equation (the decomposition of SDM) and the results are displayed in **Table 5**, **Table 6**, **Table 7**, **Table 8**, and **Table 9**, respectively.

The total effects of PCI, DPI, and ERC (local environmental regulation competition) are significantly negative at 5 and 1% levels of significance. The more intensified the local environmental regulation competition, the lower the environmental regulation intensity and the more the investment is, which is in line with H1. The direct and indirect effects of PCI, APC, and ERC are significantly negative. A more intensified local environmental regulation competition attracts local investment and increases investment

TABLE 4 | Statistics of the random effects SDM.

Variables	W^G			W^D			W^E		
	Num	R-sq	Log-l	Num	R-sq	Log-l	Num	R-sq	Log-l
INVE1	377	0.9860	376.5879	377	0.9901	413.4262	377	0.9851	363.6117
INVE2	377	0.9139	168.4569	377	0.9316	210.1774	377	0.9192	164.8825
INVE3	377	0.2199	−212.539	377	0.2093	−213.220	377	0.2541	−207.801
INVE4	377	0.5822	−142.085	377	0.5995	−134.627	377	0.5820	−141.832
INVE5	377	0.9740	172.9761	377	0.9856	262.3071	377	0.9696	131.5140

TABLE 5 | Decomposition of the random effects SDM (INVE1).

Variables	Adjacency matrix			Geospatial matrix			Economic matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
$INVE_{it-1}$	0.679*** (26.79)	0.071 (1.43)	0.750*** (13.89)	0.403*** (11.49)	0.372*** (2.97)	0.776*** (6.33)	0.725*** (29.18)	−0.018 (−0.71)	0.706*** (19.46)
PCI	−0.541*** (−18.16)	0.048 (0.63)	−0.492*** (−5.94)	−0.637*** (−23.22)	−0.042 (−0.29)	−0.679 (−4.55)	−0.479*** (−15.41)	0.034 (1.15)	−0.444*** (−10.97)
APC	−0.090*** (−5.71)	−0.025 (−0.61)	−0.115*** (−2.63)	−0.084*** (−5.34)	−0.070 (−0.85)	−0.155* (−1.84)	−0.096*** (−6.20)	−0.017 (−0.66)	−0.113*** (−3.66)
ERC	−0.671*** (−17.23)	−0.110 (−0.98)	−0.560*** (−4.66)	−0.749*** (−21.46)	−0.119 (−0.48)	−0.630*** (−2.47)	−0.589*** (−14.26)	−0.011 (−0.27)	−0.600*** (−10.85)
DPI	−0.427*** (−5.92)	−0.127 (−1.22)	−0.300*** (−2.72)	−0.040 (−0.53)	−0.249 (−1.16)	−0.290 (−1.44)	−0.233*** (−4.05)	−0.015 (−0.29)	−0.248*** (−3.10)
CEA	−0.056*** (2.12)	−0.016 (−0.21)	−0.040 (−0.49)	−0.019 (−0.81)	−0.163 (−0.78)	−0.183 (−0.85)	−0.052** (−1.91)	−0.064 (−1.22)	−0.117** (−1.97)
UPD	−0.027 (−0.55)	−0.087 (−0.89)	−0.060 (−0.54)	−0.039 (−0.78)	−1.263*** (−3.14)	−1.223*** (−2.91)	−0.108*** (−2.37)	−0.182*** (−3.67)	−0.290*** (−4.11)
ERC*DPI	−0.009 (−0.42)	−0.171** (−2.18)	−0.161 (−1.89)	−0.027 (−1.31)	−0.099 (−0.48)	−0.126 (−0.58)	−0.021 (−0.84)	−0.018 (−0.36)	−0.039 (−0.64)

TABLE 6 | Decomposition of the random effects SDM (INVE2).

Variables	Adjacency matrix			Geospatial matrix			Economic matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
$INVE_{it-1}$	0.827*** (19.05)	−0.329*** (−5.33)	0.497*** (6.81)	0.895*** (26.29)	−0.795*** (−8.02)	0.099 (0.96)	0.747** (22.68)	−0.242*** (−6.45)	0.505*** (10.49)
PCI	−0.402*** (−6.58)	−0.577*** (−4.67)	−0.979*** (−7.18)	−0.292*** (−5.55)	−0.939*** (−4.74)	−1.232*** (−6.28)	−0.487*** (−10.96)	−0.190*** (−4.08)	−0.677*** (−11.56)
APC	−0.145*** (−5.01)	−0.052 (−0.81)	−0.197*** (−3.00)	−0.073*** (−3.03)	−0.235*** (−2.41)	−0.309*** (−3.17)	−0.193*** (−7.69)	−0.067* (−1.77)	−0.261*** (−5.87)
ERC	−0.517*** (−2.66)	−0.533*** (−2.76)	−1.050*** (−5.08)	−0.374*** (−4.95)	−0.784** (−2.24)	−1.158*** (−3.29)	−0.617*** (−9.95)	−0.238*** (−3.64)	−0.855*** (−10.05)
DPI	−0.300*** (−2.66)	−0.042 (−0.26)	−0.257 (−1.41)	−0.102 (−0.95)	−0.127 (−0.45)	−0.024 (−0.09)	−0.293*** (−3.34)	−0.123 (−1.54)	−0.417*** (−3.65)
CEA	−0.027 (−0.63)	−0.126 (−1.18)	−0.098 (−0.86)	−0.014 (−0.41)	−0.412* (−1.78)	−0.427* (−1.83)	−0.029 (−0.72)	−0.281*** (−3.87)	−0.310*** (−4.08)
UPD	−0.101* (−1.84)	−0.347*** (−2.42)	−0.449*** (−2.59)	−0.103** (−2.26)	−1.378*** (−5.35)	−1.482*** (−5.29)	−0.284*** (−4.74)	−0.565*** (−7.17)	−0.849*** (−7.55)
ERC*DPI	−0.031 (−0.71)	−0.200 (−1.35)	−0.231 (−1.43)	−0.032 (−0.82)	−0.210 (−0.70)	−0.243 (−0.78)	−0.076* (−1.71)	−0.097 (−1.21)	−0.174* (−1.82)

in economically related provinces. The coefficients of direct, indirect, and total effects of *PCI* are greater than that of *APC*, indicating that *PCI* has a greater impact on enterprise location selection than APC.

The total effects of DPI, CEA, and UPD (representing public participation) are significantly negative. The higher the level of public participation, the less investment will be, verifying H2. The direct and indirect effects of DPI, CEA,

TABLE 7 | Decomposition of the random effects SDM (INVE3).

Variables	Adjacency matrix			Geospatial matrix			Economic matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
$INVE_{it-1}$	0.325*** (4.82)	−0.078 (−0.79)	0.247** (1.98)	0.408*** (4.64)	−0.067 (−0.28)	0.340 (1.32)	0.286*** (3.90)	0.042 (0.62)	0.328*** (3.43)
PCI	−0.379*** (−3.83)	0.086 (0.42)	−0.292 (−1.46)	−0.392*** (−3.42)	−0.075 (−0.18)	−0.468 (−1.13)	−0.305*** (−3.35)	−0.122 (−1.14)	−0.427*** (−3.40)
APC	−0.115 (−1.54)	−0.198 (−1.37)	−0.314** (−2.23)	−0.151** (−1.98)	−0.091 (−0.35)	−0.243 (−0.95)	−0.130** (−1.90)	−0.061 (−0.53)	−0.191 (−1.43)
ERC	−0.431*** (−3.01)	−0.141 (−0.42)	−0.290 (−0.85)	−0.437*** (−2.68)	−0.805 (−1.04)	−1.243 (−1.57)	−0.376*** (−2.74)	−0.246 (−1.53)	−0.622*** (−3.04)
DPI	−0.962*** (−3.03)	−0.191 (−0.55)	−1.153*** (−3.27)	−0.856** (−2.19)	−0.998 (−1.40)	−1.854*** (−2.95)	−0.793*** (−3.19)	−0.580*** (−2.55)	−1.374*** (−4.14)
CEA	−0.133 (−1.08)	−0.252 (−1.06)	−0.119 (−0.57)	−0.052 (−0.39)	−0.469 (−0.77)	−0.416 (−0.70)	−0.046 (−0.43)	−0.246** (−1.29)	−0.293 (−1.54)
UPD	−0.571*** (−2.86)	−0.509* (−1.64)	−1.080*** (−3.07)	−0.484*** (−2.41)	−1.243* (−1.64)	−1.727** (−2.19)	−0.591*** (−3.22)	−0.436*** (−2.34)	−1.028*** (−3.90)
ERC*DPI	−0.024 (−0.21)	−0.538* (−1.87)	−0.562** (−1.83)	−0.037 (−0.31)	−0.242 (−0.33)	−0.279 (−0.36)	−0.044 (−0.37)	−0.327 (−1.49)	−0.371 (−1.40)

TABLE 8 | Decomposition of the random effects SDM (INVE4).

Variables	Adjacency matrix			Geospatial matrix			Economic matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
$INVE_{it-1}$	0.868*** (37.82)	−0.035 (−0.76)	0.833*** (16.95)	0.851*** (35.46)	−0.162* (−1.61)	0.688*** (6.62)	0.866*** (35.71)	0.017 (0.26)	0.884*** (11.80)
PCI	−0.315*** (−4.43)	−0.033 (−0.21)	−0.349** (−2.22)	−0.269*** (−3.65)	−0.024 (−0.08)	−0.293 (−0.98)	−0.298*** (−4.89)	0.012 (0.13)	−0.285*** (−2.60)
APC	−0.055 (−1.18)	0.022 (0.22)	−0.032 (−0.33)	−0.051 (−1.13)	0.140 (0.75)	0.088 (0.50)	−0.083* (−1.70)	0.063 (0.83)	−0.020 (−0.21)
ERC	−0.317*** (−3.10)	−0.070 (−0.25)	−0.246 (−0.90)	−0.268*** (−2.51)	−0.113 (−0.19)	−0.154 (−0.25)	−0.303** (−3.20)	−0.017 (−0.11)	−0.285 (−1.46)
DPI	−0.639*** (−2.93)	−0.216 (−0.81)	−0.856*** (−3.01)	−0.624*** (−2.66)	−0.601 (−1.12)	−1.226*** (−2.38)	−0.667*** (−3.57)	−0.038 (−0.20)	−0.629** (−2.30)
CEA	−0.167** (−2.17)	−0.109 (−0.81)	−0.277** (−2.09)	−0.154** (−1.97)	−0.234 (−0.67)	−0.080 (−0.23)	−0.186*** (−2.62)	−0.067 (−0.46)	−0.118 (−0.76)
UPD	−0.185*** (−2.39)	−0.406** (−2.28)	−0.591*** (−2.67)	−0.287*** (−3.38)	−1.675*** (−3.78)	−1.963*** (−3.99)	0.173** (2.10)	−0.298** (−2.20)	−0.471*** (−2.45)
ERC*DPI	−0.077 (−0.78)	−0.385 (−1.58)	−0.462* (−1.77)	−0.125 (−1.27)	−0.832 (−1.43)	−0.957 (−1.56)	−0.136 (−1.31)	−0.091 (−0.45)	−0.228 (−0.91)

and UPD are all negative. A higher level of public participation not only restrains local investment but also reduces investment in economically related provinces. In terms of the coefficients of the total effect, UPD ranks first, followed by DPI and CEA, respectively. In terms of the coefficients of direct effect, DPI is the highest, followed by UPD and CEA, respectively. In terms of the coefficients of indirect effect, UPD is the highest, followed by CEA and DPI, respectively.

The total effect of ERC*DPI is negative, which indicates that the interaction term has a negative impact on enterprise location selection, which verifies H3. Both the direct and indirect effects are negative. The interaction term not only restrains local investment but also reduces investment in economically related provinces. The coefficient of direct effect is higher than that of indirect effect, which means the interaction term restrains local investment more. The absolute value difference between the direct and indirect effects of the five types of enterprises is very small, which also verifies the strong spatial spillover effect of enterprises under the background of economic integration.

Enterprise heterogeneity does not lead to significant differences in the results of random effects nor does it affect the significance. According to the decomposition of random effects, the top three factors affecting state-owned investment are total environmental regulation costs, urban population density, and pollution control and prevention cost. The top three impact factors on foreign investment are urban population density, urban disposable income, and total environmental regulation cost; the top three impact

TABLE 9 | Decomposition of the random effects SDM (INVE5).

Variables	Adjacency matrix			Geospatial matrix			Economic matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
$INVE_{it-1}$	0.360*** (24.40)	0.179** (4.44)	0.540*** (11.75)	0.271*** (22.74)	0.153* (1.80)	0.425*** (4.82)	0.382*** (21.27)	0.028** (2.24)	0.410*** (16.36)
PCI	−0.826*** (−21.98)	0.170 (1.44)	−0.656*** (−5.18)	−0.754*** (−25.79)	−0.095 (−0.44)	−0.850*** (−3.80)	−0.813*** (−20.05)	−0.124*** (−2.65)	−0.689*** (−11.88)
APC	−0.103*** (−3.97)	0.107 (1.36)	0.004 (0.05)	−0.089*** (−4.13)	0.095 (0.73)	0.006 (0.05)	−0.095*** (−3.46)	−0.015 (−0.31)	−0.111* (−1.87)
ERC	−0.968*** (−18.43)	−0.239 (−1.30)	0.728*** (−3.64)	−0.832*** (−19.67)	0.053 (0.14)	−0.885** (−2.26)	−0.967*** (−16.67)	−0.059 (−0.81)	−0.908*** (−9.80)
DPI	0.817*** (7.07)	−0.786*** (−4.16)	0.031 (0.15)	0.081 (0.71)	−0.006 (−0.02)	0.075 (0.21)	−0.403*** (−3.76)	−0.317*** (−3.27)	0.085 (0.56)
CEA	−0.216*** (−5.17)	−0.047 (−0.39)	0.169 (1.36)	−0.036 (−1.01)	0.101 (0.35)	0.065 (0.22)	−0.305*** (−7.36)	0.024 (0.32)	0.329 (3.82)
UPD	−0.130 (−1.43)	−0.024 (−0.14)	−0.154 (−0.75)	0.081 (1.07)	−1.865*** (−3.53)	1.783*** (−3.24)	−0.135 (−1.53)	−0.195** (−2.01)	0.059 (0.48)
ERC*DPI	−0.033 (−0.87)	−0.046 (−0.33)	−0.080 (−0.51)	0.044 (1.42)	−0.292 (−0.85)	−0.247 (−0.69)	−0.048 (−1.06)	−0.263*** (−2.61)	−0.311** (−2.55)

TABLE 10 | Robustness tests (INVE1).

Variables	Standard SDM	Robust SDM	RE
$INVE_{it-1}$	0.7259***(29.35)	0.8850***(12.09)	0.9274***(88.56)
PCI	−0.4794***(−14.29)	−0.1241**(−2.08)	−0.1851***(−7.37)
APC	−0.0963***(−6.87)	−0.0492***(−2.96)	−0.0781***(−6.06)
ERC	−0.5855***(−13.46)	−0.1575**(−2.14)	−0.2260***(−6.53)
DPI	−0.2423***(−4.91)	−0.0478 (−0.72)	−0.0861**(−1.92)
CEA	−0.0466 (−1.55)	−0.0152 (−0.79)	−0.0911***(−4.15)
UPD	−0.0966**(−2.04)	−0.0370 (−1.35)	−0.0512**(−2.33)
ERC*DPI	−0.0254 (−1.09)	−0.0367 (−1.46)	−0.0856 (−1.01)
R-sq	0.9851	0.9790	0.9751
Log-l	363.6117	319.8833	—
Wald	—	—	21968.24

TABLE 11 | Robustness tests (INVE2).

Variables	Standard SDM	Robust SDM	RE
$INVE_{it-1}$	0.7519***(22.61)	0.7766***(10.74)	0.9066***(46.73)
PCI	−0.4800***(−9.91)	−0.2186***(−3.31)	−0.2201***(−5.80)
APC	−0.1939***(−8.48)	−0.0639**(−2.11)	−0.1341***(−6.71)
ERC	−0.6061***(−9.22)	−0.2971***(−3.44)	−0.3015***(−5.59)
DPI	−0.3072***(−4.05)	−0.1553*(−1.63)	−0.2245***(−3.22)
CEA	−0.0193 (−0.44)	−0.0440 (−1.15)	−0.0462 (−1.35)
UPD	−0.2681***(−4.42)	−0.1198**(−1.97)	−0.0127 (−0.39)
ERC*DPI	−0.0843**(−2.01)	−0.0293 (−0.71)	−0.0357 (−0.74)
R-sq	0.9192	0.9281	0.8754
Log-l	164.8825	194.8346	—
Wald	—	—	4707.29

TABLE 12 | Robustness tests (INVE3).

Variables	Standard SDM	Robust SDM	RE
$INVE_{it-1}$	0.2853***(3.90)	0.7788***(19.44)	0.7781***(23.70)
PCI	−0.2934***(−2.76)	−0.0943 (−1.24)	−0.1410*(−1.63)
APC	−0.1327**(−2.07)	−0.0518 (−1.03)	−0.1091**(−2.18)
ERC	−0.3548***(−2.37)	−0.0897 (−0.86)	−0.1487 (−1.18)
DPI	−0.8281***(−3.76)	−0.4421***(−2.56)	−0.5657***(−3.20)
CEA	−0.0527 (−0.47)	−0.0950 (−1.58)	−0.1366*(−1.68)
UPD	−0.5798***(−3.04)	−0.2229***(−3.49)	−0.2125***(−2.64)
ERC*DPI	−0.0648 (−0.58)	−0.0921 (−1.06)	−0.0140 (−0.12)
R-sq	0.2541	0.4849	0.1263
Log-l	−207.8014	19.1104	—
Wald	—	—	3359.21

TABLE 13 | Robustness tests (INVE4).

Variables	Standard SDM	Robust SDM	RE
$INVE_{it-1}$	0.8640***(36.66)	0.7783***(18.14)	0.8886***(43.36)
PCI	−0.2925***(−4.03)	−0.1132 (−1.02)	−0.2383***(−3.40)
APC	−0.0897**(−2.02)	−0.0607 (−0.81)	−0.0667*(−1.67)
ERC	−0.2933***(−2.83)	−0.1214 (−0.78)	−0.2431***(−2.38)
DPI	−0.6673***(−3.57)	−0.9128***(−3.50)	−0.5752***(−4.02)
CEA	−0.1863***(−2.62)	−0.2010**(−2.29)	−0.2045***(−3.11)
UPD	−0.1731**(−2.10)	−0.1015 (−1.04)	−0.1012 (−1.58)
ERC*DPI	−0.1364 (−1.31)	−0.1013 (−0.79)	−0.1050 (−1.11)
R-sq	0.5820	0.4062	0.5712
Log-l	−141.8321	−71.0700	—
Wald	—	—	6172.53

factors on private investment are urban disposable income, urban population density, and pollution prevention and control investment; the top three factors on Hong Kong, Macao, and Taiwan investment are total environmental regulation cost, pollution control, and prevention cost and the proportion of residents with college education or above.

4.5 Robustness Tests

4.5.1 Eliminating Other Interference Items

Our research covers the extensive time-series data from 2004 to 2017 annually. Thus, changing national and provincial policies inevitably affects our regression results. Therefore, the impact of other interference items needs to be controlled. The interference

TABLE 14 | Robustness tests (INVE5).

Variables	Standard SDM	Robust SDM	RE
$INVE_{it-1}$	0.3795***(21.37)	0.2620***(22.76)	0.5355***(28.32)
PCI	−0.8188***(−17.45)	−0.5929***(−11.16)	−0.6280***(−10.19)
APC	−0.0963***(−3.86)	−0.1308***(−4.14)	−0.1137***(−3.53)
ERC	−0.9652***(−15.29)	−0.7135***(−9.66)	−0.7186***(−8.52)
DPI	−0.4466***(−4.88)	−0.4534***(−2.41)	−0.3826***(−3.62)
CEA	−0.3006***(−6.65)	−0.0365 (−0.85)	−0.1575***(−2.71)
UPD	−0.1506*(−1.66)	−0.0205 (−0.23)	−0.2794***(−3.65)
ERC*DPI	−0.0181 (−0.44)	−0.0432 (−1.09)	−0.0164 (−0.28)
R-sq	0.9696	0.9758	0.9508
Log-l	131.5140	170.1044	—
Wald	—	—	5239.86

can be effectively eliminated by shortening the data collection period. 'The Cleaner Production Promotion Law of the People's Republic of China was amended and implemented in 2012. It is a relatively authoritative legal document in the field of environmental regulation, which may cause a great disturbance to the research results before and after its implementation. The data from 2004 to 2012 are selected for the robustness test as displayed in **Table 10**, **Table 11**, **Table 12**, **Table 13**, and **Table 14**, respectively. The results show that there are no significant changes in the direction and significance of the coefficients, which are consistent with the benchmark regression results. It provides robustness checks to our regression results.

4.5.2 Robustness Test for a Panel Data Model

To avoid the estimation error caused by the wrong model selection, we use a random effects (RE) panel data model for the robustness test. The results are reported in **Table 10**, **Table 11**, **Table 12**, **Table 13**, and **Table 14**, respectively.

Although there are some changes in the magnitude and significance of some coefficients, the direction of impact remains constant. So it ensures the consistency of research results even measured with varied methods, namely, the robustness of the research.

5 CONCLUSION

Based on the panel data of 29 provinces in China from 2004 to 2017 annually, the study leverage SDM to carry out the empirical analysis on the relationship between local environmental regulation competition, public participation, and enterprise location selection. The results show that, first, the spatial spillover effect of environmental regulation competition and public participation on enterprise location choice is significant. It means that environmental regulation and public participation in one region have a significant impact on the location choice of enterprises in other regions. When local governments make environmental regulation policies, they should pay attention to the spatial spillover effect. Second, environmental regulation competition has a negative impact on the location choice of enterprises. It indicates that the more intense the competition is, the lower the intensity of local environmental regulation will be, and more enterprises will be attracted to locate. However, although environmental regulation competition can bring more investment, it is not conducive to the sustainable development of economy. Among the indicators of environmental regulation competition, the coefficient of the investment in pollution prevention and control is the largest and has the greatest impact on the location choice of enterprises. Third, the total effect of public participation on enterprise location choice is significantly negative, which means that the higher the level of public participation is, the less enterprise investment will be. Active public participation can effectively avoid the excessive investment caused by local environmental regulation competition and sustain economic development. Among the indicators of public participation, urban population density and urban disposable income index have a greater impact on enterprise location selection. Fourth, the regression results of the heterogeneity of enterprises are significant. The results show that pollution control investment and urban population density greatly affect state-owned investment. Foreign investment is more susceptible to the level of public participation that pays attention to urban population density and urban disposable income; private investment emphasizes urban disposable income and urban population density. The investment from Hong Kong, Macao, and Taiwan attaches more importance to pollution control investment and education level.

Economic sustainability can be achieved through shifting the mechanism of environmental regulation from pollution emission control system to a precautionary system. Therefore, this study proposes the following policy recommendations. First of all, a functional pollutant discharge system should be built upon enterprises, to reinforce the regulation implementation and prevent environmental deterioration. Second, pollution control investment should be enhanced to strengthen the environmental prevention capacity, therefore building a sound socio-ecological environment for the settlement of low-pollution enterprises. Finally, a special fund should be set up to encourage local enterprises to transfer into the environmental-friendly economy, preventing pollution radically.

Beyond them, it is necessary to improve the environmental information disclosure mechanism by establishing diversified communication platforms in order to enroll more participators. With the rapid development of multimedia, it is more convenient for the public to get involved in the events and raise common awareness. Meanwhile, multimedia acts as a double sword, the informal report in which might mislead the public as well arouse the wave of protest. Even so, it is believed that the environmental information disclosure mechanism should be improved, and unobstructed communication channels should be established to the informative to the public. Further, local governments should improve the feedback mechanism for public participation, and promotes the coordination between local governments' environmental regulations and public participation. Local environmental regulation competition and public participation have mutual influence and complement each other. The time-feedback of public participation can facilitate local governments to

dynamically adjust the environmental regulation intensity, standard investment from different types and achieve economic sustainable development.

This study is subject to some limitations, which is also the research direction in the future. First, we do not use enterprise data. In the next step, we will investigate the willingness of enterprises and test it with enterprise data. Second, the study of interaction effect between environmental regulation competition and public participation is not deep enough. We will discuss the interaction with more detailed variables. Third, the impact of environmental regulation on enterprise location selection maybe distinguished between short term and long term, which can be studied further.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

XM: conceptualization, data curation, methodology, and writing—original draft. ZQ: data curation and visualization. WA: visualization and editing. MKA writing and review. ZH: writing and review. AA: review and editing.

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Analyzing the Mechanism Between Local Government Debts and China's Economic Development: Spatial Spillover Effects and Environmental Consequences

*Xuesen Cai and Xiaowei Song**

School of Management, Ocean University of China, Qingdao, China

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Edited by:
Muhammad Irfan,
Beijing Institute of Technology, China

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Tomiwa Sunday Adebayo,
Cyprus International University, Turkey
Mahejabin Sayyad,
Agasti Arts, Commerce, and Dadasaheb Rupwate Science College, Akole, India

Correspondence:
Xiaowei Song
songxiaowei@stu.ouc.edu.cn

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Under the new normal of economy, a series of active fiscal policies such as tax reduction and fee reduction and new infrastructure construction in China have reduced the source of local government revenue, while the expansion of fiscal expenditure and the widening gap between revenue and expenditure have further exacerbated the motivation of local governments to borrow. Using the spatial econometric model and based on the data of 30 provinces in China from 2006 to 2018, this article deeply studies the impact of local government debt on economic growth and its spatial spillover effect and discusses the regional location heterogeneity of this growth effect. The research shows that: (1) local government debt has significantly promoted regional economic growth; (2) the growth promoting effect of local government borrowing has significant spatial spillover; (3) borrowing debt has the greatest effect on promoting economic growth in the central region, followed by the east, and the west is almost unaffected. Therefore, the Chinese government needs to continue to implement an active fiscal policy, improve the promotion and assessment mechanism of local officials, and adhere to the goal of balanced regional development.

Keywords: local government debt, economic growth, space spillover effect, China, environmental consequences

1 INTRODUCTION

In the process of accelerating China's economic construction, local governments have played an important role (Fang et al., 2022; Yang et al., 2021). Local governments are the backbone of China's rapid economic growth (Wang et al., 2022; Jinru et al., 2021). Under China's unique financial system, the local government's financial resources are limited (Abbasi et al., 2022; Irfan and Ahmad 2022), and the local economic and social construction is limited by the funding gap (Chai et al., 2021; Feng et al., 2021; Hao et al., 2020). Under the constraint of funds, local governments seek to make up the funding gap by borrowing money to better perform government functions (Cai et al., 2021; Wu et al., 2021a). In 2021, China's "Government Work Report" pointed out that it was planning to allocate 3.65 trillion yuan of local government special bonds in that year, accounting for 3.10% of the GDP of that year. Under the new economic normal, a series of active fiscal policies, such as cut taxes and fees and new infrastructure in China, have reduced the revenue source of local governments, while the local fiscal expenditure has expanded (Guo and Shi, 2021). The contradiction between local fiscal revenue and expenditure has further aggravated the motivation of local governments to borrow

(Yumei et al., 2022; Yan et al., 2021), resulting in the continuous expansion of the debt scale and the increasing financial burden of local governments (Chen et al., 2020; Rauf et al., 2021; Shi et al., 2022). According to the latest data from the Ministry of Finance of the People's Republic of China, as of the end of December 2021, the national local government debt balance was 30.47 trillion yuan. Compared with about 15 trillion yuan in 2016, the debt scale doubled in 6 years. The continuous expansion of local government debt has gradually become an important risk hidden in the operation of China's local financial system. Therefore, the problem of local government debt is a topic worthy of study and of practical significance.

Local government borrowing is a double-edged sword (Feng, 2019; Irfan and Ahmad 2021; Irfan et al., 2022). On the one hand, if the scale of local government debt is too large or uncontrolled, it may lead to the problem that it cannot be paid when it is due, which will lead to financial and even political risks (Li et al., 2022). On the other hand, local government borrowing has played a positive role in economic growth (Cuestas and Regis, 2018). Specifically, borrowing money can temporarily relieve the financial pressure of local governments. The local government's capital demand for economic infrastructure construction and investment attraction has been met. The improvement of the business environment will attract investors and promote the development of related industries. At the same time, industrial development will promote employment, stimulate the total social demand, and then have a positive impact on economic growth. With the demand of supply-side reform and high-quality economic development, China's economic growth is slowing down (Ren et al., 2022; Wang et al., 2022). So, can local government borrowing play a role in stimulating economic growth? Under the "political tournament," does this growth effect have spatial spillover? In addition, in the case of unbalanced regional development, will there be regional heterogeneity in this growth effect? It is of practical significance to discuss these issues at a time when the government's financial expenditure is expanding.

The possible contributions of this article are as follows: first, compared with the literature on the economic effects of government debt from the national level (Cheng and Gong, 2014; Yusuf and Mohd, 2021), based on the data of China's regional level, this article uses the OLS model and spatial model to illustrate that local government debt has a direct promoting effect and spatial spillover effect on economic growth. Second, this article not only analyzes the overall effect of local debt on economic growth but also further discusses the heterogeneous impact of local government debt on economic growth in the eastern, central, and western regions.

2 LITERATURE REVIEW

After the financial crisis in 2008 and the subsequent European sovereign debt crisis, the controversial classic topic of the relationship between government debt and economic growth has once again been hotly debated by domestic and foreign scholars (Tang et al., 2022; Qiu et al., 2022). Due to the limitation of the availability of China's debt data, most of the research in this period was based on foreign data and focussed on the study of the impact of national debt on economic growth (Albu and Albu, 2021; Checherita-Westphal and Roether, 2012; Cheng and Gong, 2014; Guo and Wang, 2014; Panizza and Presbitero, 2014;2021; Yusuf and Mohd, 2021). However, China's financial system is special, and the universality of these research results to China remains to be discussed. The publication of China's local debt data shed light on the severity of the local government debt problem and the downward pressure on the economy. In recent years, the research on the economic growth effect of local government debt in China has increased. However, there are differences or even great differences in the conclusions drawn by using different debt data and different research methods. At present, there are three views on the economic growth effect of local government debt.

First, the impact of local government debt on economic growth is non-linear. Local government debt can promote economic growth within a certain debt scale, but it has a negative impact if it exceeds this threshold. Scholars who hold this view believe that the increase in financial resources caused by local government debt will stimulate investment and consumption through such means as undertaking administrative affairs, infrastructure construction, and official competition, which will bring about economic growth. However, when the debt ratio exceeds a certain threshold, it will squeeze out private investment, bring huge debt repayment pressure, and have a negative impact on economic growth (Lv, 2015; Diao, 2017; Chen, 2018; Wu and Bao, 2019; Liu et al., 2020). In addition, due to the different data caliber and indicators of local government debt, scholars have not reached an agreement yet on a specific threshold.

Second, local government debt has a positive effect on economic growth. According to the research of Fan and Mo, (2014), local government debt promotes economic growth by increasing investment and lowering the price of industrial land, which provides a new perspective of the land market for studying the growth effect of borrowing. Zhu and Chen, (2014) found that by using the data of debt audits, China's local government debt has a pulling effect on regional economic growth, but this effect has convergence characteristics. In addition, local government debt can enable the government to increase investment in green technology innovation such as renewable energy (Adebayo and Kirikkaleli, 2021; Kirikkaleli and Adebayo, 2021; Adebayo, 2022; Adebayo et al., 2022; Fareed et al., 2022), thus promoting sustainable economic growth.

Third, local government debt has a negative hindering effect on economic growth. Sun and Han, (2019) made an empirical study on 30 provinces in China by using the mixed effect model and found that the increase of local government debt is not conducive to economic growth, and this negative impact is obviously heterogeneous in areas with different levels of economic development.

Based on the aforementioned analysis, we can find that the research on the economic growth effect of local government debt has made rich achievements, but unfortunately: (1) the spillover effect of debt between regions has not been taken seriously, which

may lead to the deviation of the results. Under the official promotion system in China, horizontal competition, including taxation and fiscal expenditure, exists among local governments (Diao, 2016; Wang, 2017; Zheng et al., 2017; Hong et al., 2020; Huang and Liu, 2020), and ignoring the spatial correlation of local government debt will reduce the credibility of empirical results to some extent. (2) The published articles seldom consider the regional differences of the growth effect of local government debt.

This article tries to use the spatial econometric method to evaluate the impact of local government debt on regional economic growth and its spatial spillover effect. Also, the regional heterogeneity of influence is also analyzed.

3 MECHANISM ANALYSIS AND RESEARCH HYPOTHESIS

Adam pursued liberalism and believed that the government's bond issuance would encroach on capital and hinder economic growth. Later generations summed up his view as "the theory of harmful debt"; David Ricardo advocated "debt neutrality" and thought that the effect of government bond issuance is like taxation, that is, the "Ricardo equivalence theorem." With the outbreak of the economic crisis in 1929, Keynes's "debt benefit theory" has become the mainstream of academic circles. Keynes believed that the expansionary fiscal policy (increasing fiscal expenditure) would stimulate economic growth by stimulating investment and expanding demand. Based on Keynes's "debt beneficial theory," this article holds that the mechanism of the influence of local government borrowing on economic growth is as follows: first, according to the financial functions of the new era summarized by Liu et al. (2020), namely, social protection, economic growth, and income distribution functions, the expenditure of local government borrowing is mainly divided into two parts. First, it is used for public infrastructure investment, which is the embodiment of the financial and economic growth function; second, it is used to provide the bottom guarantee for members with weak social development ability. It is the embodiment of financial social protection and income distribution functions. In addition, the increase of investment in public infrastructure will lead to the increase of private investment and increase employment opportunities. In addition, it will stimulate consumer demand by providing all-out protection to the members of society (such as relief to the bottom people and the enterprises that are temporarily struggling to operate due to force majeure) and finally stimulate economic growth. Based on this, the following research hypothesis is put forward: 1. local government debt is positively correlated with regional economic growth.

4 DESCRIPTION OF VARIABLES AND DATA SOURCES

Based on the provincial panel data of 30 provinces (autonomous regions and municipalities) in China from 2006 to 2018 (except Tibet, Hong Kong, Macau, and Taiwan Province), this article analyzes the impact of local government debt on regional economic growth and its spatial spillover effect.

4.1 The Explained Variable

The explained variable in this article is per capita GDP (Avegdp), and the ratio of GDP of each region to the total population at the end of the year represents the economic growth level of the region (Wu et al., 2019), with the unit of 10,000 yuan.

4.2 Explaining Variables

In this article, the balance of provincial debt data that has not expired after the issuance of bonds every year is selected as the proxy variable of local government debt, that is, the annual bond balance of each province is calculated according to the issuance date and the issuance period of each province, and the unit is one trillion yuan.

4.3 Control Variables

According to the economic theory, common sense, and literature in related research fields, this article selects the following control variables: (1) Labor force growth rate (Lab): expressed by the growth rate of employees at the end of the year, and the unit is %; (2) Investment growth rate (Inv): expressed approximately by the growth rate of fixed asset investments in the whole society, with the unit of %; (3) Openness to the outside world (Ope): learn from the practices of most studies, expressed by the proportion of total regional import and export trade to regional GDP, that is, the degree of opening to the outside world = (total regional import and export trade * current exchange rate)/regional GDP; (4) Education level (Edu): this article uses the proportion of the number of college students in a region to the total population of that region in that year to indicate the education level of that region. That is, the education level = the number of students enrolled as ordinary college students in different regions/the population in different regions; (5) Urbanization rate (Urb): expressed by the proportion of the urban population to the total population, with the unit of %. **Table 1** reports the descriptive statistics of each variable. Data quality is the forerunner of the empirical analysis. From the results of the descriptive statistical analysis, the data used in this article have no extreme outliers and systematic errors.

5 EMPIRICAL ANALYSIS AND TEST

5.1 The Construction of Spatial Weight Matrix

The construction of a spatial weight matrix is the key to spatial econometric analysis. Remember that the distance between regions is w_{ab}, $a, b = \{1, 2, 3......n\}$, then the spatial weight matrix is:

$$w_{ab} = \begin{Bmatrix} w_{11} & \dots & w_{1n} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nn} \end{Bmatrix}.$$

According to the different ways of distance division, there are many types of spatial weight matrices, such as adjacency matrix and economic distance weight matrix. The first-order adjacency matrix,

TABLE 1 | Descriptive statistical analysis of table variables (2006–2018).

Variable	Indicator description	Observed value	Mean	S.D	Min	Max
Avegdp	GDP per capita	390	4.24	2.51	0.63	14.02
Debt	Local government debt	390	996.9	1564.46	0	13600.15
Lab	Labor force growth rate	390	2.22	9.19	–50.99	121
Inv	Investment growth rate	390	18.1	12.74	–62.65	59.54
Ope	Opening level	390	0.29	0.33	0.01	1.67
Edu	Educational level	390	0.02	0.01	0.006	0.035
Urb	Urbanization rate	390	53.38	13.07	27.46	89.6

Data source: China Statistical Yearbook, China Financial Yearbook, Wind database, and statistical yearbooks of some provinces.

TABLE 2 | Global Moran index of local government debt and per capita GDP (2006–2018).

Debt	Moran's I	Z-value	P-value	Avegdp	Moran's I	Z-value	P-value
2006	0.405	3.866	0.000	2006	0.418	3.870	0.000
2007	0.517	4.717	0.000	2007	0.415	3.828	0.000
2008	0.497	4.765	0.000	2008	0.418	3.797	0.000
2009	0.443	4.101	0.000	2009	0.418	3.773	0.000
2010	0.390	3.602	0.000	2010	0.424	3.795	0.000
2011	0.312	3.002	0.001	2011	0.421	3.754	0.000
2012	0.298	3.004	0.001	2012	0.409	3.648	0.000
2013	0.276	2.822	0.002	2013	0.398	3.555	0.000
2014	0.215	2.388	0.008	2014	0.383	3.427	0.000
2015	0.170	2.055	0.020	2015	0.384	3.435	0.000
2016	0.163	2.087	0.018	2016	0.399	3.579	0.000
2017	0.150	0.093	0.024	2017	0.427	3.818	0.000
2018	0.164	2.100	0.018	2018	0.419	3.753	0.000

that is, 0–1 matrix, is constructed in this article. If area A and area B have a common boundary, it is 1; otherwise, it is 0, as follows:

5.2 Spatial Autocorrelation Test

If there is spatial dependence between data, it is necessary to take the spatial effect into account in the empirical analysis; otherwise, the classical econometric analysis can be used. In this article, Moran 'I is used to test the spatial autocorrelation of the explained variable per capita GDP:

$$\mathrm{Moran's\,I} = \frac{\sum_{a=1}^{n}\sum_{b=1}^{n} w_{ab}\left(x_a-\bar{x}\right)\left(x_b-\bar{x}\right)}{S^2\sum_{a=1}^{n}\sum_{b=1}^{n} w_{ab}},$$

where sample variance $S^2 = \frac{\sum_{a=1}^{n}(x_a-\bar{x})^2}{n}$, w_{ab}, a, b as defined previously. Moran 'I is [- 1,1], when $-1 \le \mathrm{Moran'\,I} < 0$. The spatial correlation of the variables analyzed is negative; when $\mathrm{Moran'\,I} = 0$, there is no spatial correlation among the analyzed variables; when $0 < \mathrm{Moran'\,I} \le 1$, the larger the absolute value of the index, the stronger the spatial correlation of the variables. **Table 2** shows the global Moran index test results of China's per capita GDP from 2006 to 2018.

According to **Table 2**, from 2006 to 2018, the global Moran index of the local government debt level and regional per capita GDP were both greater than 0 and passed the significance test of 1%. This result shows that there is a strong spatial positive correlation between the level of local government debt and economic growth in various regions of China and shows a trend of increasing volatility.

In order to further analyze this spatial dependence, this article uses the constructed spatial weight matrix, i.e., the first-order adjacency matrix, to draw the local Moran scatter diagram of the local government debt and economic growth level in some years (2006, 2010, 2014, and 2018), as shown in **Figure 1**; **Figure 2**. From the Moran scatter diagram, we can see that most of China's provinces are in the first and third quadrants, and there are "high–high" and "low–low" agglomeration phenomena, that is, high (local government debt level or economic growth) level and high (local government debt level or economic growth) level, and low (local government debt level or economic growth) level and low (local government debt level or economic growth) level agglomeration phenomena. Among them, Beijing, Tianjin, Shanghai, Jilin, Heilongjiang, and other provinces (municipalities directly under the central government) are located in the first quadrant, while Gansu, Qinghai, Ningxia, and Xinjiang are in the third quadrant. At the same time, we can see from the local Moran scatter charts in 2006, 2010, 2014, and 2018 that the quadrants of each province are relatively stable, indicating that the spatial dependence of the local government debt and economic growth level in China is relatively stable.

5.3 Setting and Selection of the Spatial Metrology Model

In the aforementioned research and analysis, Moran's I value is greater than 0, which shows that there is spatial dependence

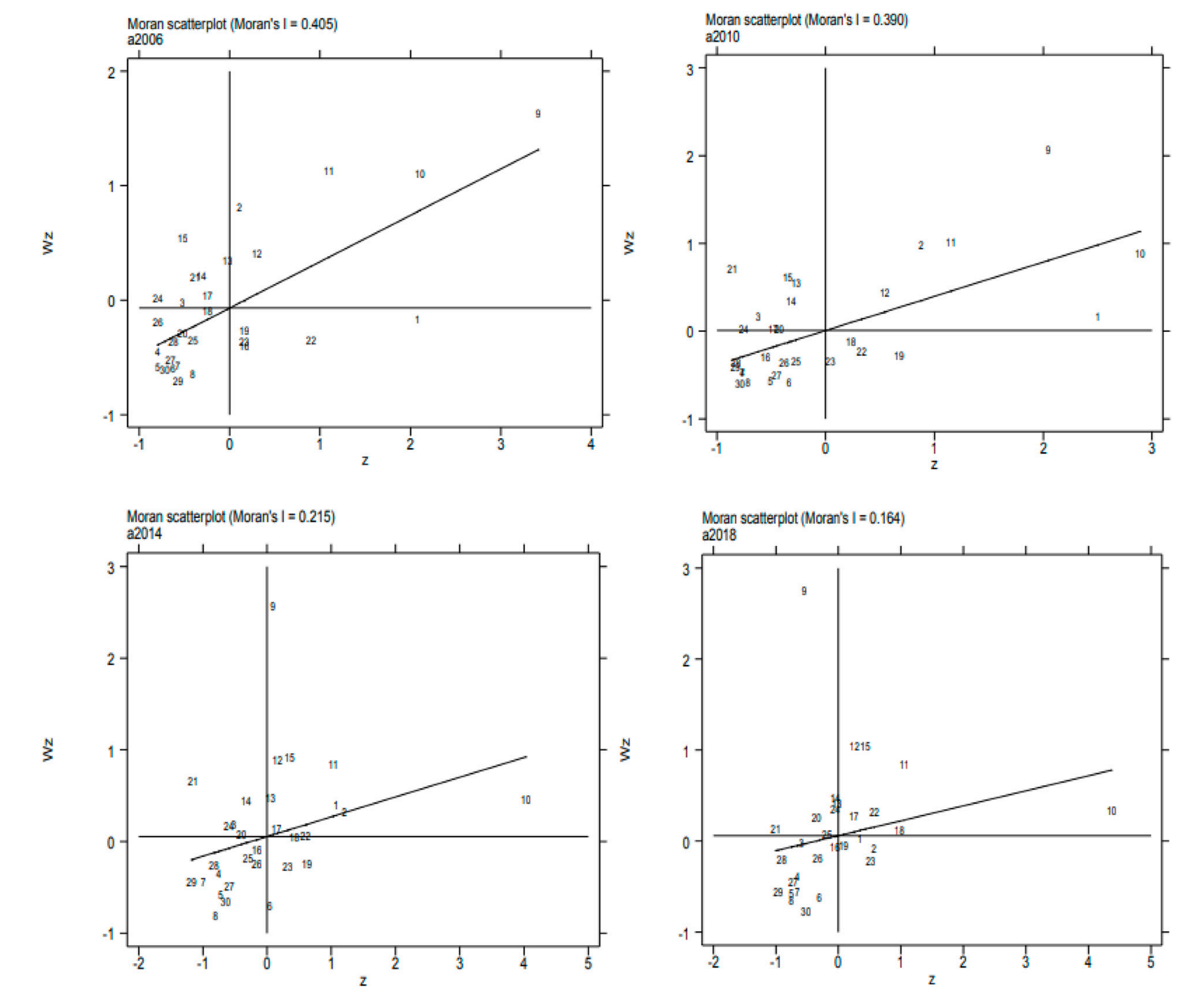

FIGURE 1 | Local Moran scatter chart of the local government debt level (2006, 2010, 2014, and 2018).

between the local government debt and economic growth level in China. If we only use ordinary OLS to carry out regression analysis on variables, this spatial effect will be ignored and the regression results will be biased. Based on this, this article uses the spatial lag model (SLM) and spatial error model (SEM) to analyze the impact of the local government debt level on regional economic growth.

5.3.1 Spatial Lag Model

Based on the ordinary econometric model, the spatial lag model adds the spatial lag term of the explained variables and considers the influence of adjacent regions on a region and takes the spatial spillover effect into account in the econometric model. The formula is as follows:

$$y = \gamma Wy + X\beta + \varepsilon,$$

where y is the explained variable, γ is the spatial autoregressive coefficient, β is the coefficient of the explanatory variable, W is the spatial weight matrix, X is the explanatory variable, and ε is a random error term. According to the research content and the choice of variables, referring to Zhang et al. (2022), the model can be expanded to the following forms:

$$Avegdp_{it} = \beta_1 debt_{it} + \beta_2 lab_{it} + \beta_3 inv_{it} + \beta_4 ope_{it} + \beta_5 edu_{it} + \beta_6 urb_{it} + \delta \sum_{b=1}^{N} W_{ab} Avegdp_{it} + \varepsilon_{it}.$$

5.3.2 Spatial Error Model

This kind of spatial error may not be explained by the spatial variable but by the spatial error. The specific formula is as follows:

$$y = X\beta + \varepsilon, \varepsilon = \sigma W\varepsilon + \mu,$$

where y is the dependent variable; X is an independent variable; β is the coefficient of the independent variable; ε and μ are the error

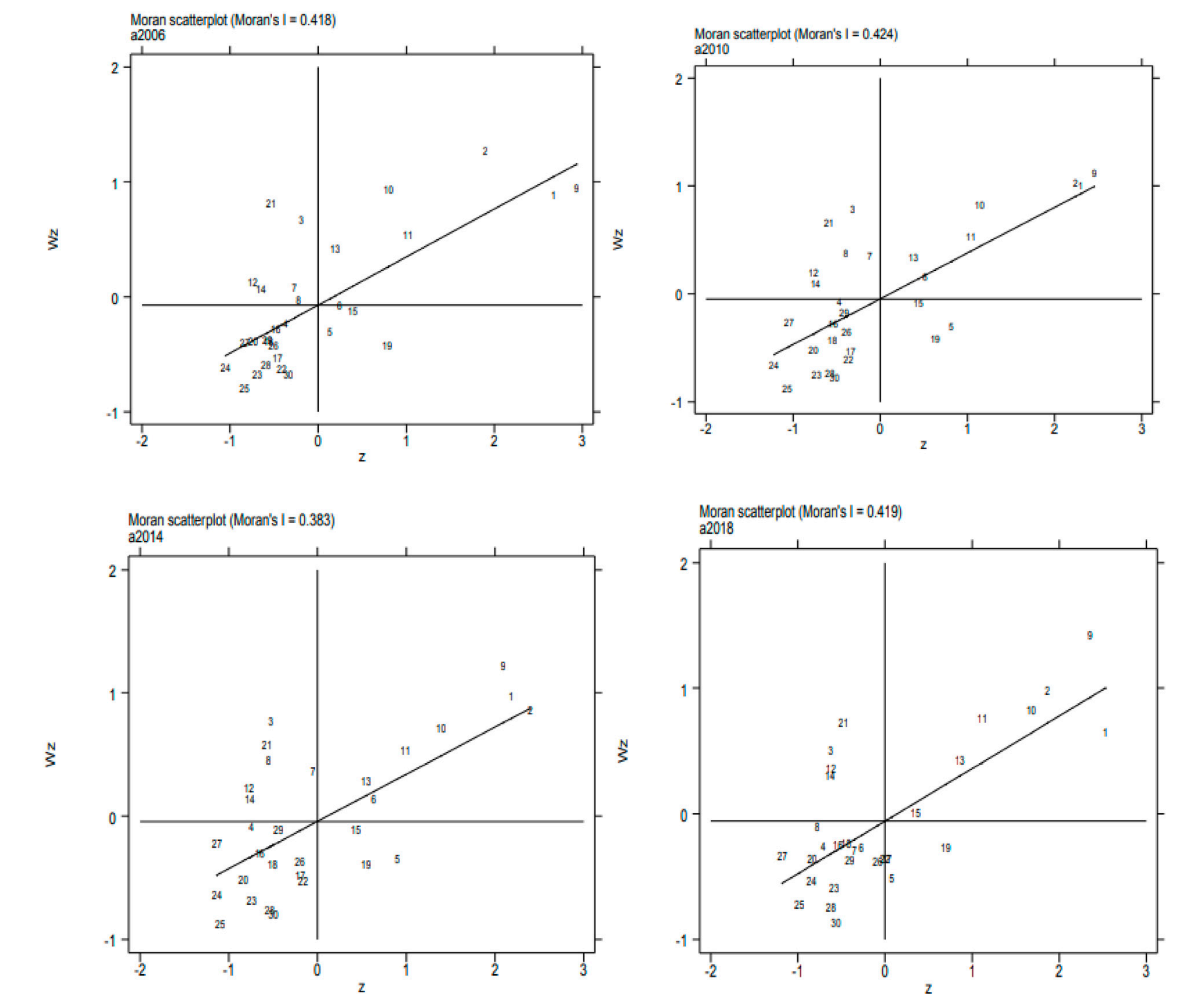

FIGURE 2 | Local Moran scatter chart of per capita GDP (2006, 2010, 2014, and 2018).

terms; W is the spatial weight matrix; and $\partial\sigma$ is the spatial error coefficient. Combined with the research content of this article, referring to Shi et al. (2021), the specific spatial econometric model formula is as follows:

$$Avegdp_{it} = \beta_1 debt_{it} + \beta_2 lab_{it} + \beta_3 inv_{it} + \beta_4 ope_{it} + \beta_5 edu_{it} + \beta_6 urb_{it} + \sigma \sum_{b=1}^{N} W_{ab} Avegdp_{it} + \mu_{it}.$$

5.3.3 Selection of the Spatial Metrology Model (LM Test)

Whether to choose the spatial lag model or the spatial error model, or both, we need to perform LM lag, LM error, and robust tests to make the final judgment. If the LM lag result is significant but the LM error result is not significant, the spatial panel lag model is selected for econometric analysis; otherwise, the spatial panel error model is selected for econometric analysis; if both are significant, SLM and SEM can be used for regression analysis. This article studies the impact of local government debt on regional economic growth. On this basis, it uses Stata software to conduct the LM test on OLS regression results of total samples. **Table 3** shows the results of the OLS regression test. It can be seen

TABLE 3 | Results of the OLS regression test.

Test	Statistic	P-value
Lagrange multiplier (error)	0.588	0.443
Robust Lagrange multiplier (error)	16.607	0.000
Lagrange multiplier (lag)	56.150	0.000
Robust Lagrange multiplier (lag)	72.168	0.000

TABLE 4 | OLS and SLM test results of the impact of the local government debt level on regional economic growth in 2006–2018.

Variable	(1)	(2)	(3)
	OLS	Panel SLM	
W*Avegdp		0.630***	0.648***
		(0.065)	(0.062)
Debt	4.975***	1.839***	1.946***
	(0.376)	(0.511)	(0.530)
Lab	0.014**	0.005***	0.007***
	(0.376)	(0.001)	(0.002)
Inv	−0.016***	−0.001	−0.001
	(0.005)	(0.003)	(0.004)
Ope	−0.462**	−2.816***	−2.954***
	(0.223)	(0.582)	(0.541)
Edu	39.93***	−34.30	−28.31
	(12.58)	(43.00)	(57.84)
Urb	0.128***	0.060**	0.052
	(0.008)	(0.025)	(0.034)
Cons	−3.399***	−0.327	0.068
	(0.353)	(1.156)	(1.333)
R-sq	0.838	0.276	0.174
Obs	390	390	390

from **Table 3** that the Lagrange multiplier for the spatial error fails the significance test; both Lagrange multiplier and robust Lagrange multiplier tests for spatial errors are significant at the level of 1%. This result shows that the spatial lag model can be used in the quantitative analysis of samples.

5.3.4 Results and Discussion

Table 4 shows the test results of the benchmark model and spatial econometric model of the relationship between local government debt level and economic growth. From the OLS regression results, the coefficient of the local government debt level (Debt) is 4.975, which means that if the local government debt level increases by 1%, the per capita GDP will increase by 4.975% and the debt level of local government will promote economic growth. This result is consistent with Zhu and Chen, (2014) and Fan and Mo, (2014). The possible reason is that bonds issued by local governments are mainly used for infrastructure projects and the provision of public services (Huang and Du, 2018). The provision of public goods and services by the government can create a good investment environment, which is conducive to local investment (Shahbaz et al., 2020). Furthermore, government purchase can boost the total social demand, thus stimulating economic growth (Erdoğan et al., 2020).

In the third column of SLM, we can see that the positive effect of debt on local economic growth is 1.9%. The effect of debt on local economic growth is 1.9%. The coefficient of the spatial lag of the dependent variable is 0.630, which has passed the significance test of 1%, and it shows that the growth effect of the local government debt level has obvious spatial spillover. The possible reasons are as follows: under China's unique financial system and official promotion system, officials will launch promotion tournaments with the goal of GDP, especially referring to the fact that higher-level officials mainly assess and promote lower-level officials according to economic growth, so lower-level officials have a strong motivation to develop the economy in order to get political promotion (Li and Zhou, 2005). In this context, the mutual reference and imitation of government debt decisions between neighboring provinces will create an impact on economic growth. Therefore, the impact of local government debt on economic growth will produce spatial spillover (Zhao et al., 2019).

In addition, the elasticity coefficient of the labor growth rate (Lab) is 0.00541. Through the significance test of 1%, it shows that a labor force increase promotes economic growth. The coefficients of investment in fixed assets (Inv) and education level are −0.00110 and −34.30, respectively, which failed to pass the significance test. The regression coefficient of the degree of opening to the outside world (Ope) is −2.816, and it has passed the significance test of 1% in statistics. It shows that the degree of opening to the outside world has played a significant negative role in China's economic growth during the observation period. The reason may be that local government officials blindly pursue political achievements and blindly attract foreign investment without evaluating the quality of foreign investment, thus affecting China's economic growth (Wu et al., 2020; Irfan et al., 2021). The elasticity coefficient of the urbanization rate (Urb) is 0.0602, which indicates that urbanization plays a positive role in economic growth (Ren et al., 2021).

6 ROBUSTNESS TEST

In the aforementioned part, this article discusses the growth effect and spatial spillover effect of local government debt but does not systematically discuss the endogenous problem. The robustness of the empirical results needs to be tested. The possible endogenous problems in this article are: (1) the model setting error is caused by missing variables. The economic growth of a region will be affected by many factors, which are impossible to list the models one by one, but they are mistakenly placed in the error terms, which leads to the deviation of causal identification. (2) Two-way causality: there is a bidirectional causal relationship between local government debt and economic growth that leads to endogenous deviation, that is, "simultaneous equation deviation." On the one hand, the debt level of a region will affect its growth; conversely, the speed of economic growth in a region will also have an impact on the scale of government bond issuance, so the independence and exogenous nature of variables cannot be guaranteed (Wu et al., 2021b; Yang et al., 2021).

The solution proposed in this article is to learn from the Diao (2016) method, and select the future period of per capita GDP (Avegdp) as the dependent variable to conduct the robustness test. The empirical results are shown in model (3) in **Table 4**, which are basically consistent with the regression results of model (2). The empirical results after considering endogeneity are still robust and reliable.

7 HETEROGENEITY ANALYSIS

There is a large gap in local government debt and economic growth in the eastern, central, and western regions of China (Cai

TABLE 5 | Descriptive statistical analysis of eastern, central, and western regions of China.

Variable	East		Central section		West	
	Mean	S.D	Mean	S.D	Mean	S.D
Avegdp	6.062	2.874	3.239	1.299	3.134	1.585
Debt	0.146	0.216	0.082	0.108	0.066	0.092
Lab	3.588	14.768	1.407	2.101	1.447	2.663
Inv	14.680	12.833	20.172	12.271	20.026	12.342
Ope	0.598	0.374	1.111	0.034	0.115	0.074
Edu	0.021	0.006	0.018	0.003	0.015	0.005
Urb	64.188	13.231	48.862	6.554	45.853	8.488

TABLE 6 | Regression results of SLM in eastern, central, and western regions of China.

Variable	East (4)	Central section (5)	West (6)
W*Avegdp	0.561***	0.379***	0.393***
	(0.068)	(0.079)	(0.107)
Debt	1.612***	2.386*	0.675
	(0.507)	(1.285)	(1.209)
Lab	0.005***	0.0004	0.002
	(0.001)	(0.007)	(0.017)
Inv	−0.006	−0.011**	−0.005**
	(0.006)	(0.004)	(0.002)
Ope	−3.849***	−3.311*	1.253
	(0.793)	(1.863)	(0.949)
Edu	−79.29	107.9	−20.76
	(57.17)	(99.75)	(23.30)
Urb	0.048	0.031	0.136***
	(0.031)	(0.058)	(0.027)
Cons	3.541	−1.127	−4.051***
	(2.598)	(1.180)	(0.913)
R-sq	0.247	0.887	0.886
Obs	143	104	143

et al., 2002). From **Table 5**, there are large differences in local government debt (Debt), economic growth (Avegdp), labor growth rate (Lab), opening degree (OPE), and education level (Edu). Therefore, it is of great significance to explore the growth effect of regional government debt.

In **Table 6**, models (4), (5), and (6) give the results of sub-sample regression in eastern, central, and western China, respectively. The regression results of SLM show that: (1) the debt coefficient of eastern and central China is significantly positive at the significance level of 1 and 10%, while that of the western region is not significant, and the elasticity coefficient is 1.612 and 2.386, respectively. For each unit of increase in the level of local government debt in the eastern and central regions, the per capita GDP will increase by 1.612 and 2.386 units, respectively. Local government debt has the greatest pulling effect on the economic growth of the central region, followed by the eastern region, and has little impact on the western region. (2) In terms of the coefficient of the spatial lag term of the dependent variable, the eastern, central, and western regions are significantly positive at the level of 1%. Among them, the eastern region has the largest spatial spillover effect, followed by the western region, and the central region has the smallest.

8 CONCLUSION AND POLICY RECOMMENDATIONS

Based on the panel data of 30 provinces in China (excluding Tibet) from 2006 to 2018, this article analyzes the impact of local government debt on regional economic growth and its spatial correlation by constructing a spatial econometric model. The empirical results show that, in the sample observation period, the local government's borrowing behavior can promote economic growth to a certain extent. At the same time, this growth effect has a spatial correlation. Further analysis shows that the growth-promoting effect of local government debt on the economy is heterogeneous in regions. Based on the aforementioned conclusions, this article puts forward the following policy recommendations:

(1) Local government should continue to implement a proactive fiscal policy, improve its efficiency, and prevent systemic local government debt risks. First, in the case of controllable risks, a moderately proactive fiscal policy can inject vitality into the economy and promote short-term economic recovery and long-term economic growth, especially in the period of increasing uncertainty risks such as COVID-19 pandemic, the proactive fiscal policy should be more active and promising, and local government bonds of a certain scale should be issued under the controllable deficit level. Second, China's local governments need to comprehensively promote budget performance management, monitor local financial operation, continuously improve financial resource allocation efficiency and financial capital performance, and prevent and resolve local government debt risks. Third, the local debt limit should match its level of economic development. Local governments should actively explore market-oriented ways for development, encourage and promote market-oriented investment and financing of platform companies, and broaden investment and financing channels.

(2) Improve the promotion and assessment systems of local officials, and advocate that "Whoever borrows money is responsible." Under the assessment systems that pay too much attention to the GDP, local competition will easily lead to the increase of expenditure scale, which will lead to the expansion of local debt and aggravate the possibility of debt risk. In addition, excessive and ineffective competition among local governments will lead to redundant construction and waste of resources, which will lead to inefficient use of local financial funds. Therefore, it is necessary to improve the evaluation systems of government officials' promotion. Specifically, the promotion appraisal systems should not only pay attention to whether the short-term economic growth target is achieved but also pay attention to long-term and hidden achievements such as environmental protection and people's livelihood and emphasize on high-quality economic development.

(3) According to the research conclusion of this article, there is regional heterogeneity in the role of local government debt in promoting economic growth in China. Based on this conclusion, this article holds that China should continue to adhere to the goal of regional balanced

development. Specifically, policies on the scale and structure of local government borrowing should be formulated "according to local conditions" to avoid "one size fits all." At present, the development gap between regions in China is still relatively large. In different stages of economic development, the economic growth-promoting effect of local government borrowing is different. Therefore, the local government bond-issuing policy should be formulated according to the actual regional development.

Furthermore, we must point out that due to the limitations of the data, this article only discusses the impact of local government debt on economic growth at the provincial level. In addition, due to the short time span of the data, the research of this article is limited to the direct impact of local government debt on economic growth in the short term but failed to investigate the indirect impact of government expenditure in transportation and education on local economic growth in the long term.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XC: conceived the idea and contributed to the writing of the manuscript. XS: performed the data collection and statistical analysis. All authors have read and agreed to the published version of the manuscript.

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Linking Responsible Leadership and Green Innovation: The Role of Knowledge Sharing and Leader-Member Exchange

Chunhui Huo[1], Muhammad Arslan Safdar[1], Muhammad Waheed Akhtar[1,2] and Misbah Ahmed[1]*

[1]Asia-Australia Business College, Liaoning University, Shenyang, China, [2]Department of Management Sciences, COMSATS University Islamabad, Sahiwal, Pakistan

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Bahria University, Pakistan

****Correspondence:***
Muhammad Waheed Akhtar
waheed.mgt118@gmail.com

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This study aims to explore how to encourage employees to engage in green innovation (GI). Drawing upon social learning theory, a moderated mediation model was theorized and tested to determine how responsible leadership triggers GI in fostering knowledge sharing. Additionally, two critical processes were distinguished by introducing leader-member exchange (LMX) as a moderator. A multi wave study collected from 228 employees from hospitality sector organizations generally supported the predictions. Specifically, responsible leadership was a significant predictor of GI. Moreover, LMX strengthened knowledge sharing mechanisms and attenuated the relationship between responsible leadership and GI. The findings and the theoretical underpinning of this study shed new light on GI in a responsible way that shapes knowledge sharing among organizational members and provides practical implications for leaders determined to improve environmental sustainability in organizations.

Keywords: responsible leadership, LMX, knowledge sharing, green innovation, hospitality

1 INTRODUCTION

Pollution, ecological deterioration, and global warming pose serious challenges to the globe, requiring organizations to safeguard the ecological environment and strive for environmental sustainability (Alvarado et al., 2018; Pham et al., 2020; Jahanger et al., 2021; Kamal et al., 2021; Nguyen et al., 2021; Khan et al., 2022a; Usman et al., 2022). Organizations are improving their environmental stewardship by developing and implementing green policies and practices. As a consequence, firms are encouraging the green behavior of employees due to growing environmental and resource usage concerns, as well as the introduction of increasingly rigorous environmental legislation in many countries (Cheema et al., 2020). This is particularly the case in hotels (Ahmed et al., 2021), which depend on natural resources, energy, and human abilities to safeguard the environment and achieve sustainability objectives (Su and Swanson, 2019; Chaudhary, 2020; Khan et al., 2022b). As a result, many leading hotel groups, such as Pearl Continental, Avari Towers, Royal Swiss, Hotel One, and Marriott Hotel, promote resource recycling, conservation, and waste reduction and are dedicated to sustainable development through fulfilling its responsibilities to the environment and community in terms of energy conservation, reusing water for secondary applications, reusing and recycling materials.

Academic research and corporate practices are focusing more on how to encourage employee green behavior in the service sector. Green behavior at hotels differs from that in the workplace, where it is

influenced by people's ages, environmental awareness, knowledge, values, worries, beliefs, and life satisfaction (Wells et al., 2016; Wang and Kang, 2019). Individual differences have been the prevailing paradigm for analyzing employee green behavior to date. According to research, leadership is crucial in promoting green behavior in the workplace (Liao and Zhang, 2020; Khan et al., 2022b). Managers have problems in today's corporate world in terms of being responsible leaders and maintaining productive staff (Haque et al., 2020). Individuals may mimic proper actions and standards by seeing the behavior of others, especially those who are trustworthy, according to social learning theory (SLT) (Bandura and Walters, 1977). Leaders are prime targets for subordinates' observational learning in hospitality organizations. As a result, some researchers have looked for barriers to green innovation (GI) from the standpoint of leadership. Existing research on the link between leadership and GI has focused mostly on owner/shareholder-centric leadership, such as ethical (Arici and Uysal, 2022) and transformational leadership (Singh et al., 2020), and has shown that such leadership can foster GI under certain circumstances. This is rather discouraging because traditional leadership approaches have limits in terms of addressing the GI problem. In light of this, the focus of this research is on stakeholder-centric leadership, a promising area of leadership study. Responsible leadership (RL) is a new leadership style that arose from stakeholder theory, that identifies followers as stakeholders both inside and outside of the company (Pless and Maak, 2011).

RL refers to "*a social-relational and ethical phenomenon, which occurs in social processes of interaction to achieve societal and environmental targets and objectives of sustainable value creation and positive change*" (Maak and Pless, 2006). As per its definition, RL proposes that the environment is an important stakeholder (Han et al., 2019) prioritizing societal and environmental sustainability and striving for harmony among citizens, society, and nature (Miska and Mendenhall, 2018), all of which are values expressed in green behaviors.

Employees are motivated to share knowledge when they see RL as role models (Akhtar et al., 2020a), are highly motivated and perform over their capabilities as a result of RL (Haque et al., 2019). To address these problems, hotels need considerable RL (Miska and Mendenhall, 2018). According to Han et al. (2019), Wang, RL encourages workers to participate in decision-making and provides them with a sense of psychological ownership, which satisfies their intrinsic wants and drives them to achieve more knowledge sharing (Lin et al., 2020). Scholars have claimed that RL might help motivate employees to share their expertise.

Seemingly, recent research focuses on RL's independent influence on green behavior (Javed et al., 2021). Leadership activities, on the other hand, influence the implementation of green behavior (Aguinis and Glavas, 2019). RL supports environmental preservation and resource conservation (Afsar et al., 2020), whereas RL indicates informal personal ability to encourage employee outcomes (Akhtar et al., 2020a), such as GI. RL stands for the procedures and behaviors that provide organizational context for employee behavior (Han et al., 2019; Akhtar et al., 2020a; Haque et al., 2020). These situations must be explored more thoroughly to find possible synergies, as proposed in this study.

The mediating influence of knowledge sharing behavior was also investigated in this study. The influence of RL on GI is still unknown. The majority of prior research has looked at the favorable links between leadership and GI (Arici and Uysal, 2022). A leader is critical in establishing and maintaining a knowledge-sharing culture in the workplace. Knowledge sharing has been shown to increase crucial outcomes, such as decision-making, innovation, and performance in studies (Jiang and Chen, 2018). In the hotel sector, where services are provided and consumed concurrently, leaving minimal tolerance for errors, knowledge management, particularly information sharing, is critical for reducing service failures. This research investigates whether information sharing has a positive impact on GI.

To describe the theoretical approach, SLT (Bandura and Walters, 1977) was employed. Individuals are likely to look to their leaders for guidelines on how to behave and are more likely to adopt the behavior of the leader when the leader–member relationship is marked by high levels of mutual respect, trust, liking, and support (Graen and Uhl-Bien, 1995). Furthermore, because RL emphasizes the significance of ethical norms, workers in high LMX connections will respond by adopting knowledge sharing attitudes and eventually engage in comparable responsible behaviors, such as GI.

In three ways, this research contributes to the RL literature. First, by investigating the detrimental impact of RL on GI, existing knowledge of the role of leadership in the development of GI is expanded upon and a contribution to research on GI inhibitors and RL outcomes is made. Second, in response to the request for an underpinning mechanism to reveal the link between RL and outcomes (Akhtar et al., 2020a; Javed et al., 2021), light is shed on the function of knowledge sharing as an underpinning mechanism in the relationship between RL and GI in hospitality firms. Third, insight is provided into the effect of RL on information sharing by investigating the moderating influence of LMX, which broadens the effect's boundary conditions and increases understanding of the process of RL and knowledge sharing.

The organization of the study includes, first the introduction comprising the background, why study is important and study contributions. Second, the literature review is discussed, including the study of variables and the hypotheses framed. Third, the research method via research design, variable measurements and common method bias is described. Fourth, the results *via* confirmatory factor analysis, correlation analysis and regression analyses are discussed. Finally, the final section includes a discussion of the implications, limitations, future directions and conclusions.

2 THEORY AND HYPOTHESES DEVELOPMENT

2.1 SLT

According to SLT (Bandura, 1977; Bandura, 1986), people learn the appropriateness and acceptability of conduct from

their social surroundings and subsequently make decisions or perform depending on those social signals. The social learning process is divided into two stages: 1) humans learn from their surroundings by analyzing cues or stimuli, and 2) they utilize these insights to choose how to respond or behave. Individuals learn whether conduct is suitable from their leaders. Leaders are frequently seen as acceptable role models in workplaces. On the one hand, because leaders are so close to their followers, their actions are extremely apparent to them. Supervisors, on the other hand, have official power over employees (Yukl and Lepsinger, 2004). As a result, supervisors are frequently identified as valid sources of knowledge (Ambrose et al., 2013) and are the subject of imitation and identification (Mayer et al., 2012). Employees can learn the acceptability of conduct by looking at RL behaviors and their effects (Javed et al., 2021). Rewarding and knowledge-sharing activities, for example, are seen favorably.

Employees will determine and seek to mimic the rewarded behaviors based on what they learn from their leaders (Bandura and Walters, 1977) The chance of individuals deciding to implement a behavior learnt via role models, according to Liu et al. (2012), is dependent on the perceived consequences of that conduct. People want to achieve pleasant outcomes, while avoiding undesirable repercussions (Bandura, 1986). This implies that individuals will choose to imitate activities praised by RL since they will produce favorable results. Employees will do so by setting performance goals for themselves, monitoring their own actions, and adjusting them until they fulfil the goals. They will eventually succeed in imitating the positive actions of their RL.

2.2 RL and GI

Employees are sensitive to cues that show management's normative ideas (Lindenberg, 2000). Management practices, in their opinion, are instances of normative conduct that demonstrate the proper way to act (Pache and Santos, 2013). Technical and administrative procedures in environmental management targeted at reducing polluting externalities (Carmona-Moreno et al., 2004) convey that the firm cares about the environment (Norton et al., 2014).

According to current research, various individual and contextual factors may influence employee green workplace behavior (Norton et al., 2015), with motivation (Javed et al., 2020) and good affect as examples of individual variables. Furthermore, situational factors play an influence, such as organizational practices (Abbas and Sağsan, 2019) and leadership (Arici and Uysal, 2022). Leaders today face a complicated and dynamic corporate climate that demands them to meet financial objectives, while also paying increased attention to environmental problems (Voegtlin et al., 2012). Three important elements are captured by RL: 1) *Effectiveness*. Employees and organizations benefit from RL, which includes improved business performance and reputation (Javed et al., 2020), increased employee trust in the leader, and whistle-blowing intentions (Akhtar et al., 2020a). 2) *Ethics*. Ethics are followed by RL. They lead by example, encouraging their followers to do the right thing (Freeman and Auster, 2011). Voegtlin (Voegtlin, 2011), for example, found that RL minimizes unethical conduct among followers. 3) S*ustainability*. Organizational sustainability may be led by RL concentrating more on social, environmental, and economic performance (Miska et al., 2014).

Although research has shown that RL has a beneficial impact on companies and individuals (Akhtar et al., 2020a), its influence on GI has yet to be rigorously studied. As a result, RL is especially important for employees in developing GI since it pays attention to ecological and environmental problems and encourages employees to engage in green workplace behavior (Han et al., 2019).

Supervisors support organizations' sustainable development goals, according to RL, which include adopting social responsibility for rising pollution, resource waste, and food safety concerns (Liao and Zhang, 2020). RL influences employee green behavior through informal supervisor-employee ties (Wang et al., 2015). RL has the authority to promote and assist workers who participate in environmentally friendly initiatives, such as recycling and pollution reduction (Afsar et al., 2016). Furthermore, RL places a high value on organizational sustainability, meaning that they are, not only concerned about financial success, but also consider environmental sustainability and work to achieve these goals (Doh and Quigley, 2014). Thus, it was hypothesized that:

H1: *RL is positively related to GI.*

2.3 Mediating Role of Knowledge Sharing

Leaders who are responsible are likely to influence the attitudes and behaviors of their employees (Haque et al., 2019). Responsible leaders also take into account their employees' needs by taking an interest in their career advancement and personal development, as well as establishing a cooperative and human work environment. These activities may encourage employees to provide input to the company, such as contributing personal energy or time to the establishment of sustainable policies (Zhao and Zhou, 2019). According to Stahl and Sully de Luque. (2014), RL focuses on a broader variety of stakeholders' interests involved in business; for that purpose, he exchanges information and opinion when interacting with his employees. RL shares vital information with his subordinates during interaction, eventually adopting and absorbing their leader's principles by witnessing and emulating its conduct.

According to Srivastava and Joshi. (2018), technology-oriented leadership encourages people to share their knowledge. Organizations regard knowledge as a valuable resource and asset, therefore, employee knowledge sharing is critical for improving organizational efficiency (e.g., knowledge adoption, innovation). When employees generate and exchange knowledge with other individuals, knowledge is produced and perpetuated in the workplace. When an organization demonstrates trust, empathy, openness to knowledge sharing, and accessibility to aid, knowledge sharing is promoted (Hsu, 2012). This indicates that effective knowledge sharing requires a

relational context that is open to variety and encourages social connections (Brachos et al., 2007). A leader who demonstrates and practices interpersonal competences (person-related competencies) will have a beneficial impact on the creation and maintenance of such an environment.

Wang and Ahmed. (2003) propose a couple of ideal scenarios for shaping and sharing organizational knowledge. The first context concerns the nature of the connection or the working environment. The second is managerial policies and actions. Employees will be more engaged in GI if policies encourage knowledge development and sharing. According to Lei.et al. (2021), Gui, knowledge sharing has an impact on innovation. Wu. (2013) discovered that the key to GI success is for organizations to acquire and share external green knowledge and skills with all employees. Researchers have observed that information sharing improves GI (Chen and Hsieh, 2015). As RL offers the support needed for subordinates to accept new ideas, share information, and recognize individual contributions, proactive and collaborative interpersonal ties among workers are fostered (Owens and Hekman, 2016). Hence,

H2: *Knowledge sharing mediates the link between RL and GI.*

2.4 Moderating Role of LMX

Furthermore, current research suggests that, due to the legitimacy of their positions (Javed et al., 2021), a supervisor's unethical actions might affect bad outcomes among followers through role modeling effects. As a result, it is argued that subordinates can role model RL, which may be easily adopted and mimicked by subordinates due to its less trustworthy character, particularly in high LMX interactions.

Behavioral learning happens through observation, according to SLT (Bandura and Walters, 1977). Individuals learn what behaviors are socially acceptable and proper by seeing how others act and the repercussions of their actions. Individuals extract information from their observations of trustworthy individuals (i.e., role models), allowing them to assess the appropriateness of activities and determine whether to engage in them. As a result, the observer is more likely to mimic a behavior if a trustworthy role model (e.g., an RL) does so. A previous study revealed that leaders act as prominent role models for workers and may greatly affect their behaviors through social learning processes, which is consistent with SLT (Akhtar et al., 2021).

Individuals have many daily interactions with their bosses; thus, they have many chances to pay attention to, watch, learn, and copy their RL habits. Moreover, managers' official positions of authority and prestige within their companies make them extremely apparent to staff and provide them power over staff positive and negative reinforcement (Akhtar et al., 2020b), Supervisors are becoming increasingly significant parts of employees' work environments. Employees are prone to mimic their managers' behavior, according to SLT (Brown et al., 2005).

When managers participate in responsible behaviors, such as knowledge sharing related to environmental rules and practices, it is believed that workers will imitate these responsible behaviors. However, by evaluating the role modeling impact with respect to the quality of LMX, it can be seen how intricate it is. According to SLT, a role model's status (Bandura et al., 1963) and appreciation for a role model (Lankau and Scandura, 2002) have an impact on how far followers replicate the role model's actions. As a result, it is believed that high-quality partnerships will improve knowledge sharing modeling because high LMX leaders are more likely to be considered appealing role models.

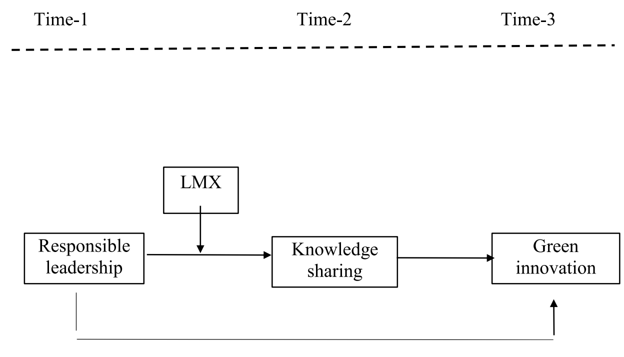

FIGURE 1 | Research Model.

Strong social emotional interactions define high-quality LMX relationships, in which supervisors and workers are mutually cordial, helpful, and trusting of one another and have an expressive tie to and like for one another (Dulebohn et al., 2012). Employees in high LMX relations are encouraged to see their leaders as attractive role models who should be followed. Because of their strong socioemotional link, employees will be more aware of and accepting of the leader's actions. Because of the high levels of trust, like, and emotional attachment found in high LMX relationships, employees are more likely to pay close attention to their leaders and want to imitate their trusted, well-liked leaders' behaviors (Lankau and Scandura, 2002). Furthermore, in high-quality LMX interactions, workers engage with their supervisors more than normal (Cogliser and Schriesheim, 2000), giving them additional opportunity to watch, attend to, and mimic their supervisors' behaviors. Thus,

H3: *The link between RL and knowledge sharing is moderated by LMX, which makes the association stronger in high LMX cases and* vice versa *in low LMX cases.*

Knowledge sharing was proposed as a mediator in the association between RL and GI in H2, as well as the moderating influence of LMX on the direct link between RL and knowledge sharing in H3. Furthermore, it is proposed that these theories support an integrative moderated mediation connection in which LMX enhances the indirect relationship between RL and employee GI through knowledge sharing. SLT supports this integrated approach (Bandura, 1986). Knowledge sharing may also be regarded as a psychological and social process that connects RL with GI through SLT. This study argues that a high degree of LMX will reduce the indirect knowledge exchange link between RL and GI (**Figure 1**). In light of this, the following hypothesis is proposed:

H4: *LMX moderates the relationship between RL and GI via knowledge sharing such that the relationship will be stronger in the case of high LMX or* vice versa.

3 METHODS

3.1 Sample and Procedures

Employees from hospitality organizations in the service industries provided information between January 2022 and April 2022. Specifically, the human resource departments of the selected organizations were contacted by phone and email to request their cooperation in the study, and in order to acquire a better understanding of the potential links, a hospitality industry sample was chosen. Hotels with stated green-related policies that prioritized the environment were chosen. A total of 47 organizations were visited for data collection. Authorities from 32 of the 47 companies consented to participate in the survey. The respondents were given the option of filling out the questionnaire on paper or online *via* a Web link.

A total of 410 employees were requested to partake in the RL survey, sharing their demographic details at time 1, when 351 filled responses were received. After a one-month interval, the 351 surveys on LMX and GI were distributed among the same respondents at Time 2. Finally, 228 usable surveys from respondents were received.

Data were self-reported and received from hotel and restaurant managers. Although self-assessment does not always occur or generate homogeneity, common method bias (CMB) appears in management studies, and technique variance can deflate or inflate the genuine connection between study variables (Podsakoff et al., 2003). Procedural methods to test for and decrease CMB were investigated and established because the results were self-reported. For example, we ensured the respondents' anonymity, changed the order of items, and conducted a pretest scale item improvement. Furthermore, the participants were told that their comments were important and essential during the personal encounter where they were collected. These steps were taken to decrease and minimize the social desirability factor (Doluca et al., 2018). Respondents are known to be unable to recognize the moderation effect when CMB is used in research, thus these actions reduce the risk of erroneous results (De Clercq et al., 2014). Harman. (2000) single-factor test was utilized. If one factor accounts for most of the covariance in the measurements, significant CMV occurs. One component accounted for 40.48 percent of the variation, according to the findings. As a consequence, no single factor explained the large percentage of the variation.

3.2 Variable Measurement

English is an official language in Pakistan (Akhtar et al., 2022). Consistent with recent similar studies, surveys were distributed in English (Akhtar et al., 2021). A five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) was used to assess all research variables.

3.2.1 RL

A five-item scale was created by Voegtlin (2011) with a reliability of 0.93 to assess RL. The following was an example question: "My direct leader/manager tries to achieve a consensus among the affected stakeholders" (α = 0.94).

TABLE 1 | CFA.

Latent variables	Standardized loadings	AVE	CR
Responsible leadership		0.68	0.92
RL1	0.800		
RL2	0.828		
RL3	0.846		
RL4	0.821		
RL5	0.839		
Leader-member exchange		0.52	0.87
LMX1	0.701		
LMX2	0.855		
LMX3	0.700		
LMX4	0.802		
LMX5	0.766		
LMX6	0.536		
Knowledge sharing		0.71	0.88
KS1	0.889		
KS2	0.791		
KS3	0.837		
Green innovation		0.68	0.94
G1	0.821		
G2	0.737		
G3	0.800		
G4	0.883		
G5	0.854		
G6	0.854		
G7	0.805		

3.2.2 LMX

Individual LMX was assessed using a 7-item scale created by Scandura and Graen (1984). For example, "my immediate supervisor understands my problems and needs" (α = 0.93).

3.2.3 Knowledge Sharing

Wilkesmann, Wilkesmann et al. (2009) used a three-item scale to assess knowledge sharing at Time 1. As an example, "I show my colleagues special procedures so that they can learn them" (α = 0.94).

3.2.4 GI

To assess GI, a six-item scale modified from Chang (2016) was used. As an example, "The company chooses green and environmentally friendly materials in the product-design stage" (α = 0.94).

A demographic sample there were 164 men (72%) and 64 women (28%) among the respondents. The majority of the responders (53%) were between the ages of 20 and 30. The plurality of respondents (46%), with fewer than four years of work experience, held a bachelor's degree (61%). In this study, demographic factors (age, gender, education, and tenure) associated with knowledge sharing and GI were controlled.

4 RESULTS

4.1 Convergent and Discriminant Validity

The discriminant validity of RL, LMX, knowledge sharing, and GI was investigated using confirmatory factor analyses. **Table 1**

TABLE 2 | Discriminant validity test results.

Latent constructs	1	2	3	4
1. Responsible leadership	*0.827*	—	—	—
2. LMX	0.662	*0.721*	—	—
3. Knowledge sharing	0.340	0.445	*0.840*	—
4. Green innovation`	0.391	0.312	0.602	*0.823*

Notes: The √ of the average variance extracted is shown on the diagonal.
√ of the AVE

TABLE 3 | Means, standard deviations, and correlations for relevant variables.

Sr #		Mean	SD		2	3	4
1	RL	4.62	1.52	***1***	_	_	_
2	LMX	4.89	1.17	0.60**	**1**	_	_
3	Knowledge sharing	4.67	1.54	0.30**	0.46**	**1**	_
4	GI	4.24	1.58	0.38**	0.35**	0.55**	**1**

shows that the four-factor model had adequate fit indices: 2/df = 2.171, TLI = 0.922, CFI = 0.932, GFI = 0.860, RMSEA = 0.072, indicating that the measurements in this research had outstanding discriminant validity.

The average variance extracted (AVE) and composite reliability were calculated to determine whether these variables were convergent (CR). **Table 1** shows that the values of the AVE and CR of the study variables were above 0.50 and 0.80, respectively, indicating that RL, LMX, knowledge sharing, and GI had adequate convergent validity.

The discriminant validity verified by assessing the√ of each AVE was > than the correlation between the corresponding variables (**Table 2**) (Fornell and Larcker, 1981). **Table 3** summarizes the descriptive statistics and correlations between RL, LMX, knowledge sharing, and GI.

4.2 Hypothesis Testing

H1 stated that RL is positively associated with GI. The results (**Table 4**) reveal that RL positively influences GI (Model 4, B = 0.24, $p < 0.001$), which supports H1. H2 suggested that knowledge sharing mediates the link between RL and GI. Referring to **Table 4**, knowledge sharing mediates the effect of RL on GI (B = 0.15, CI = 0.08, 0.23), and the 95% CI excludes 0. H2 received support.

H3 3 expected that LMX attenuates the influence of RL on knowledge sharing. **Table 5** shows that RL interacts with LMX to predict knowledge sharing (B = 0.203, $p < 0.05$). **Figure 2** also suggests that the association of RL with knowledge sharing was stronger when LMX was high (simple slope = 0.15, $p < 0.01$) than when LMX was low (simple slope = −0.12, ns), in support of H3.

To examine H4 (moderated mediation effect) *via* Model 7. **Table 5** shows that the indirect effect through knowledge sharing was significant (B = 0.07, 95% CI = [0.03, 0.18]) when LMX was high but nonsignificant (B = −0.06, 95% CI = [−0.19, 0.05]) when LMX was low. Consequently, H4 received support.

5 DISCUSSION

This study investigated the influence of crucial environmental and contextual factors (RL, LMX, and knowledge sharing) on SLT-based GI. GI benefited from the combined and synergistic benefits of RL, LMX, and information exchange. The findings of the cross-sectional, quantitative study design demonstrated that knowledge sharing acted as a mediator between the interaction effects of RL, LMX, and GI in the hospitality industry.

5.1 Theoretical Implications

This study adds to our understanding of RL and GI in the workplace and provides four significant theoretical advances. The first and most important contribution is to connect RL theory to the existing GI literature. There is minimal available information on the function of leadership in GI (Arici and Uysal, 2022) because most GI research has mostly focused on an individual's psychological processes (Cui et al., 2021). Furthermore, only a few leadership styles, such as ethical leadership (Cui et al., 2021) and transformational leadership, have been reported to stimulate GI (Begum et al., 2022). However, there is a need to comprehend how RL affects followers' environmentally beneficial behavior (Liao and Zhang, 2020), such as GI. This research confirms that RL inhibits GI and builds on the work of Su and Swanson (2019), Akhtar et al. (2021) by examining how RL influences the conduct of GI. This research also contributes to the literature on leadership by demonstrating how leadership style influences GI. The findings highlighted the potential usefulness of RL in businesses, as well as its influence on the workforce.

TABLE 4 | Mediation results.

	M (knowledge sharing)					Y^1 (green innovation)		
	Path	**B**	**SE**	***p***	**Path**	**B**	**SE**	***p***
RL	a	0.30	0.06	0.000	ć[1]	0.24	0.06	0.000
Knowledge sharing	—	—	—	—	b[1]	0.49	0.06	0.000
Constant	i[1]	3.28	0.31	0.000	i[2]	0.83	0.35	0.01
		R^2 = 0.09				R^2 = 0.35		
Indirect effect (RL on GI *via* knowledge sharing)								
Indirect effects (bootstrap)							0.15* [0.08, 0.23]	
Indirect effect (Sobel Test)							0.15* (z = 4.10)	

Note: n = *228. Control variables: gender, age, education, department and total working experience.* *p < *0.05.*

TABLE 5 | Regression coefficients and conditional indirect effect estimates.

	M (knowledge sharing)				Y (green innovation)			
	B	**SE**	***p***		**B**	**SE**	***p***	
RL (X)	0.56	0.24	0.02		0.24	0.06	0.00	
LMX (W)	0.16	0.19	0.39		—	—	—	
X*W	0.12	0.05	0.01		—	—	—	
Knowledge sharing	—	—	—		0.49	0.06	0.00	
		R^2 = 0.23				R^2 = 0.35		
Moderator	Conditional effect of RL on KS				Conditional effect of RL on GI *via* KS			
LMX	B	SE	LLCI	ULCI	B	SE	LLCI	ULCI
LMX − 1 SD	0.12	0.09	−0.31	0.06	−0.06	0.06	−0.19	0.05
LMX M	0.01	0.07	0.13	0.16	0.01	0.05	−0.09	0.09
LMX + 1 SD	0.15	0.09	0.02	0.33	0.08	0.05	0.03	0.18

Note: n = 228. Control variables: gender, age, education, department and experience.

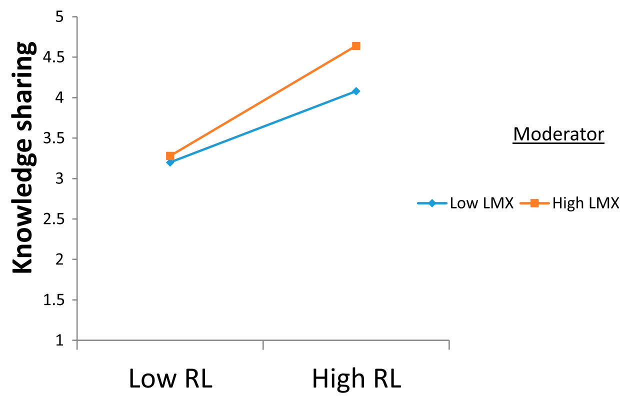

FIGURE 2 | Interaction plot.

Second, the finding that RL indirectly links to GI through knowledge sharing, which is based on the SLT (Bandura, 1977), deepens the understanding of the psychological phenomena between RL and the establishment of ethically driven links. The results support both the relational and ethical aspects of RL (Maak and Pless, 2006). Despite the fact that Scius-Bertrand. (2019), Voegtlin analyze how workers interact with the business and society, research has demonstrated that responsible conduct spreads to followers (Cheng et al., 2019). Furthermore, the social learning method explains why RL may support the formation of ethical relationships and the promotion of GI through knowledge sharing.

Third, these findings propose that LMX be incorporated into SL theory as a fundamental boundary condition for determining whether RL is a role model. By improving knowledge sharing for workers with high LMX, RL was more likely to create mutually courteous, helpful, and trusted relationships with followers (H3). However, the findings corroborate Hypothesis 3b, indicating that RL was more likely to increase knowledge sharing among employees with high LMX than low LMX. A potential explanation is that high LMX personnel have a high level of trust and emotional connection to their leaders, so they are more inclined to pay attention to them and wish to copy their trusted, well-liked leaders' behaviors (Lankau and Scandura, 2002). Employees with a high LMX, on the other hand, engage with their supervisors more than usual (Cogliser and Schriesheim, 2000), inspired by RL's knowledge sharing. Finally, whether the indirect effect was moderated by LMX was investigated.

5.2 Managerial Implications

This research has a number of practical consequences. First, the findings show that companies could improve their managers' levels of RL. Organizations must appreciate the selection and training of RL through external recruitment and internal training in elevating the expectations of RL among senior managers and shaping a work environment of responsibility inside the organization to realize the reform process through GI.

Second, organizations should spend more on GI. Organizations should aspire to increasing their understanding and knowledge of GI, as well as strengthen the new competencies that it necessitates. The findings of this study show that revolutionary GI has a greater impact on organizational environmental performance. Because businesses often have scarce resources, organizations should find a balance between evolutionary and revolutionary GI and search out the most appropriate innovation base for future development to enable optimal GI and increased supply from innovative outputs.

Third, organizations should boost knowledge sharing, while encouraging and executing GI, so that executives may fully discuss and implement their strategies related to GI.

5.3 Conclusion

Using SLT, this study examined the impact of RL on GI *via* knowledge sharing at various stages of LMX. This study discovered a positive significant correlation between RL and the GI link, providing important insights into the understudied information regarding the antecedents of GI. Furthermore, the link between RL and GI was mediated via information exchange. LMX also oversees the RL-knowledge sharing relationship. LMX also expedites the RL-GI relationship through information sharing. In conclusion, this study demonstrates the relevance of RL in maintaining a strong connection between leaders and followers, as well as in promoting ethical ideals in their members, which enhances GI.

5.4 Limitation and Future Direction

Like other studies, this work does not go without certain notable limitations, which, in turn, lay the foundation for future research. First, it is acknowledged that the measurements of RL, LMX, knowledge sharing and GI are subject to self-awareness, leniency and social desirability. All variables were measured *via* self-reports; however, future research should utilize additional measurement strategies to complement self-report data on GI. This study utilized a multiwave rule for data collection, where RL and LMX were reported by the focal person at T1, knowledge sharing was reported by the focal person at T2, after one month, and GI was reported by the focal person at T3, after one month. Future studies could use a dyad design (focal person and peer reported) for better results and authenticity (Akhtar et al., 2021). Second, the present study used the assumption of SLT to uncover the effect of RL on GI *via* knowledge sharing at the different levels of LMX. Therefore, future studies will use other theoretical frameworks, such as person-fit theory and role theory, to address the consequences of RL. Third, the current study investigated the consequences of the RL in-hospitality industry operating in Pakistan. According to Hofstede (1983), Pakistan is ranked high in power distance and uncertainty avoidance. A high power distance between leader and follower creates favorable situations for leaders because in such a culture leaders demand unquestioned obedience from employees and restrict them to reporting wrongdoing. Future research may conduct cross-country investigations and compare study outcomes based on cultural characteristics and other aspects to assess the external validity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The studies involving human participants were reviewed and approved by the School of Business, Liaoning University constitutes School Ethics Approval Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CH worked on idea generation, theorization, and discussion. MS worked on the original draft, particularly the introduction and literature review. MWA worked on data analysis. MA worked on the research method and data collection section

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Nexus Between Energy Poverty and Technological Innovations: A Pathway for Addressing Energy Sustainability

Kiran Batool[1], *Zhen-Yu Zhao*[1]*, *Faraz Atif*[2] and *Azer Dilanchiev*[3]

[1]Beijing Key Laboratory of New Energy and Low Carbon Development, School of Economics and Management, North China Electric Power University, Beijing, China, [2]Department of Business Administration, Federal Urdu University of Arts, Sciences and Technology, Karachi, Pakistan, [3]Department of Economics, Faculty of Business and Technologies, International Black Sea University, Tbilisi, Georgia

Pakistan has experienced energy poverty, as most of the people live in rural areas. Poor people are stereotyped as collecting the firewood and using the unclean energy sources to meet their residential energy needs. As a result, respondents in the provinces with the highest rates of energy poverty set a high priority on this research. Structured interviews were used to conduct the research in rural parts of Punjab and Sindh provinces. Due to the apparent country's large population and rapid industrialization, conventional energy sources cannot meet the country's present energy needs. Results revealed that energy poverty in rural areas had exposed the residents to security problems such as health dangers, fire accidents, time poverty, financial poverty, illiteracy, and other issues at various levels of severity. As a result, alternative energy sources must be explored. This research aims to determine the best renewable energy choice for Pakistan's rural areas. In terms of pricing, life duration, operation, and maintenance costs, the results show that solar energy is the best renewable energy source for Pakistan. The key barriers that continue to promote energy poverty have been identified. Finally, the study suggests policy recommendation for public and private sectors to overcome energy related barriers to alleviate energy poverty in rural areas by utilizing maximum solar energy.

Keywords: energy poverty, firewood, solar power, assessment, alleviation, Pakistan

Edited by:
Asif Razzaq,
Dalian University of Technology, China

Reviewed by:
Rakhshanda Kousar,
University of Agriculture, Faisalabad, Pakistan
Yacouba Kassouri,
Leipzig University, Germany

Correspondence:
Zhen-Yu Zhao
zhaozhenyuxm@263.net

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1 INTRODUCTION

Energy is crucial to advancing contemporary economic and social development and welfare (Owusu and Asumadu-Sarkodie, 2016). All human activities, including education, health care, and agriculture, require energy to work properly. Without appropriate energy usage, a nation cannot develop. It is regarded as the most crucial aspect of its economy (Naseem and Khan, 2015). Electricity is the backbone of a country's economic and social growth. However, 1.1 billion people worldwide do not have access to electricity (Warner and Jones, 2017). This energy-related poverty is termed "energy poverty" worldwide (Halkos and Gkampoura, 2021a). World Economic Forum (2010) defines the lack of access to sustainable and cheap renewable energy services as energy poverty (Sher et al., 2014). Energy poverty is defined as a person who does not have access to at least 35 kg of liquid LPG per year for cooking and 120 kW-hours of electricity per capita per year for illumination (Sher et al., 2014). Energy poverty affects the rural areas of the developing country's population. Even it also affects the developed countries such as Europe (Bollino and Botti, 2017). The majority of the people affected by this scenario live in rural zones of Sub-Saharan Africa(SSA) and South Asia (Das et al., 2016).

Worldwide energy consumption is predictable to be five times greater than current statistics due to growing technical industrial developments and larger electrical grids (Longe, 2021). The struggle against energy poverty is becoming crucially influential as the world's population grows by slightly more than one billion people over the coming 13 years, reaching 8.6 billion in 2030, 9.8 billion in 2050, and 11.2 billion by 2100 (United Nations), (Hassani et al., 2019). However, to meet rising energy demand, the energy industry could not increase the capacity of polluting power plants. Otherwise, the global average surface temperature would be rise by 2°C. (Geggel, 2017), resulting in dangerous climate change and the extinction of some flora and animals, among other things. To decrease global energy poverty, we must promote the usage of renewable energy sources to meet the world's ever-increasing energy demands. According to NASA's Goddard Institute for Space Studies (GISS), 2020 reports being 1.02°C degrees Celsius warmer than the 1951–1980 baseline (NASA) (Longe, 2021). As a result, global energy poverty should alleviate through renewable, affordable, and long-term energy sources. Women are frequently stigmatized as being responsible for providing and utilizing filthy energy in their homes. As a result, they collect and consume firewood, kerosene, coal, and animal dung regularly (Das et al., 2016; Bollino and Botti, 2017; Hassani et al., 2019; Longe, 2021; United Nations).Residential smog is caused by inefficient burning of dirty energy sources within homes, and it is estimated that it affects four million people each year (Longe, 2021).Modern cooking fuels enable mothers and children to live a healthy lifestyle (Mahmood and Shah, 2017).

Pakistan is still a developing nation, confronts with societal and ecological problems. A large percentage of Pakistan's population lives in rural regions, and mostly lack access to electricity. Furthermore, the country's growing population leading the higher energy demand. The country's current electricity demand is 25,000 MW, but the country's power supply is just 17,000 MW, resulting in an 8000 MW deficit (Raheem et al., 2016a). As a result, the electricity shortage in metropolitan areas is 12 h per day, while in rural regions, it is 18 h per day (Mirjat et al., 2017). The situation is riskier in Punjab's rural districts, where power outages sometimes last several days. Pakistan's electricity consumption is expected to rise to 40,000 MW (MW) by 2030 (Rehman et al., 2017). Not only do people's lives suffer as a result of energy poverty, but so makes the country's economic progress.

Long-term shutdowns have impacted all sectors, including agriculture, manufacturing, transportation, and residential (Wakeel et al., 2016). Pakistan's energy structure is totally dependent on thermal power. Solar energy is the cost-effective technology on the planet. By the end of 2017, the IEA estimated that the global solar power capacity had reached 402 GW (Irfan et al., 2019a). Solar power has effective potential to overcome energy poverty (Papadopoulou et al., 2019), such as Pakistan is located in the sunbelt and receives a lot of radiation all year. It is necessary to utilize existing solar energy resources to address current challenges and overcome energy poverty. Governmental and non-governmental organization investment is essential to achieve its full energy (Bakhtiar and Ahmed, 2017). As observed by Lucknow, solar energy has both institutional and technological barriers that need to be overcome (Luckow et al., 2015). The European Commission has been conducting solar energy research programs for more than 2 decades to reduce the global warming (PALZ et al., 1994). Solar power access has the technical potential to generate electricity (Farooq and Kumar, 2013).Solar energy is an essential natural resource for Pakistan (Shaikh et al., 2013).

No doubt, many researchers have assessed energy poverty but mostly in western countries. Current research tried to determine the energy poverty in Pakistan. This research aims to find out the underdeveloped areas of Pakistan where energy poverty is at an extreme level and suggest the policy recommendations that would contribute to national energy mitigation plans to alleviate the energy poverty. It will promote the slandered life at the community and national levels. It is a unique approach to access energy poverty by exploring the people who experience it the most in rural areas of Punjab and Sindh. Male and female respondents participated in the survey. The data reveal a strong relationship between energy poverty and the multifaceted poverty that individuals in rural areas face in terms of health, time, literacy, and the economy. The survey consequences provide the beneficial information for any entity (Governmental and Non-governmental organizations) to alleviate the energy poverty in rural areas of Pakistan. Just access to energy poverty in urban areas does not mean fulfilling energy sustainability at the national level. Both rural, urban, and suburban areas are part of the country. All of these areas need energy development. So, further researchers should also identify and access those areas where energy poverty is at an extreme level. Due to the COVID19 outbreak, selected rural areas from only two Pakistani provinces to design a solution model at both the provincial and national levels. And try to motivate the rural residents towards renewable energy (e.g., Solar Power) because solar energy is renewable energy and affordable energy. In addition, as far as the author is aware, no previous research has covered an in-depth analysis of energy poverty in these selected areas of Pakistan as contribute the novelty in this current research. The remaining part of this paper is structured as follows: **Section 1** consisted of a literature review including the energy poverty access at a national and global level. And this section also describes the potential of solar power to alleviate energy poverty at the national and international levels. The research methodology describes in **Section 2**, and **Section 3** consisted of result a discussion. Barriers to alleviating energy poverty in rural areas in **Section 4**. The recommendations from the research findings and the conclusion are presented in **Sections 5** of this paper, respectively. **Section 6** discusses the limitations and future research directions.

2 LITERATURE REVIEW ACCESS TO ENERGY POVERTY

Several research articles, books, and news reports give a detailed insight to access the energy poverty at the national and global levels. The findings from the literature are presented below:

TABLE 1 | Energy poverty in rural areas at the global level.

Country	Africa	Sub-saharan africa	Development asia	Latin America	% In rural areas
Lack of electricity	587million	585million	779 million	31million	1.227billion 85%
Relying on biomass	657million	653million	1.937million	85million	2.679 billion 82

TABLE 2 | Power installed capacity sources.

Fiscal year	Thermal	Hydroelectric	Nuclear	Renewable	Total generation
2014–15	58,635	32,563	4,996	803	96,997
2015–16	61,448	34,272	3,854	1,549	101,123
2016–17	66,468	31,786	5,868	2,937	107,059
2017–18	79,649	28,239	8,720	3,907	120,715
2018–19	61,003	24,931	2,903	7,941	96,792
2019–20	56,320	29,799	7,941	2,322	96,382
2020-21	61,052	31,357	8,038	2,294	102,742

2.1. Energy Poverty Access at Global

The United Nations' 7th Sustainable Development Goal, introduced in 2015, focuses on maintaining that everyone should have access to sustainable energy sources, such as poverty. Inefficient energy access is also a significant issue worldwide (Carlsen and Bruggemann, 2021). To maintain a healthy lifestyle, everyone needs access to power and clean cooking fuel. Eastern and southern European countries are classically identified as having the highest levels of energy poverty, while Scandinavian countries have the lowest levels. According to Thomson and Snell's research, Bulgaria have the highest levels of energy poverty in 2007 (Thomson and Snell, 2013). Energy poverty conditions worsened when the effects of the economic crisis were visible, particularly in Bulgaria, which experienced high levels of energy poverty from 2004 to 2019 (Halkos and Gkampoura, 2021b). Ethiopia, like many African countries, was experiencing severe energy poverty. On the other hand, Egypt and Morocco have low levels of energy poverty (Halkos and Gkampoura, 2021a).

In Latin America, energy poverty is particularly severe in Haiti, Guatemala, and Honduras. Although, Mexico have low ratio of energy poverty, but still they are facing higher problems with their population's access to energy facilities (Santillán et al., 2020). In Asian countries, energy poverty had badly effected Afghanistan and Bangladesh, India and Pakistan (Abbas et al., 2020). China has advanced economically compared to other Asian countries, resulting in a considerable reduction in energy poverty. However, energy-related problems persist in several country regions (for example, the Yellow River's middle reaches) (Wang et al., 2015). (International Energy Agency, 2010), and **Table 2** shows power installed capacity sources (Irfan et al., 2020).

Table 1 depicts the energy poverty in rural areas at the global level (International Energy Agency, 2010), and **Table 2** shows power installed capacity sources (Irfan et al., 2020).

Energy poverty indicates a socio-economic problem that is not the same as "poverty" in the traditional sense. Energy poverty at the residential level means a lack of access to energy resources such as appropriate electricity or technical devices for cooking, heating, and lighting in underdeveloped countries. Traditional home appliances, including wood and biofuels, have been used for cooking and heating (Maxim et al., 2016).In the late 1970s, the phrase "fuel poverty" was first used to describe households with disproportionately high fuel expenses than the rest of the population (Liddell et al., 2012).In 1990, the total final energy consumption was 6,267,177 kilotons, and in 2018, it was 9,937,703 ktoe. It considers the global population growth, which has increased from 5.28 billion in 1990 to 7.59 billion in 2018. It is evident that world energy consumption has grown per capita and that the world's energy use has reached extremely high levels. In 2015, fossil fuels accounted for 79.7% of total global energy use, whereas renewable energy sources accounted for 18.05%. Industry and the transportation sector consume the highest energy at the global level. In 2018, the residential sector consumed 2,109,205 ktoe, and it is the third-largest energy consumer sector. Globally, energy poverty has had a significant influence on the residential sector. In comparison, limited energy access cannot fulfill basic human needs (Halkos and Gkampoura, 2021a).

Fuel poverty is caused by a combination of variables, including low income, increased energy bills, and poor home conditions (Boardman, 1991). Energy poverty affects about 100 million individuals in Europe (Brunner et al., 2012), almost 1.2 billion people lack the access to power at global level (Maxim et al., 2016). Bouzarovski (Bouzarovski, 2014) mentions additional terms for the same purpose, such as "domestic energy deprivation" or "energy precariousness." Households in this category spend more than 10% of their income on energy (Isherwood and Hancock, 1979). Bouzarovski defines it as "a scenario in which a household lacks a socially and materially required level of energy services in the home" (Bouzarovski,

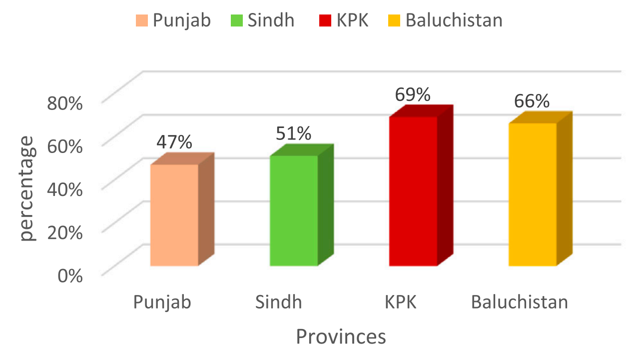

FIGURE 1 | Comparison of energy poverty at provincial level (Sher et al., 2014).

2014). The Millennium Development Goals (MDGs) could not be accomplished without first tackling energy problems. A reliable energy source such as solar power requires sustainable development and energy poverty alleviation (Adenle, 2020).Energy is a vibrant element of sustainability, such as more effective use of energy results in cost savings and a higher quality of life (Maxim et al., 2016). A growing population means a greater need for energy. Advanced energy availability, for example, creates a foundation for better labor force employment. It expands job opportunities and boosts pay, leading to a more excellent standard of living (Markandya et al., 2016). According to Boardman's research, the cold seasons have a higher death rate than the other seasons, partly attributable to low indoor temperature (Rudge, 2012). According to previous studies, people feel anxious when paying their unaffordable energy bills (Brunner et al., 2012). Despite the progress made in Asia, it is critical to promote policies to alleviate energy poverty and ensure that as many people as possible have access to essential energy services (Halkos and Gkampoura, 2021a).

2.2 Energy Poverty at the National Level

The global demand for energy has risen dramatically, and Pakistan has no exception. Pakistan is also facing the energy poverty, which is impeding the country's progress and harming the lives of its citizens. Pakistan's major sectors, such as agriculture, transportation and residential, all require a constant supply of energy. All of Pakistan's provinces are affected by energy poverty (Javed, 2016).

In 2017, another researcher described energy poverty in rural areas of Pakistan. There is a large rural-urban gap. In urban and rural Punjab, the share of energy-poor families (H) is 18.5% and 70.7%, respectively. Sindh's ratio is 14.4%–80.3%, KP's is 24.3–74.6%, and Baluchistan's is 31.3%–84.9%. In urban Punjab, the intensity of deprivation (A) is 36.6%, compared to 43.5% in rural Punjab. In urban Sindh, deprivation is 37.5%, and in rural Sindh, it is 48.6%. The equivalent A values for urban and rural KP are 36.2% and 47.6%, respectively, and 47.0% and 57.6% for urban and rural Baluchistan (see **Figure 1**). The author stated that most energy poverty is caused by the insufficiency of contemporary cooking fuels at the household level. Conventional fuels are used in 67% of Pakistani homes. In rural KP, the use of modern fuels is relatively low, with 91% relying on traditional fuels. In rural areas, particularly in rural KPK and Baluchistan, the MEPI's mobility factor is more important. The lack of a refrigerator in 64% of houses and a television or radio in 36% of households indicates decreased power usage for entertainment and services like cooking and heating (Mahmood and Shah, 2017).

Pakistan's existing energy system is based on fossil fuels. 86.5 percent of the country's energy demands are met by thermal energy (Irfan et al., 2019a), (Ahmed et al., 2016).The use of fossil fuels on a large scale has hindered economic progress. Still, it has also resulted in several ecological problems. Furthermore, natural resources are decreasing due to the excessive use of traditional energy. As a result, a new energy economy will need to be built. In this future economy, solar energy will lead to sustain energy requirements, and also reducing the price of imported fossil fuel (Sharma et al., 2012). Pakistan's energy consumption is growing at more than 9% per year. Pakistan's energy consumption will rise eight-fold by 2030 and twenty-fold by 2050 (Noureen, 2014).

As a result, the government is exploring alternate and sustainable energy sources to help address these issues. For electricity generation, Pakistan has tremendous contemporary energy potential. Wind energy has a potential of 346 GW (GW), whereas solar energy has a potential of 2900 GW, hydropower has a potential of 6 GW, and biomass has a potential of 5 GW (Solangi et al., 2019). Punjab's provincial government is successfully generating electricity through renewable energy. Despite the government's best efforts, the province's rural areas remain underserved due to four fundamental factors. First, rural areas account for 37% of Punjab's population, with 7432 villages still without electricity (Irfan et al., 2019b). These areas are far dispersed and disconnected from the national grid. Connecting these places to the national grid is both uneconomical and prohibitively costly. Second, in rural regions, electricity consumption is just 50 to 100 W per home, which is comparatively low than metropolitan areas (Bhutto et al., 2012). Because tiny dwellings usually only have one room, maximum two electric fans and a few lights are generally sufficient. It is very costly to supply on-grid transmission to these settlements (Arefin et al., 2018).

Due to the remoteness of the areas and the absence of infrastructure, renewable energy projects are not viable. Meanwhile, generating electricity with diesel generators is uneconomical due to the high cost of delivering oil to remote areas. As a result, grid-connected electricity is unlikely to be available in the future (Mirza et al., 2009). Finally, the country's economic situation is precarious, and it cannot afford to import expensive fossil fuels, particularly oil, to solve its energy concerns. As a result, the government has chosen to shut down some current renewable energy initiatives that have hampered the adoption of renewable energy technology. The Punjab province has been suffering the higher energy problems due to the government's decision since freshly begun projects are shut down entirely (Irfan et al., 2019b).

Pakistan is a developing country with significantly lower per capita energy consumption than comparable countries. It is essential to analyze the present situation and determine which

TABLE 3 | NEPRA approved a 25-years solar PPA in 2016.

Category	>1 ≤ 20 MW	>20 ≤ 50 MW	>50 ≤ 100 MW
Northern Pakistan - Levelized Tariff (US Cents/kWh	11.5327	11.4460	11.3560
Southern Pakistan- Levelized Tariff (US Cents/kWh)	10.8920	10.8101	10.7251

areas require immediate attention. According to Awan, Sher, and Abbas (2013), the country has been experiencing higher levels of energy poverty. According to Awan et al. (2013), energy poverty affects 54.6% of households. Rural areas have a greater rate of energy poverty than metropolitan ones (Mahmood and Shah, 2017). According to Mirza and Szirmai (2010), extreme level energy poverty affects 91.7% of rural households in Punjab (Mirza and Szirmai, 2010). Due to growing population, a significant quantity of energy is required to keep everything running smoothly (Fatai et al., 2004). However, there is an energy supply shortfall, and Pakistan is experiencing its most profound energy problems. The disparity between power demand and supply has widened in recent years, most noticeable during the summer (Irfan et al., 2019a). Complete power outages lasted 10–12 h in urban areas and 16–18 h in rural areas (Farooq and Shakoor, 2013; Ghafoor and Munir, 2015; Ghafoor et al., 2016).

2.3 Potential of Solar Power to Alleviate the Energy Poverty

Solar energy has potential and true alternative energy options among several renewable energy technologies. As an example, mostly rural communities use fuelwood for household purposes because the risk of deforestation produces environmental issues and a difficult trade-off. Pakistan has a total landmass of 79,610, 000 ha (ha), but just 1,686,000 ha of forest (Irfan et al., 2020).Pakistan is located in sunbelt, has the potential of solar energy. To promote the off-grid solar power to produce the electricity in rural areas (Bataineh et al., 2014; Haghighat Mamaghani et al., 2016; Irfan et al., 2019c). Due to its high solar irradiation (Wakeel et al., 2016), the province enjoys more than 300 sunny days per year and receives 2 MW h/m2. Asian Development Bank reported that off-grid solar power is cost-effective, quick installation, and improves the socio-economic condition (Irfan et al., 2019b). Various scholars have recommended off-grid solar power in rural areas (Ghafoor and Munir, 2015), (Haghighat Mamaghani et al., 2016). Moreover, several additional studies have demonstrated that an off-grid solar PV system is the most environmentally friendly and cost-effective energy option for rural people. As a result of developing the solar PV system, people's living conditions have improved (Sandwell et al., 2016), (Mishra and Behera, 2016) (Irfan et al., 2019b). The solar PV system is safe for human health, reduces carbon emissions, and produces no noise (Hosenuzzaman et al., 2015).The solar house has significantly enhanced internal settings and boosted thermal comfort for residents. Solar house can be an effective way to alleviate rural households' energy poverty (Liu et al., 2018). Strong political determination, appropriate policy frameworks, and a proactive ecosystem with businesses are all necessary for a successful transition to off-grid solar-based regimes for rural and remote inhabitants (Yadav et al., 2019). According to the Alternative Energy Development Board (AEDB), 35 projects with a total capacity of 1111.4 MW are in the works under the AEDB's policies and processes. Ten developers have been accepted for FITs (or upfront tariffs as they are known in Pakistan), and three of them have signed power purchase agreements with the public off-taker. **Table 3** below shows the FITs for a 25-years Solar PPA approved by NEPRA in 2016 (Tait and Alam, 2019).

3 RESEARCH METHODOLOGY

This study used hybrid research approaches to understand better the respondents' subjective viewpoints on the current topic. This study aimed to explore the perspectives on the subject to describe qualitative and quantitative results that could lead to practical policy recommendations for addressing energy poverty in Pakistan's rural areas. Structured interviews with predefined questions were developed for all respondents to accomplish this quickly, with an opportunity for each person to convey their ideas. Because the work focuses on energy poverty, the interviews were only from rural areas where energy poverty was extremely high. So, this research used purposive and snowball sampling techniques to collect subjective reality from the study. The research process is mentioned in **Figure 2**. The study area was chosen from the two provinces (Punjab and Sindh). In Punjab and Sindh, interviews were done in underdeveloped areas with the highest rate of energy poverty. However, in the Punjab province, more interviews were conducted. Interviews were done in Punjab's undeveloped districts, which included Bahawalpur, Multan, Dara Ghazi Khan, Faisalabad, Lahore, and Sargodha, as well as Sindh's Larkana, Sukkur, Nawab Shah, Hyderabad, Mir Pur Khas, and Karahi. Each division had two districts' data collection. In Punjab, data collecting duration was 6 weeks, while in Sindh it was 9 weeks. Accessing participants for the empirical investigation was problematic due to COVID-19. As a result, data collection takes up more time. The researcher could not use conventional survey technique of distributing questionnaires in this study due to the COVID-19 pandemic in the country and the limitations imposed by the government to stop the virus's spread (such as limiting human face-to-face contact). As a result, the questions were created in Google Forms and filled out based on the residents' responses. Two parts make up the form. Part A was designed for statistical measurement. The respondents were granted the right to respond in their own arguments with brief discussions in Part B, consisted of a qualitative analysis. As a

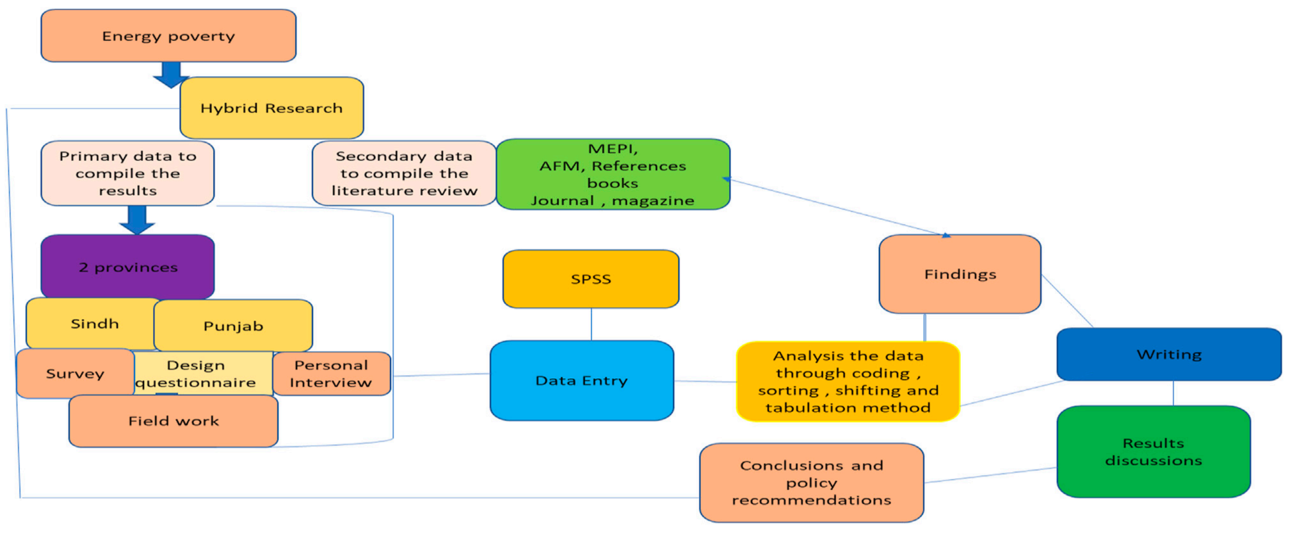

FIGURE 2 | Research process.

TABLE 4 | Demographics of the respondents.

Gender	Province	Age	Respondents	%
Male and Female	Punjab	0–17	112	11.2
		18–30	213	21.3
		31–50	249	24.9
		51and above	66	
	Sindh	0–17	94	9.4
		18–30	102	10.2
		31–50	115	11.5
		51and above	49	4.9
	Total		1000	100

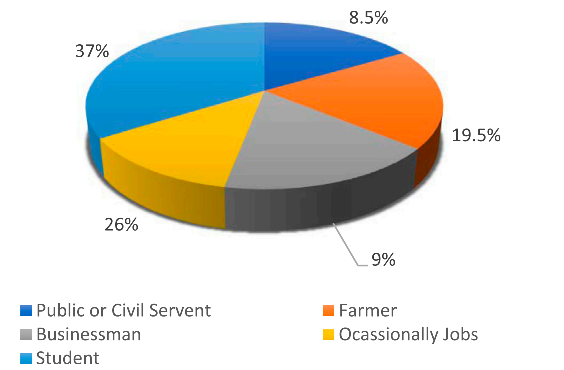

FIGURE 3 | Employment statics.

result, they were free to voice themselves, and the interviewers could record their responses (See **Supplementary Appendix**).

Depicts the demographics of all respondents (see **Table 4**). Structured interviews were conducted among 1000 respondents who used polluted energy sources for lighting, cooking, and heating in the divisions of Sindh and Punjab stated above.

Also shows the age groups of the respondents in the provinces that were considered. The survey's results can be verified because of the vast number of respondents who have been exposed to unclean energy.

4 RESULT AND DISCUSSIONS

This section contains the survey findings from the two provinces visited for this study for Parts A and B of the questionnaire (as shown in **Supplementary Appendix Table 10**).

4.1 Results From Survey questions—part A

Error! Reference source not found. shows that the residential respondents in these country areas were of different ages. The survey lasted 9 weeks, with 6 weeks spent in Punjab and 3 weeks in Sindh. The average household size ranged from five to six people. Including both provinces, only 20.5% of respondents were under 18 years old, while 79.5% were older than 18 years old. According to the current employment statistics shown in **Figures 3**, **9** % of respondents run their own business, 8.5% were civil workers, 37% were students, and 19.5% were agriculturalists. The remaining 26% work part-time and rely on landlords for their livelihood. The respondents were also totally dependent on agriculture cultivation, with only a minority relying on wages, pensions, and grants.

This study proves that energy poverty cannot be alleviated by low income. Respondent's income level was also a great determinant of their energy choice. Furthermore, as seen in **Table 5**, most households (29.5%) earned less than Rs 5000 per month. Only 11%, which comprises government officials and company owners, earned more than Rs 20,000. However, they cannot take advantage of sustainable energy due to a lack of awareness. The results indicate that people live in financial

TABLE 5 | Levels of monthly household income.

Monthly income	Respondent percentage (%)
0-5000	29.5
5001-10,000	31
10,001-15,000	16
15,001-20,000	12.5
Above 20,000	11

TABLE 6 | Energy use for lighting during load shedding.

Energy source for Lighting	Respondents	%
Batteries	420	42
Candles	678	67.8
Firewood	321	32.1
Solar Energy	47	4.7

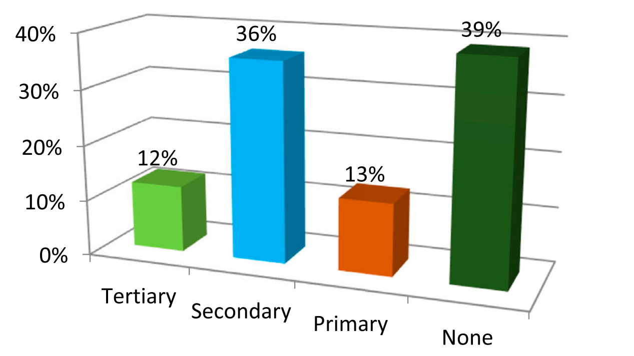

FIGURE 4 | Highest educational level obtained by respondents.

poverty, which depict their energy poverty and impact their choice of sustainable energy. According to current statistics, 60.5% earned less than Rs15,000, and just 23.5% earned more than Rs15,000. But it could not give the offer to enjoy clean energy. As previously mentioned (Clancy et al., 2003), (Wang and Jiang, 2017), their financial situation influenced their energy choice. When looking at household structure as an indicator of income, it is evident that non-poor households prefer to use clean energy (such as solar) for illumination. In contrast, poor households prefer to use solid fuel (Dash et al., 2018). The lowest quartile is the most affected by energy poverty compared to the richest quartile (Awan et al., 2022). Improvements in financial inclusion have the potential to alleviate energy poverty (Koomson and Danquah, 2021).

Figure 4 depicts the distribution level of high educational qualification achieved by respondents, indicating that around 61% of all ages are educated. This helped us during the survey because most of them understood the questions and responded correctly in English or their native languages (Urdu, Saraki, Punjabi, Sindhi, etc.). Furthermore, if given the opportunity, this would contribute to their acceptance, adaption, and usage of renewable energy.

Both provinces (Sindh and Punjab) are included. The majority of the undeveloped regions lacked adequate illumination. Respondents claimed they face load-shedding for 12–14 h each day, with some days being without power for up to 24 h. Previously published work by (Valasai et al., 2017) showed that Pakistan is suffering from chronic electricity shortages, which have resulted in forced power outages ranging from 8 to 12 h per day in urban areas and up to 18 h per day in rural regions over the last decade. Due to lack of energy, 94% of rural residents relied on one or two lights in their homes. This power does not satisfy them. Most respondents stated that they had a flawed energy system but paid extra bills. As a consequence of rising energy costs and lower monthly income, they choose to live without electricity. **Table 6** shows that only 4.7% of rural households have access to solar energy. Rural inhabitants should be encouraged to use solar lamps for lighting to improve their energy quality and prevent them from using energy sources. Previous work by (Irfan et al., 2019b)showed that off-grid solar power is the supportable solution for rural areas because of its net energy, low life-cycle cost, and ecological quality. It would also allow people to work, study, and spend time with their families and online job facilities. Furthermore, 96.3% were excited about moving from filthy energy sources to clean energy sources using adequate renewable energy with the aid of government and non-government organizations. So that they can purchase solar lamps during load shedding, it is a potential prospect for the government or an independent power company to provide solar access to these energy-poor areas. Because at the time of the survey, they did not have convenient access to clean energy. The majority of them were entirely unaware of the benefits of renewable energy, highlighting the need for increased renewable energy awareness in rural areas. In Pakistan, Firewood and candles are the most vulnerable, so the government should implement policies and facilitate people in purchasing the positively effective energy sources (solar lamps, solar cooking stoves, and solar heaters). As mentioned earlier in (Urmee et al., 2009) showed that renewable energy-based rural electrification initiatives need policies and strategies. In addition, number of studies indicate that an off-grid solar PV system is the most environmentally friendly and cost-effective energy option for rural electrification (Irfan et al., 2019b), (Akikur et al., 2013). The government should create a national energy research program. Prioritize R&D investment for home-based, energy-efficient solar energy devices. University students and research groups should conduct studies to develop current, cost-effective solar energy equipment for home and commercial users (Irfan et al., 2019a).

Table 6, **Table 7**, **Table 8** indicates that many respondents use more than one energy source to fulfill their energy demand, such as lighting, cooking, water heating, and space heating.

4.1.1 Lightning

Both provinces (Sindh and Punjab) are included. The majority of the undeveloped regions lacked adequate illumination. Respondents claimed they face load-shedding for 12 to 14 h

TABLE 7 | Energy sources for cooking.

Sources	Respondents	%
Animal Dung	167	16.7%
Coal	253	25.3%
Firewood	886	88.6%
Solar Energy	-	-
Gas/LPG	105	10.5%

TABLE 8 | Energy sources for space heating and water heating.

Energy sources	Respondents	%
Animal Dung	321	32%
Coal	355	35.5%
Firewood	766	76.6%
LPG	-	-
Electric and Solar Heater	-	-

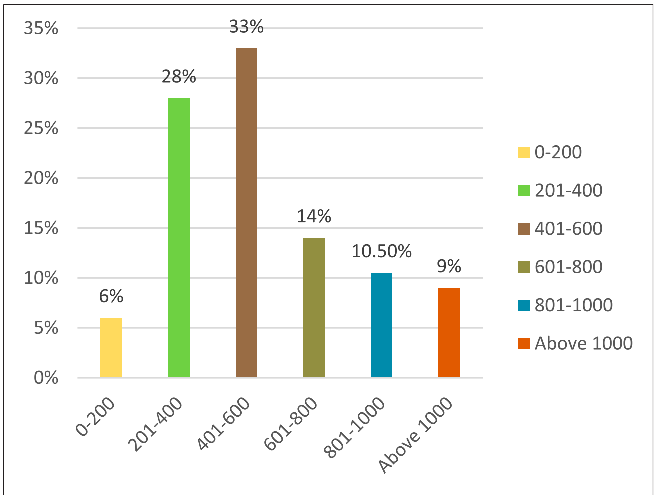

FIGURE 5 | Household monthly average energy expenditure.

each day, with some days being without power for up to 24 h. Previously published work by[69] showed that Pakistan is suffering from chronic electricity shortages, which have resulted in forced power outages ranging from 8 to 12 h per day in urban areas and up to 18 h per day in rural regions over the last decade. Due to lack of energy, 94% of rural residents relied on one or two lights in their homes. This power does not satisfy them. Most respondents stated that they had a flawed energy system but paid extra bills. As a consequence of rising energy costs and lower monthly income, they choose to live without electricity. **Table 6** shows that only 4.7% of rural households have access to solar energy. Rural inhabitants should be encouraged to use solar lamps for lighting to improve their energy quality and prevent them from using energy sources. Previous work by [46] showed that off-grid solar power is the supportable solution for rural areas because of its net energy, low life-cycle cost, and ecological quality. It would also allow people to work, study, and spend time with their families and online job facilities. Furthermore, 96.3 % were excited about moving from filthy energy sources to clean energy sources using adequate renewable energy with the aid of government and non-government organizations. So that they can purchase solar lamps during load shedding, it is a potential prospect for the government or an independent power company to provide solar access to these energy-poor areas. Because at the time of the survey, they did not have convenient access to clean energy. The majority of them were entirely unaware of the benefits of renewable energy, highlighting the need for increased renewable energy awareness in rural areas. In Pakistan, Firewood and candles are the most vulnerable, so the government should implement policies and facilitate people in purchasing the positively effective energy sources (solar lamps, solar cooking stoves, and solar heaters). As mentioned earlier in [70] showed that renewable energy-based rural electrification initiatives need policies and strategies. In addition, number of studies indicate that an off-grid solar PV system is the most environmentally friendly and cost-effective energy option for rural electrification[46], [71]. The government should create a national energy research program. Prioritize R&D investment for home-based, energy-efficient solar energy devices. University students and research groups should conduct studies to develop current, cost-effective solar energy equipment for home and commercial users[17].

4.1.2 Cooking

Firewood is the primary source of cooking energy. **Figure 5** depicts the average monthly energy cost for consumers. According to the findings, 33% of respondents claimed to spend more than Rs 600 per month on energy to buy wood. Only 9% of those surveyed said they spent more than Rs 1000 on firewood. As seen in many developing countries, people's reliance on firewood as a key energy source is producing serious deforestation concerns. Reliable data on firewood use rates are required to build afforestation initiatives and control deforestation, as previously also mentioned by (Fox, 1984)–(Bakehe and Hassan, 2022).

Table 7, just 10.5% of people in rural areas have access to LPG gas, while 88.5% depend on firewood and other forms of energy to cook. Many inhabitants did not cook the meal because they lived below the poverty line. Generally, these types of respondents work for landlords or as baggers. Most respondents do not have a chimney or a smoke hood in their kitchen and cook food in their backyard. They used it for the entire year and cooked twice a day using firewood. Most respondents said they spend more than 10% of their income purchasing firewood. 76% of respondents stated they want to improve the energy system. It is very polluted. 69% indicated this fuel source is entirely unsafe in stormy and windy seasons. Previously research work by (Longe, 2021) showed that 98% responded they would be willing to switch from dirty to clean energy sources if they had access to electricity. However, 95% of those respondents stated they would welcome the solar energy as a source of electric power. It is a positive sign for the government or a private organization interested in providing electricity to these communities. However, some respondents

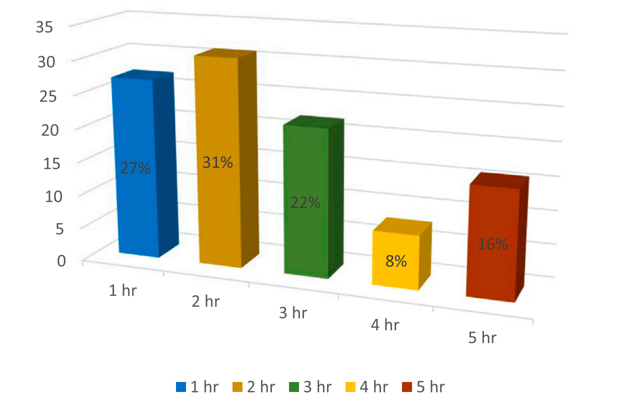

FIGURE 6 | Time spent fetching firewood per day by the respondents.

desired only wood since they claimed they did not have enough money to enjoy a lavish lifestyle. The government should install LPG meters and solar panels in rural communities. In order to properly implement the new solar home system policy, the Pakistani government must build solar power plants, increase solar panel installation, and provide financing and complete information to conduct independent research. In addition, approximately 90% of respondents believe that the government should take the lead in developing the SHS sector, as previously also mentioned by (Zhou et al., 2017). **Figure 6** illustrates that most individuals (31%) spend 2 h per day going to the forest to collect firewood for domestic energy usage. This time could have been better spent on other productive activities to boost their income and improve their living conditions. Previous work by (Agea et al., 2010)showed that Firewood collectors traveled 8–12 km and spent 4–6 h collecting firewood each day.

The accessibility of high-quality firewood in the bushes and forests has decreased due to deforestation. These magnificent forests are in danger of extinction because they are not consciously replanted after being destroyed. Obtaining and using firewood will be more challenging if there is no access to renewable energy sources. The rate of deforestation will be high. In many developing countries, people's reliance on firewood as a key energy source is producing serious deforestation concerns. Reliable data on firewood use rates are required to build afforestation initiatives and control deforestation, as previously also mentioned by (Fox, 1984; Bhatt and Sachan, 2004; Adeoye and Ayeni, 2011; Bakehe and Hassan, 2022).

4.1.3 Space Heating

During the winter, 94% of respondents reported they did not have enough heat in their homes and were exposed to harsh cold for 3–4 months. They cannot keep their rooms warm due to a lack of energy resources. Due to a shortage of electric and solar heaters, they heated their home with an open fire. As previously also mentioned by (Jaber, 2002; Jaber et al., 2008; Papathanasopoulou, 2010), fossil fuel combustion is widely used in household space and water heating, contributing significantly to environmental pollution and carbon dioxide emissions. **Table 8** shows the energy sources used to keep respondents warm during the winter months. Even in this technological era, people still use animal dung and coal for space heating and to heat water for showering. For example, 32% reported using animal dung to heat their residences and water. Firewood was utilized for the same purpose by 76.6% of such respondents. Mostly said that they suffered injuries due to an open fire system. Earlier work in (Reyes et al., 2015) showed that energy poverty significantly influences people's health and living conditions. Increased indoor CO2 emissions in the morning and evening hours pose major health risks to households due to intensive firewood use. Therefore, significant public awareness and pollution control actions should be proposed to improve the rural population's indoor air quality and health (Tika Ram and Hom Bahadur, 2020).

4.1.4 Cooling

Summer lasts for about 5–6 months. From April to September, the temperature is unbearably humid (Archer and Fowler, 2008). As a result, they take showers three to four times a day to cool off their bodies. Due to poverty and flirty energy, they cannot enjoy a contemporary and hearty lifestyle. However, they are confronted with various issues. In hot weather, 80% of people feel aggressive. Summer has the highest rate of aggressive crime, whereas winter has the lowest rate, as previously mentioned by (Butke and Sheridan, 2010). Only 20% of respondents said they felt normal. Due to their large family and limited appliances, they cannot obtain sufficient cooling air. 99.5% of rural households lacked an exhaust system in their kitchen, resulting in indoor pollution. Earlier work by (Jerneck and Olsson, 2013)showed that cooking using solid fuels over an open fire causes incomplete combustion and indoor air pollution, which causes respiratory and other illnesses, as well as around two million premature deaths each year. Smoke-free kitchens should be established to promote health and well-being while reducing carbon emissions. Green technology innovation improves the economy and reduces the CO2 emissions (Razzaq et al., 2021). Furthermore, 61.5% of respondents stated that they do not own any electric cooling appliances. Such as **Figure 7**, 47.5 % said they get cooled water by using clay pots, as they lacked the money to purchase a refrigerator. 14% of respondents said they buy ice from a shop and keep their water cold in a cool box. Just 10% have an electric refrigerator for storing food and cold water, but none have used a solar refrigerator. 68% clearly stated that their home is not cool enough during summer, such as previous research mentioned by (Zahid and Rasul, 2010) showed that the weather in Punjab and Sindh remain scorching during summer.56% do not utilize electric equipment to cool their homes; as **Figure 8** Shows, 31% used electric fans to cool their rooms. Only 13% of rural areas used air conditioners.21% have used homemade fanes.23% of people open their doors and windows to get some fresh air.

4.1.5 Education and Communication

According to data from both provinces, 48% are illiterate, with only 52% of their children pursuing higher education. But they are facing various challenges, including the fact that most youngsters stated they did not have the internet to communicate with their teachers during COVID 19. **Table 9** shows that 8.9% of respondents have Android phones and 28.7%

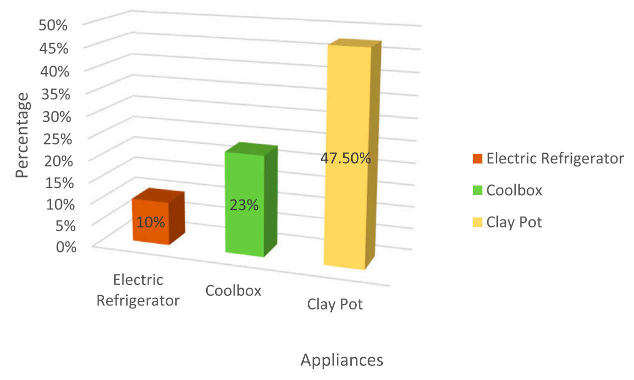

FIGURE 7 | Electric and non-electric appliances.

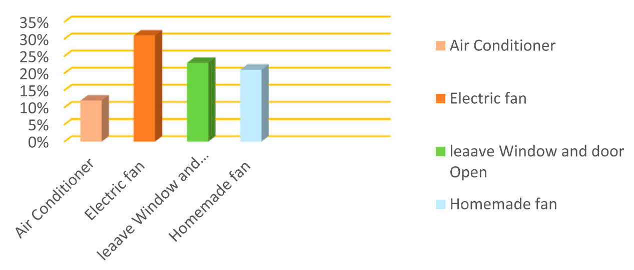

FIGURE 8 | Sources to cool the residence.

have smartphones. Due to long-term vocations, parents claim that their children are uninterested in going to school. They could not afford an Android or the internet at home, and they did not even have an alternative system to maintain their children's education. Mostly, parents were depressed and opposed to extended vacations. Most parents expressed their unwillingness to send their children back to school. Radio is being used by 31.1% for news and entertainment. Only 17.2% of people have a television in their house. However, they only use it for 1–2 h due to the energy crisis. Earlier work by (- Pandemic, Mamica, G ł owacki, Makie ł a) showed that energy poverty influences student academic performance during COVID-19 outbreaks. Students from electrified homes are more competitive and academically successful than students from non-electrified homes. The responders in both provinces sadly demanded that the government should promote energy production in rural areas. Due to increasing load-shedding at night, their children seem unable to devote more time to study, with 37.8% of students devoting 4 hours to study, as shown in.

Figure 9 Many organizations in these areas have promised access to clean energy. Unfortunately, they are still unable to complete their projects. However, many respondents supported renewable energy, but still not being implemented due to low monthly income and higher household expenses.

TABLE 9 | Sources of information and communication.

Sources	Respondents	Percentage%
TV	172	17.2
Smart Phone	287	28.7
Android Mobile	89	8.9
Radio	311	31.1
None	141	14.1%

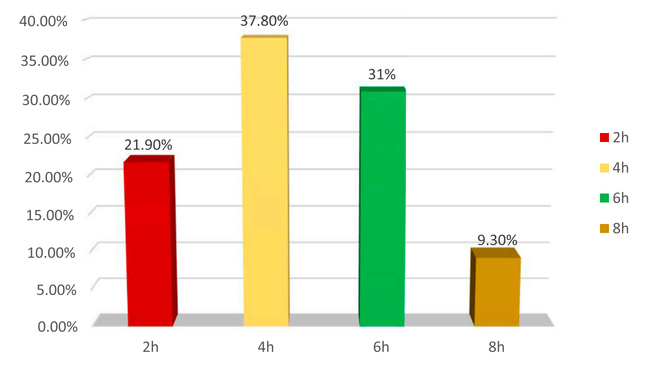

FIGURE 9 | Student study time duration.

4.2 Results From Survey questions—part B

This section's central purpose is to analyze energy poverty-related issues in-depth. However, due to space and length constraints in this article, only ten respondents per question are chosen, and related conversations are described in this section.

4.2.1 Responses

i. It is difficult for girls to cut firewood when they are experiencing menstrual cramps.
ii. My children don't take bathe before going to school because of the cold water. This is a horrible thing, especially for women who might be experiencing their monthly cycles on those days.
iii. Since my family and I do not work, cooking with firewood is too expensive.
iv. We don't have any other energy source for cooking or heating, so that I couldn't refute the firewood.
v. *Occasionally, I get annoyed by firewood.*
vi. It was initially uncomfortable. But now that I'm used to it, I feel firewood is faster than animal dung.
vii. It irritates me because it requires the maximum amount of time. My children collect wood from the forest due to a low monthly income, and they can't devote time to their studies.
viii. As it's our tradition, I always prefer to cook with firewood.
ix. It's a problem because teenagers prefer to buy firewood for their homes rather than travel to the forest, which we can't always afford. They suffer from an inferiority complex.
x. I always prefer alternative energy sources instead of firewood.

Despite the fact that most respondents are dissatisfied with their use of firewood, they continue to do so because they cannot afford to purchase alternative energy sources. It is difficult for girls to cut firewood when experiencing menstrual cramps. They could not refute the firewood due to the lack of contemporary energy sources like Solar Heater or LPG. Occasionally, they get annoyed by firewood. It irritates them because it requires the maximum amount of time for cooking, as previously mentioned in (Bhatt and Sachan, 2004); (Katuwal and Bohara, 2009). Due to financial constraints, some households cannot even afford firewood. Students are particularly affected by this traditional energy source, wasting their time fetching firewood. It's a big problem for young people because they prefer to buy firewood for their homes rather than travel to the forest. Most parents can't always afford it. Their children suffer from inferiority complexes. Minor responses were satisfied with firewood and claimed that using firewood is traditional. So, they never leave it.

4.2.2 Responses

i. Fetching firewood from the forest is extremely dangerous. My children had faced kidnapping.
ii. My relative was bitten by a snake and died while fetching firewood.
iii. It is perilous for one's life. I get hurt in the bushes sometimes.
iv. Many snakes have tried to bite me. I'm afraid to go into the forests to collect firewood.
v. Going into the forest alone is risky, as rape cases have been reported in our area.
vi. In the bushes, it's risky. Some trees are hazardous due to their prickles, while others are harmful due to unknown fluids that leak out and hurt the eyes.
vii. Honey bees attacked me three times as I was cutting firewood. These last few days were horrible because I had to face too much pain.
viii. It is challenging to cut forests, especially in the summer. We mostly face the wild animals in the bushes.
ix. *I get burns on my skin when I cook with fire. In the forest, I also had several encounters with wild animals. This conventional energy does not accord with me.*
x. We always encounter the deadliest animals in the bush, such as snakes and dogs. Some rapists also attack our little girl on the way to and from the jungle.

According to these responses, every responder faces various threats associated with gathering and consuming the firewood, such as health issues (lungs problem, cough, skin allergy etc.) and criminality (rape, kidnapping, etc.). It is extremely dangerous for one's life. Due to using firewood, they have skin problems, such as rashes on their faces. They are injured in the bushes due to unknown fluids leaking out and injuring their eyes. Deaths have occurred as a result of snake bites and due to some other wild animals. Women are worried about going into the forest to collect firewood. Because going into the forest alone is dangerous, as there have been many reports of attempted rapes of young girls. Therefore, replacing conventional energy with contemporary energy will contribute to improving lifestyles. Safe and clean energy contribution will also decrease crime rates like kidnapping, raping, murder, etc. This has also been supported by work in (Longe, 2021; Chowdhury et al., 2008; Ochola et al., 2018; Adei et al., 2019; Nduwayezu et al., 2021).

4.2.3 Responses

i. It affects their academic performance because sometimes they are getting late to school due spending the more time in wooded areas where they collect firewood.
ii. Due to load shedding at night, reading near a firewood fire is incredibly unsafe for youngsters. When they tried to study in the light of a fire, they occasionally burned pages of books.
iii. My children have less time to do their homework.
iv. When most of the children are studying, my children collect firewood in the bushes. It makes me quite unhappy.
v. On rainy days, cooking with moist firewood takes too much time. My children eat late. This condition creates the aggressive behavior among child.
vi. My children spend 4 hours a day fetching firewood because the forest is too far away from our house.
vii. It's a time-consuming process. I get up at 4 a.m. to prepare breakfast for my school-going children. When my children are 5 minutes late for school, the teacher often punishes them.
viii. Cooking with firewood is more efficient than cooking with gas. We prefer to buy firewood from a woodchopper because getting it from the jungle takes too much time.
ix. Firewood cooks faster, but fetching it from the jungle requires too much energy. It is not suitable for girls during their menstrual cycles.
x. My children enjoy playing in the bushes and arrive late at home. They do not fully concentrate on their schoolwork. According to their teacher, my children's academic performance is very poor.

According to the respondents, obtaining and using firewood has a negative impact on children's academic performance. Students are frequently late to class because they enjoy playing in the bushes. It is clear that firewood consumption negatively impacts the students' productive time. Instead, they may put this valuable time to good use by improving their educational activities. Unfortunately, academic achievement has been poor. Furthermore, during COVID-19, load shedding limits their potential to communicate with their teachers online as mentioned earlier in (Longe, 2021), (- Pandemic, Mamica, G ł owacki, Makie ł a), (Kiri et al., 2022). The literacy gap will worsen if this energy poverty continues. As a result, there is an urgent need to address energy poverty in Pakistan's rural areas. Some of the first responders are unaware of the risks associated with using firewood. The government should focus on public knowledge of the dangers of using firewood in these energy poor areas. The best solution is to encourage renewable energy consumption rather than conventional energy as previously mentioned in (Farooq and Shakoor, 2013; Omer, 2008; Akintande et al., 2020; Shahbaz et al., 2020).

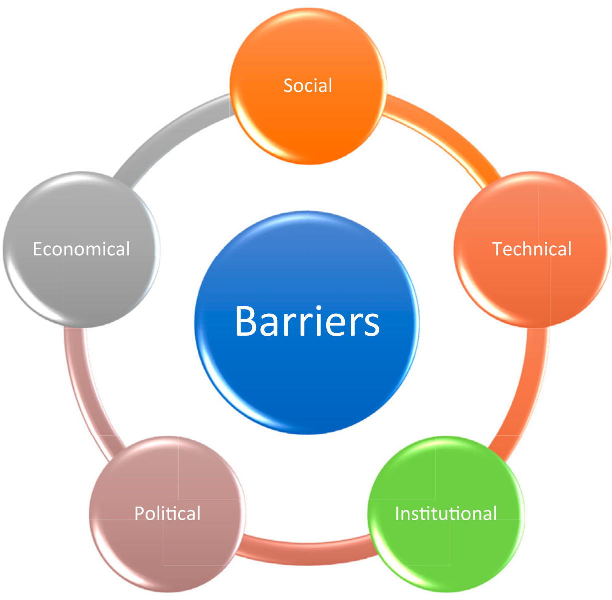

FIGURE 10 | Barriers lead to energy poverty.

5 BARRIERS TO ALLEVIATE THE ENERGY POVERTY IN RURAL AREAS

Although the Pakistani government has recently launched many projects to accelerate the deployment of solar energy to tackle energy poverty, the sector still confronts many barriers. As seen in **Figure 10**, some of these roadblocks are social, political, technological, and economical.

5.1 Economic Barriers

Contemporary energy sustainability is being hampered by a lack of capital and import tariff subsidies to boost local manufacturing (Abdullahi et al., 2017). Financial restraints and loan arrangements for solar energy projects, particularly at the local level, impede the smooth growth of the solar market and, on the other hand, the structure of consumer service infrastructure. The initial costs of launching a new solar energy plant are too high. Due to a lack of government subsidies, banks are reluctant to lend money to large-scale projects (Irfan et al., 2019a; Mirza et al., 2009). Low income, high-energy prices, and inefficient energy use are the primary causes of energy poverty. Like under-developed countries, developed countries also face energy poverty dilemmas due to financial constraints (Maxim et al., 2016). Low-income and inefficient energy housing stocks have resulted in high rates of energy poverty (Healy and Clinch, 2004). Due to high energy prices, energy poverty is defined as a lack of energy affordability (Brunner et al., 2013). These barriers make it very difficult to adopt and maintain sustainable energy to alleviate energy poverty in rural areas. Economic policy uncertainty has a big and negative impact on climate change (Zahra and Badeeb, 2022). Policymakers should achieve the optimal level of decentralization in order to encourage energy innovation. Inadequate fiscal decentralisation hampers public support for sustainable energy technology. The negative effects of fiscal decentralisation are minimised in nations with higher public energy RD&D expenditures (Kassouri, 2022). Improving environmental quality and fiscal management are the most critical policies for sustainability development (Sun and Razzaq, 2022). Fiscal decentralisation boosts environmental sustainability by increasing green investment and the transition to renewable energy (Sun et al., 2022a). Renewable energy development is a very important component of green economic growth (Zhao et al., 2022; Sun et al., 2022b). Inefficient resource policies can exacerbate energy poverty (Li et al., 2021). The disparity between revenue and expenditure decentralisation causes a vertical fiscal imbalance, dramatically affecting energy and environmental performance. To reduce energy and environmental efficiency losses, boost the fiscal reform and eliminating vertical fiscal imbalances (Lin and Zhou, 2021).

5.2 Technological Barriers

A lack of training facilities and a weak framework for entrepreneurship growth are technical barriers that promote energy poverty (Luthra et al., 2015). First, there is no national processing plant for solar cells, reliance on western technology for crucial parts and equipment. Dependency on western workers to build and run huge solar energy plants illustrates unreliable local technology. Second, inadequate R and D activities; in Pakistan, there is no known national institution for the R and D of the solar sector. Unauthentic solar maps are used to assess the strength of Sun radiation (Naqvi et al., 2018); (Irfan et al., 2019a). Lack of high-quality equipment, difficulty in providing maintenance, and logistical issues such as shipping and installation are significant barriers (Sovacool, 2012). All of these barriers impede the alleviation of energy poverty (Pasqualetti, 2011). One of the most effective approaches to achieve the transition to a worldwide clean energy system is through energy technology innovation. The impact of government energy technology research, development, and demonstration (RD&D) budgets on cleaner energy supply and carbon footprints, which is the fundamental input of energy technology advancements (CFP). The contribution of renewable energy to total primary energy supply is used to determine a greener energy supply (RE) (Altıntaş and Kassouri, 2020). The use of renewable energy reduces carbon emissions significantly (Sun et al., 2022c).

5.3 Social Barriers

Lack of consumer understanding of modern energy, particularly solar energy potential, and public rejection of new technology are key barriers (Akinwale et al., 2014). Solar energy is underutilized, especially in rural areas. There is a lack of consumer education, awareness, and demonstration at the domestic level. Local communities have shown strong opposition to some solar energy projects. Residents have no idea how to fix problems on their own if they arise unexpectedly. People continue to rely on traditional forms of electricity, which creates a significant barrier for new solar energy projects. Solar power project development is hampered by a scarcity of experts and human resources. Residents are unaware of the benefits of solar energy. There are no community demonstration projects, and developers of

solar energy projects are under-trained (Javed, 2016), (Irfan et al., 2019b). The barrier also negatively impacts market projection, cultural and religious faith disputes, and economic progress and sustainability (Abdullahi et al., 2017).

5.4 Political Barriers

Long-term planning and the political willpower to develop renewable energy are absent (Luthra et al., 2015). Energy poverty is also caused by a lack of government subsidies and incentives (Iqbal, 2018). The government's policies are unclear. There is no feed-in tariff scheme in place. Traditional energy sources are prioritized, while renewable energy is not subject to any structural regulations. Fossil fuels receive more subsidies than solar energy and other renewable energy sources (Irfan et al., 2019a), (Raheem et al., 2016b). Another problem occurs as a result of the provincial government's approval need for energy costs. On the other hand, provincial governors are unwilling to take political risks by adopting a higher energy tariff. Despite technological advances that make renewables more economically viable, this political challenge prevents governments from adopting renewable energy sources. As a result, on-grid electricity generation attracts most private sector investment rather than off-grid energy generation (Setyowati, 2020). These barriers impede strategic work for renewable energy such as solar energy development and sustainability. The government should attempt to shift from fossil fuels to renewable energies to reduce CO_2 emissions, installing solar panels on verandas for low-income residents. The most major motive for installing solar PVs in their homes is determined to be lower electricity bills. Government energy policies and financial incentives influence low-income households' adoption of residential solar PVs (Lee and Shepley, 2020).

5.5 Institutional Barriers

The illegal framework, administrative challenges, non-integration of the energy mix, non-participation of the private sector, inadequate R&D culture, and the non-interference of stakeholders are vital barriers that lead to energy poverty (Aliyu et al., 2015), (Fagbenle et al., 2011). Decentralization strategies also hamper rural renewable energy. Changes in ministerial leadership frequently drive changes in government policy and priorities. Far from mobilizing private climate finance, changes in regulatory frameworks have proved counterproductive to that goal. The private sector's investment in renewable energy has been hampered by regulatory uncertainty. This is evident in the decreased amount of investment in renewable energy throughout the years (Setyowati, 2020). The barriers result in uncertainty about solar energy assistance, a lack of communication mechanisms to reach institutional authorities for reform, and a negative perception of the technology (Abdullahi et al., 2017). In the current setting of the fourth industrial revolution, energy research and development (R&D) and environmental sustainability are usually referred to as two interrelated developments. R&D in the energy sector is critical in tackling global environmental and energy concerns because it is a main input of energy innovations. From the 50th to the 90th quantiles, energy efficiency research and development reduces CO_2 emissions significantly, with the magnitude of the negative sign becoming more obvious at the highest quantile (90th). Policymakers are developing long-term energy research and development programmed that balance the environment while encouraging energy innovation (Bilgili et al., 2021).

6 CONCLUSIONS AND POLICY RECOMMENDATIONS

This research aims to explore energy poverty in Pakistan's rural areas, using data from two of the country's most populous provinces as a sample. Still, rural people facing the electricity problems. Due to to12-14h load-shedding, the respondents relied on candles for light and firewood and animal dung for cooking and space heating. The study also revealed that energy poverty is associated with insecurity, financial poverty, illiteracy, time poverty, physical hazards, and societal and political barriers. Due to a lack of affordability and clean energy, rural students have been unable to communicate with their teachers. As a result, energy is a must for online classes due to COVID-19. Solar energy is an affordable and clean energy source. Most rural areas agreed to install it in their home. However, they really cannot manage it due to their low salary. Hence, this paper proposes new policy changes to enhance access to inexpensive and sustainable energy in Pakistani rural families. Government should promote the off-grid microgrids to develop the highly centralized energy generation. And increased socio-economic awareness of the merits of renewable energy and the detriments of traditional energy, affordable energy tariffs, and income-based energy incentives have all been proposed as additional solutions to alleviate energy poverty in Pakistan's rural areas. The findings presented in this study explore an innovative method of alleviating energy poverty in Pakistan's rural areas. Energy poverty can be alleviated by implementing the right plan to access modern energy. Since 1997, policies have been developed but not fully implemented, and the issue of energy poverty has been debated. On a geographical level, Pakistan remains in the sunbelt. As a result, solar power is the most suitable energy source for dealing with it. Because without energy, existence is nothing more than taking a breath, and rural areas are still locked in the 14th century. Surprisingly, researchers have found that some rural people do not want electricity due to income poverty. As a result, both government and non-government organizations should concentrate their efforts in these areas, attempting to overcome energy poverty.

These results highlight the important energy development policies to reduce hazardous risk of energy poverty and also provide opportunity for rural people to improve their living conditions. It is crucial to provide sustainable solutions to the country's energy poverty. The recommendations in this section are based on the research findings. The following policy recommendations are highlighted to alleviate energy poverty as soon as possible by leveraging the best available technology. Off-grid solar power rural electrification

FIGURE 11 | Policy recommendations.

programs should be implemented in the Punjab and Sindh provinces to alleviate the energy poverty. Pakistan has a large amount of solar energy potential for electricity production. As a result, the relevant authorities should take the initiative and design well-organized policies to launch off-grid solar PV rural initiatives in Pakistan's underdeveloped regions to alleviate energy poverty. Solar power should be installed in underserved areas through public and commercial incentives. As a result, it is recommended that the government announce supportive policies to reduce energy poverty by maximizing solar energy use. **Figure 11** depicts the policy recommendation.

There are certain limitations to the study. Due to COVID-19, only two provinces of Pakistan were selected for the study. As a result, the research findings are inappropriate for Pakistan's other three provinces. Hopefully, future scholars can visit the remaining provinces to assess energy poverty more comfortably. Furthermore, researchers can propose a hybrid renewable energy system in the above-mentioned rural areas, such as solar power implementation. Above all, the government's participation is critical in assisting rural areas with hybrid systems and overcoming Pakistan's energy poverty. The current study averaged the data from two provinces. As a result, it could be considered a crucial future research direction.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by This research study was conducted according to the Declaration of Helsinki guidelines, and the Institutional Review Board of North China Electric Power University, China (protocol code 737–4 on 21 November

2021) has proved the study. . The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KB: writing—original draft, formal analysis, data handling, variable construction, and methodology. Z-YZ: supervision, funding acquisition FA: conceptualization, software, writing review and editing. AD: Writing review and editing. All authors have read and agreed to the published version of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.888080/full#supplementary-material

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Variations in the Yamuna River Water Quality During the COVID-19 Lockdowns

Bhupendra Pratap Singh[1]*, Pallvi Rana[2], Nishtha Mittal[3], Sumit Kumar[4], Mohammad Athar[5,6], Zainularifeen Abduljaleel[5,6] and Shakilur Rahman[7]

[1]Department of Environmental Studies, Deshbandhu College, University of Delhi, New Delhi, India, [2]Department of Business School, University of Sydney, Sydney, NSW, Australia, [3]Department of Commerce, Panjab University, Chandigarh, India, [4]School of Social Science, Jawaharlal Nehru University, New Delhi, India, [5]Science and Technology Unit, Umm Al-Qura University, Makkah, Saudi Arabia, [6]Department of Medical Genetics, Faculty of Medicine, Umm Al-Qura University, Makkah, Saudi Arabia, [7]Department of Medical Elementology and Toxicology, School of Chemical and Life Sciences, Jamia Hamdard, New Delhi, India

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Muhammad Kamran Khan, Bahria University, Pakistan

***Correspondence:**
Bhupendra Pratap Singh
bpsingh0783@gmail.com

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The COVID-19 pandemic that emerged in Wuhan city of China in December 2019 has adversely impacted the health and the economy, society, and other significant spheres of the human environment. The pandemic has severely impacted economic activities, especially the industrial production, transportation, tourism, and hoteling industries. The present study analyses the impact of varying severity of lockdowns of economic activities during various phases of the pandemic on the water quality of the Yamuna river on parameters like pH values, biological oxygen demand, chemical oxygen demand, dissolved oxygen, total suspended solids, and electrical conductivity. The study has found a significant improvement in water quality parameters with closing economic activities during lockdowns. The average levels of concentration of these parameters of water quality were quite low during the lockdown period at 7.26 (pH value), 31.32, 136.07, 7.93, 30.33 mg/L, and 1500.24 μS/cm compared to pre lockdown periods levels at 7.53 (pH), 39.62, 116.52, 6.1, 57.2 mg/L and 1743.01 μS/cm for biological oxygen demand, chemical oxygen demand, dissolved oxygen, total suspended solids, and electrical conductivity, respectively. In addition, the study has found a strong significant positive correlation between COD with BOD and TSS during the lockdown period. The major findings from the present study could be instrumental in making environmentally sustainable policies for the country's economic development. There is also a huge scope of scaling up of the study at the national level to analyze the health of the rivers in the backdrop of lockdowns.

Keywords: COVID-19 lockdowns, water quality parameters, lockdown, yamuna river, correlation

INTRODUCTION

COVID-19 pandemic started with the detection of a novel coronavirus in Wuhan City in late December 2019 China. The pandemic has been found to have impacted every aspect of human life, health, social and economic (Arora et al., 2020; Conforti et al., 2020; Sohrabi et al., 2020; Travaglio et al., 2020; Wu et al., 2020). The World Health Organization (WHO) declared the outbreak a Public Health Emergency of International Concern on January 302020, named the novel Coronavirus disease COVID-19 on February 11, 2020, and finally declared it a pandemic on March 11, 2020

(Rothan and Byrareddy, 2020; WHO, 2020; Singh et al., 2021a). As of January 10, 2022, the confirmed cases of the COVID-19 pandemic have surpassed 308 million, with over 5.5 million deaths and about 260 million instances of recovery, leaving around 42 million active cases globally (Worldo meters, 2021). The evolving nature of the COVID-19 pandemic due to the continuous emergence of new variants of varying severity and infectivity has multifariously complicated the economic impact estimation (Bachman, 2020; Sarkis et al., 2020).

Countries across the globe have implemented nationwide lockdowns with restrictive measures, coercing people to work from home (whenever possible) and observing social distancing to avoid the unhindered escalation of the pandemic (Singh et al., 2021b). However, it must be noted that in several studies, the lockdowns which negatively impacted the economy have led to sudden revival and restoration of the physical environment and its various components like air and water (Beine et al., 2020; Huang et al., 2020; Ma et al., 2020; Bera et al., 2020; Ray et al., 2020; Sharma et al., 2020; Yongjian et al., 2020; Singh et al., 2021a; Singh and Kumar, 2021; Singh et al., 2022). In addition, several studies have attempted to estimate the economic effects of the pandemic across countries, such as Wiener Zeitung, 2020 (5–11%) for Australia, Ministry of Finance of Finland, 2020 (4%) for Finland, Rapport Cazeneuve, 2020 (2.4%) for France, (Ministry of Transport and Local Government, 2020 (1.1%) for Iceland, ANCI, 2020 (21%), respectively.

While negative effects of economic growth on the environment are well established, it is quite intriguing that even high levels of pollution can hinder economic growth and inflict catastrophic costs in terms of lives and property (Lei Ding et al., 2015). The understanding of the complex relationship between economic development and environmental degradation is further obfuscated and fragmented by disciplinary biases. Cracolici et al. (2010) claimed that only a few countries had managed to achieve simultaneous favorable environmental health and high levels of economic development. Gross Domestic Production (GDP) per capita ignores the considerations of the impact of a polluted environment on human lives and provides a very narrow and limited measure of well-being (Hobijn and Franses 2001; Neumayer 2003; Marchante and Ortega 2006).

A report released by the World Bank indicated a significant relationship between a reduction in economic growth, losing between 0.5 and 2.0 percent of economic growth, and polluted rivers (Desbureaux et al., 2019). The relationship between economic growth and water pollution has been explored quite extensively (Grossman and Krueger, 1995; Shen, 2006; Diao, Zeng, Tam, and Tam, 2009; Lee, Chiu, and Sun, 2010; Jayanthakumaran and Liu, 2012; Choi et al., 2015). In this backdrop, the complete shutdown of economic activities under the COVID-19 pandemic has had two massive environmental impacts. First, it has dramatically improved the air and water quality and reduced our material consumption, water usage, and waste production. Second, the environment underwent a partial and limited self-revival. This phase helped me better understand the magnitude of the contribution of even the non-industrial sources of pollution to the environment, especially water and air (Singh et al., 2014; Singh et al., 2016; Hader et al., 2020; Singh et al., 2021b,c). The improvement in the river water quality has been reported worldwide, including in India (Dhar et al., 2020; Mitra et al., 2020).

Recent studies claimed that the water quality and quantity in many rivers have consequently improved in a short span of time during the lockdown period, especially in river Ganga, India, 2020 (Dutta et al., 2020; Shukla et al., 2021). Similar to river water quality, domestic and non-domestic water sectors were also affected across the major economic sectors during the COVID-19 (Cooley et al., 2020; Balamurugan et al., 2021). However, few studies reported a variation in demand for domestic and non-domestic water consumption during the COVID-19 (Daijiworld, 2020; Sivakumar, 2021). A report released by the World Bank indicated a significant relationship between a reduction in economic growth, losing between 0.5 and 2.0 percent of economic growth, and polluted rivers (Desbureaux et al., 2019). However, a study conducted in Pakistan revealed that the use of technology and renewable energy may help boost economic development and reduce environmental pollution

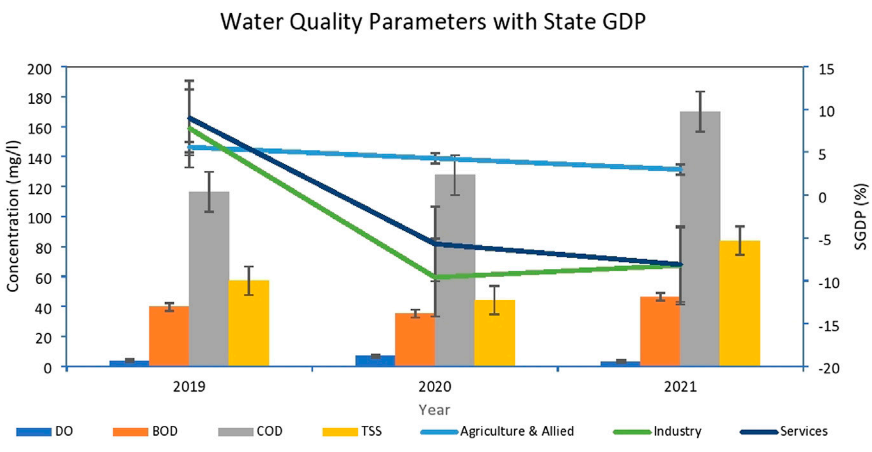

FIGURE 1 | Water quality parameters with state GDP for the respective years.

(Abid et al., 2020). Furthermore, technology indicated a significant positive association between green growth, and ISO 14001 (Abid et al., 2021).

Improved water quality has been reported on beaches of Bangladesh, Maldives, Malaysia, Indonesia, and Thailand (Kundu, 2020; Rahman et al., 2020) mainly due to a significant reduction in pollution load from major sources of water pollution in the rivers, such as industrial water waste disposal, crude oil, heavy metals, and plastic during the lockdown period (Ghildyal et al., 2020; Hader et al., 2020; Manuel and Zambrano, 2020). The pH level and values of electric conductivity (EC), Biological oxygen demand (BOD), and chemical oxygen demand (COD) have been reported to have declined by about 1–10%, 33–66%, 45–90%, and 33–82% across monitoring stations in the world during the lockdown period as compared to pre lockdown period (Cripps, 2020; Zambrano-Monserrate et al., 2020). Cooper (2020) conducted a study on the textile sector around the globe and reported that the total industrial water consumption massively declined during the lockdown period. A similar finding was reported in the case of the river Ganges, a highly polluted river in India, which witnessed a drastic reduction in pollutant load during the lockdown period (Mani, 2020). Despite the showing an improvement in water quality parameters in COVID-19, few studies claimed that environmental pollution load reported an increase in water bodies which were attributed to pharmaceuticals and plastic pollution (Gwenzi et al., 2022).

It is pertinent to study the effects of the COVID-19 lockdowns on the water quality of rivers in the short and long terms. The Yamuna River in National Capital Region is considered one of the most polluted rivers in India and the world due to the rapid increase in industrialization, urbanization, and high-density population growth (Upadhyay et al., 2011; Sharma et al., 2020). Due to very high levels of water pollution in this river, it is interesting to study the impact of lockdowns on the water quality of this river which passes through the northern industrial region of India. In the present study, the concentrations of pH, EC, DO, BOD, SS, and COD have been measured at monitoring sites on the bank of the Yamuna river. The water quality parameters were compared between the pre lockdown (previous year), during the lockdown, and post lockdown period. The study is unique as similar studies on the interaction of economic activities and water pollution in the catchment of the Yamuna river are lacking. The present investigation focuses mainly on evaluating the relationship between economic activities and water quality parameters during the COVID-19 pandemic on the upper stream of the Yamuna river in Haryana.

2 MATERIALS AND METHODS

2.1 Study Area

The Yamuna river is the major tributary of the Ganga river. It is also considered a sacred river in India. It originates from the Yamunotri glacier near Bandar Punch (38°59′N 78°27′E) in the Mussoorie (lower range of the Himalayas) at an elevation of about 6,387 m above mean sea level (MSL) in the Uttarkashi district (Sharma and Kansal, 2011). The Yamuna River has a vast catchment area of 366,223 km^2. The Yamuna enters Haryana near the Kalesar forest in the district of Yamuna Nagar and flows through the districts of Karnal, Panipat, Sonipat, and Faridabad before it enters the National Capital Region of Delhi. The major contributory industries to the water pollution in the Yamuna river are pulp and paper, sugar, tannery, steel plant distillers, textiles, leather, rubber, chemicals, glass, pharmaceuticals, and oil refineries, food, and discharge of polluted water from thermal power plants. The current study focuses on the analysis of water quality parameters of the Yamuna river in the state of Haryana only.

2.1.1 Conceptual Framework of the Water Quality Index

Water quality assessments gauge has categories in different categories according to suitability for a specific purpose (bathing, industrial or domestic purposes) which is adversely affected by any pollutants within it (Bagchi and Bussa, 2011). Several studies have developed methods for measuring water quality (Tyagi et al., 2013). The different measured variables are standardized and converted into a composite number that best denotes the suitability of the use of a particular water sample (Kumar and Dua, 2009). In addition, various agencies such as European Community, World Health Organization, Central Pollution Control Board (CPCB), and Indian Standard Specifications for drinking water have formulated their own respective standards regarding the permissible limits of measured parameters for rating a sample as different categories for specific use (Sargaonkar and Deshpande, 2003; Bharti and Katyal, 2011; Rout, 2017).

2.2 Data Collection

The variations in the water quality of the Yamuna river have been analyzed for the pre-lockdown, lockdown, and post-lockdown periods. The study has used secondary data due to lockdown-related restrictions. The data was directly procured from the "Haryana Pollution Control Board" department from November 1, 2019, to January 10, 2021 (https://hspcb.gov.in/yamuna). The pandemic duration has been was classified into three periods: pre lockdown, during the lockdown, and post lockdown.

The data for water quality was obtained between November 1, 2019, to March 23, 2020, which was referred to as the "pre-lockdown period" while the time between March 25 to May 31, 2020, was referred to as the "during lockdown", and the "post-lockdown" period refers to the time between June 1, 2020, to January 10, 2021. In the present study water quality data for the corresponding year, 2019 were compared with the years, 2020 and 2021. Water quality data has been procured from 13 different monitoring stations in Haryana state namely Gharaunda Drain before the meeting (Village Ali Asgarpur), Gharaunda Drain after the meeting (Village Ali Asgarpur), Drain No. 2 before meeting Panipat drain (near village Dadola), Panipat Drain (Village Sewah), Drain No.2 after meeting discharge of Panipat drain (village Simla, Gujran), Drain No. 2 after meeting Gharanunda drain at G.T. Road (Panipat), River Yamuna before meeting (Village Sanjoli), river Yamuna (village Khojkipur), Nohra

TABLE 1 | A comparative study of variation of environmental water quality parameters in different cities across the world during the pandemic.

Study area	River	Study period	Key findings	Reference
Haryana (India)	Yamuna	Nov 2019-January 2021	the average water quality concentration was 7.26 (pH value), 31.32, 136.07, 7.93, 30.33 mg/L, and 1500.24 μS/cm for BOD, COD, DO, TSS, and EC during the lockdown periods, respectively.	Present Study
Uttarakhand, Uttar Pradesh (India)	Ganga	25 March–14 April 2020	the temporal change study showed that reflectance in each visible NIR region has reduced, which might be attributed to a reduction in turbidity in the water of the river.	Garg et al. (2020)
Tamil Nadu (India)	Tuticorin	25th March to 30 May 2020	The significant reductions (>50%) in metals were noticed probably owing to trick wastewater discharge from metal base industries, seafood- base industries, and thermal power plants during the lockdown period.	Selvam et al. (2020)
Tamil Nadu (India)	Kosasthalaiyar, Cooum, and Adyar	-	SPM concentration decreased by 15.48 and 37.50% in the Chennai and Ennore ports, respectively, due to minimal vessel movement and cargo handling concentration decreased by 15.48 and 37.50% in the Chennai and Ennore ports, due to minimal vessel movement and cargo handling	Vijay Prakash et al. (2021)
Lucknow, Uttar Pradesh (India)	Gomati	January -July 2020	The DO levels fell across ~69% and ~88% of the sites during the lockdown and post-lockdown periods, respectively. Moreover, there was an increase in the BOD5 levels across ~69% and 75% of the sites during the lockdown and post-lockdown periods, respectively	Khan et al. (2021)
Lucknow, Uttar Pradesh (India	Gomati	June 2020	The concentration of all the six heavy metals (As, Cd, Cr, Fe, Mn, and Pb) clearly shows a significant reduction, highlighting the impact of the closure of agricultural, industrial, and commercial activities.	Khan et al. (2021)
Uttar Pradesh (India)	Ganga	January—May 2020	An increase in the dissolved oxygen (DO) by about 23% from 6.5 to 8ppm in 2019 and 2020, respectively, during the same period of lockdown, along with a decrease of about 25% in biological oxygen demand (BOD) from 4 to 3 ppm, during the same periods, respectively	Lokhandwala & Gautam
Uttarakhand, Uttar Pradesh, West Bengal (India)	Ganga	March—May 2020	A 55% decline in turbidity at that site during the lockdown was attributed to the abrupt halt in pilgrimage activities.	Muduli et al. (2021)
Kerala (India)	Vembanad Lake	January March 2020	A decrease of about 15.9% in suspended particulate matter (SPM) due to the COVID-19 lockdown	Yunus et al. (2020)
Ahmedabad (India)	Sabarmati River	February—May 2020	the average SPM has significantly decreased by about 36.48% when compared with the pre-lockdown period, and a drop of 16.79% was observed from the previous year's average SPM	Aman et al. (2020)
Hyderabad (India)	Lake Hussain Sagar	March and April for the years 2015–2020	The results show notable changes in SR values and FUI due to lockdown compared to before lockdown and after unlock, suggesting a significant reduction in lake water pollution. In addition, the historical variations within April indicate that the pollution levels are least in the year 2020.	Wagh et al. (2020)
Delhi (India)	Yamuna	January—April 2020	The water quality index indicated an improvement of 37% during the lockdown period. However, compared to the pre-lockdown period, the BOD and COD values declined by over 40.83 and 39.25%.	Patel et al. (2020)
Nepal	Bagmati		Compared to the pre-lockdown, the level of DO was increased by 1.5 times, whereas the BOD and COD were decreased by 1.5 and 1.9 times, respectively, during the post-lockdown, indicating the improvement of the quality of water.	Pant et al. (2021)

(Continued on following page)

TABLE 1 | (*Continued*) A comparative study of variation of environmental water quality parameters in different cities across the world during the pandemic.

Study area	River	Study period	Key findings	Reference
Malaysia	Putrajaya Lake	February—March 2020	there is a significant increase in the WQI Class I, from 24% in February 2020 to 94% during the month of March 2020.	Najah et al. (2021)
Italy	Venice lagoon	January—February 2020	The retrievals of TSM imply a remarkable reduction of the turbidity during the lockdown due to the COVID-19 pandemic and capture the high values of TSM during the flood condition.	Niroumand-Jadidi et al. (2020)
Southern Jiangsu (China)	Beijing-Hangzhou Grand Canal	January—April 2020	The water quality parameters and intensities of fluorescent components decreased to a low level due to the collective shutdown of all industries during the pandemic.	Shen et al. (2021)
Landon	Thames	-	The tributaries to the River Thames are more vulnerable than the Thames themselves to potential changes that may have occurred under the COVID-19 anti-contagion measures, highlighting rivers' critical role in diluting effluent.	Dobson et al. (2021)
Northwest Turkey (Turkey)	Meric-Ergene River basin	January to June 2020	The heavy metal pollution index and heavy metal evaluation index values indicated a significant improvement in the water quality of almost all the stations during the lockdown period. Also, hazard index values for children and adults were reduced by 60 and 94%, respectively.	Tokatli and Varola, (2021)
Morocco	Bokhalef River		The improved water quality at the discharge mouth into the Atlantic Ocean to be significantly improved mainly due to the COVID-19 lockdown, and hence cease of industrial activities, increasing the quality class from class D onward up to class A.	Cherif et al. (2020)
China	Groundwater		Drainage channel number-1 results showed that E. coli (positive), coliform count (22.75–48.66 /100 ml), and BOD (8–25.75 mgL1) remained above the permissible limit of the World Health Organization (WHO). Besides, drainage channel number 2 results exposed that E. coli (positive), coliform count (17.7–47 /100 ml), and BOD (6.25–21.5 mg/ L) were not within the permissible limit of WHO.	Hou et al. (2021)

Drain (Village Kakoda), NWMP station (Delhi Parallel Branch), NWMP station (Village Khojkipur) River Yamuna. Data for water quality parameters have been obtained from thirteen representatives for each monitoring station.

The present study analyzed the data (n = 113) for 15 water quality monitoring stations in Haryana to evaluate the variability in the concentration levels of water quality parameters during the pandemic period. The parameters used for this research are pH value, dissolved oxygen (DO), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solid (TSS), and Electrical Conductivity (EC). According to the Bureau of Indian Standard (IS 2296:1992), recommended by CPCB (Central Pollution Control Board), a table was made depicting the quality of surface water (**Supplementary Table S1**). Haryana's economic activities data were taken from Economic Survey, Haryana, 2020.

2.3 Statistical Data Analysis

To understand the changes in the individual water parameters between the pre- lockdown, during the lockdown, and post lockdown periods, statistical analysis was performed using the hypothesis testing (t-test) tool from SPSS version 26.0 (SPSS Inc., Chicago, IL, United States). Using MS-Excel Statistical attributes, trend analysis and box-whisker plots were computed and visualized (Kumar et al., 2014; Kumar et al., 2015). The Decimal Point Normalization (also sometimes referred to as the Floating-Point Number) technique is among the most frequently used normalization techniques (Nardo et al., 2009) and was employed to rank the drains during the pre-lockdown and lockdown periods based on the resulting additive aggregation (arithmetic mean) scores (Tate, 2012). In this normalization method, the maximum number of decimal points to be moved is dependent on the maximum values of the attribute data (Han et al., 2011; Punia et al., 2015), and the data attributes are transformed by simply moving the decimal points of the original data (Kumar et al., 2014a).

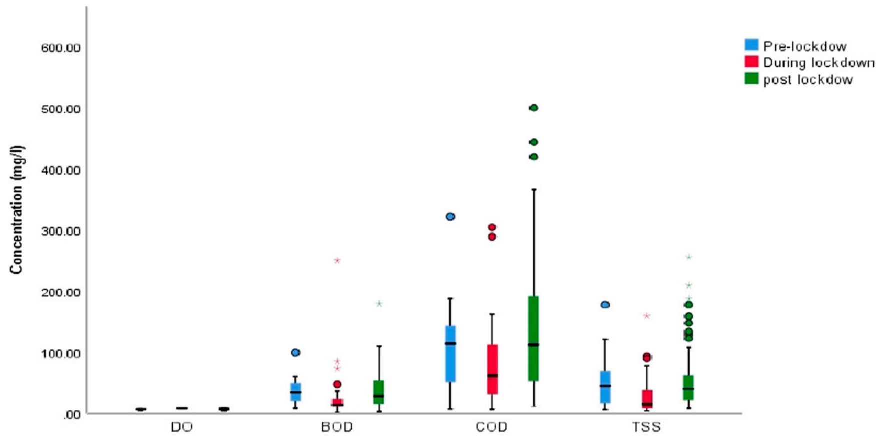

FIGURE 2 | Water quality parameters for pre-, during, and post lockdown period in Yamuna river.

3 RESULTS AND DISCUSSION

3.1 Relationship Between Economic Growth and Water Quality

The economic impact of the COVID-19 is supposed to vary across the countries depending upon the structural strengths of individual economies, although all the countries would face an economic decline. In the current study, Haryana's Gross State Value Added (GSVA), a state of India, grew at 8.0% in 2019–20, whereas it declined by 5.2% for 2020–21 (Government of Haryana, 2021). The decline was main contributed by a major decline in GVA of the Industrial Sector (−9.6%) and the Services Sector (−5.7%) for the year 2020–21 (**Supplementary Table S1**).

On the other hand, the water quality parameters such as TSS, BOD, and COD have been observed to have improved in the year 2020 during the lockdown period compared to the corresponding period in 2019 (**Figure 1**). This improvement in the water quality parameters of the Yamuna river can be partly attributed to the reduction in the discharge of industrial effluent during the lockdown period. It can be highlighted here that the discharge from industries was the primary source of pollution in the Yamuna river water as compared to other sources like domestic and agricultural activities. Post lockdown, the water quality of the Yamuna river was observed to have again declined with the resumption of industrial and other environmentally harmful activities. A comparative studies **Table 1** has been presented for the relationship between economic growth and water quality parameters during the pandemic period across the world.

3.2 Water Quality in the Pre-, During, and Post Lockdown Periods

In developing countries like India, water pollution is a common phenomenon where industrial and domestic wastes are dumped directly into the rivers without proper treatment (Yunnus et al., 2020). As a result, India's water bodies, especially the Yamuna river, have poor water quality. Moreover, most rivers and streams flowing by the major industrial sites have turned into sewer canals, making their rejuvenation and treatment very difficult. In this study, we have also evaluated the varying impacts of different phases of the lockdowns, pre-lockdown, during, and post lockdowns on the water quality of the Yamuna river. (**Figure 2**). The minimum, maximum, and mean values of Physico-chemical variables examined in this study are shown in **Table 2**. It can be mentioned here that several studies have underlined the positive impact of the lockdowns on river water qualities in many rivers for a relatively short period of few months, especially in the Ganga and the Yamuna rivers (Jain, 2015; Dutta et al., 2020; Singhal and Matto, 2020; Somani et al., 2020; Shukla et al., 2021).

3.3 Yamuna River's pH Level

The average values of pH of the Yamuna river water were found to be 7.53, 7.26, and 7.64 for pre-lockdown, during the lockdown,

TABLE 2 | Mean, maximum and minimum values of water quality variables determined in the pre-lockdown, during the lockdown, and post-lockdown periods.

Parameter	Pre-lockdown			During-lockdown			Post-lockdown		
	average	max	min	average	max	min	average	max	min
pH	7.53	7.77	7.27	7.26	7.80	6.59	7.64	7.80	6.59
TSS	57.2	178.00	6.00	30.33	160.00	5.00	60.40	256.00	8.00
BOD	39.62	100.00	8.00	31.32	250.00	1.30	40.50	180.00	2.80
COD	116.52	322.00	6.80	136.07	784.00	6.40	148.69	724.00	8.80
Conductivity	1743.01	3310.00	8.10	1500.24	3020.00	7.10	1467.39	3290.00	7.20

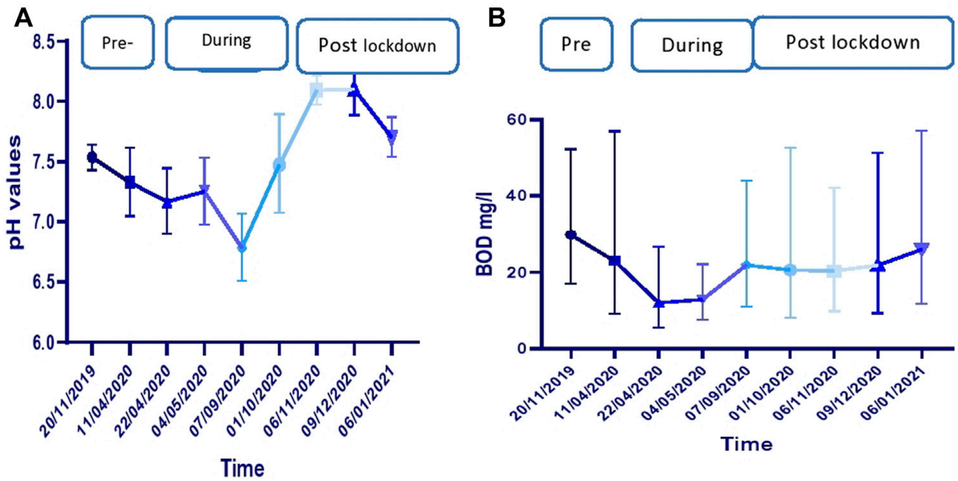

FIGURE 3 | Time series plot for the pH and BOD values during the pandemic in Yamuna river.

and post-lockdown periods, respectively. The maximum pH values were reported to be 7.77, 7.80, and 7.81 during these three time periods (**Figure 3A**). Moreover, the pH values for all the monitoring stations were the lowest during the lockdown period. The pH values of the Yamuna river water were observed to be alkaline in nature which varied between 7.2 and 7.8 from the pre- to post-lockdown period. In the post-lockdown period, the increase in pH values was probably due to an increase in the inflow of organic waste products from the resumption of anthropogenic activities. The highest pH value (8.33) among the monitoring stations was observed at drain No. 2 at village sanjoli and the lowest (6.44) at village Khojkipur during the lockdown period. The present study indicated that the values of pH were correlated with primary water quality criteria for bathing water and designated usable water quality (https://cpcb.nic.in/wqm/Primary_Water_Quality_Criteria.pdf). During the lockdown period, the pH values were observed lower than the threshold limit (6.5–8.5) at all the monitoring stations across the designated stretch of the Yamuna river. Therefore, an alkaline pH was observed during the lockdown period. According to Yashvardhini et al. (2020), an alkaline pH indicates that industrial wastes are composed of various components which could promote acidity.

3.4 Yamuna River's Biological Oxygen Demand Level

Biological Oxygen demand (COD) indicates the amount of dissolved organic matter and is an indicator of water pollution. The present study has found a drastic decline in BOD values during the lockdown period compared to pre-lockdown and post-lockdown periods. The mean values of BOD were found to be 39.62, 30.33, and 40.50 mg/L for pre-, during, and post lockdown periods, respectively (**Figure 3B**). Furthermore, reduction in the BOD levels during the lockdown period was reported by Dutta et al. (2020).

One of the significant factors behind the decline in BOD levels in the Yamuna river water is the closure of industries during the lockdown period. Another study on the Yamuna River water quality reported that the average BOD values increased by 7.09% during the same period and indicated quite a significant impact of domestic sewage load on the BOD levels in the river water. Khan et al. (2021) have also reported an increase in the average values of BOD by 19.44% in the post lockdown period. The findings of the present study indicate that values of BOD declined by 30.32% during the lockdown and increased by 39.5% during the post lockdown period, as also reported by Khan et al. (2021).

Moreover, another study conducted on the Ganges River water quality indicated a reduction of BOD values by 35–40% during the lockdown period due to the closure of automobile workshops, floating population, saree dyeing units, reduction in cremation, closure of hotels, and restaurants, and check on dumping of solid wastes into the river water. Besides, due to the shutdown of lift canals, the flow of the river water also surged (Time of India, 2020). Chauhan et al. (2020) reported that before the lockdown, the BOD ranged between 1.24 mg/L to 5.56 mg/L, whereas during the lockdown period, it ranged between 1.05 mg/L to 4.32 mg/L in the surface waters (river and canal) of Rajasthan. A similar result was reported in another study where BOD levels declined by 9.46, 24.25, and 5.59% in the Gomti, the Hindan, and the Ganges rivers, respectively (Ghildyal et al., 2020).

3.5 Yamuna River's Chemical Oxygen Demand Level

Chemical Oxygen demand (COD) indicates the amount of dissolved susceptible matter and is an indicator of water pollution. The major sources of COD are industries and wastewater treatment plants which were halted during the lockdown period. An increase in the level of COD severely affects dissolved oxygen, which adversely affects aquatic life (Yashvardhini et al., 2020). The present study has found the

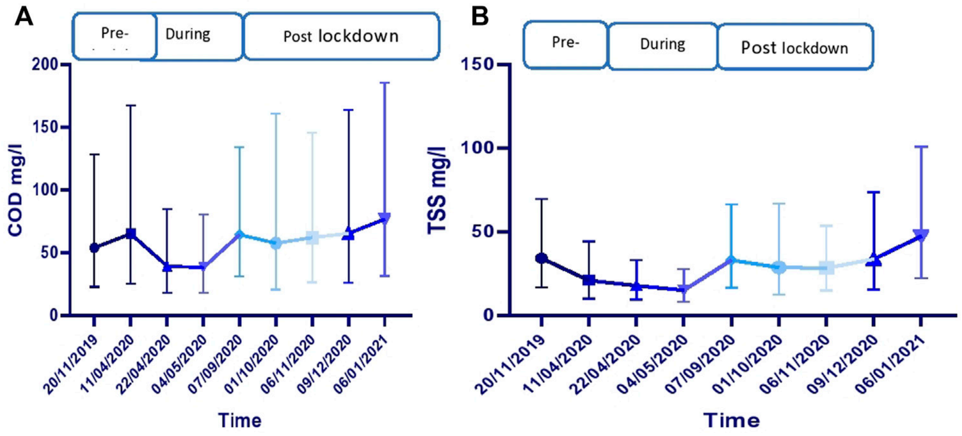

FIGURE 4 | Time series plot for the COD and TSS values during the pandemic in Yamuna river.

average values of COD to be 116.52, 136.07, and 148.69 mg/L, for pre-lockdown, during the lockdown, and post-lockdown periods, respectively. Similar results were reported by Yashvardhini et al. (2020). The maximum values of COD were 322.00, 784.00, and 724.00 mg/L for the pre-lockdown, during the lockdown, and post-lockdown periods respectively in the upper stream of Yamuna river (**Figure 4A**).

COD concentration declined during the lockdown period compared to pre-and post- lockdown periods. The high values of COD could be because of the rise of discharge of the untreated and moderately treated wastewater from the municipal sewage and a slower speed of dissolution in the pre-lockdown and post-lockdown periods. A study, conducted on the Ganges River during the pre-lockdown period reported the values of COD in the range between 6.14 and 17.7 mg/L, which was much lower than the current study (Dutta et al., 2020). The low levels of COD in the Ganges river indicated a complete stoppage in the flow of industrial pollutants owing to the complete lockdown, which significantly increased the water quality during the lockdown period. As a result of a halt in industrial activities and stoppage of discharge of pollutants and polluted water in the river, the Yamuna River's water quality has significantly improved during the lockdown period (Times of India, 2022). A study in Rajasthan indicated a general decrease in COD between 7.0 and 41.0 mg/L during the lockdown period in rivers and canals of the state (Chauhan et al., 2020). Another study conducted on COD levels in the Yamuna river water reported that the COD levels declined by 24% during the lockdown period (Ghildyal et al., 2020).

3.6 Yamuna River's Dissolved Oxygen Level

Dissolved oxygen (DO) indicates oxygen availability in the water, which is opposite to biological oxygen demand (BOD). The higher value of DO refers to better water quality which is necessary for water bodies in order to sustain aquatic life. The average concentrations of DO in the Yamuna river water were observed to be 6.1, 7.93, and 6.12 mg/L for pre-lockdown, during the lockdown, and post-lockdown periods, respectively. The maximum values were found to be 7.4, 8.4, 9.0 mg/L, whereas the minimum was 4.3, 7.1, 3.6 mg/L for the same periods. Similar values were reported in another study during the lockdown phase from 0 to 8.1 mg/l with a mean value of 3.2 mg/L (Yashvardhini et al., 2020). The drastic improvement in DO values during the lockdown period indicated a significant reduction in the effluent from the industrial and agricultural activities, accounting for the rejuvenation of the DO levels during the same period.

A study conducted in the Damodar river reported the DO levels in the range of 4.2–5.67 mg/L with an average value of 4.85 ± 0.49 mg/L for the pre-lockdown period, and 6.15–815 mg/L with an average value of 7.31 ± 0.59 mg/L for the during lockdown period (Chakraborty et al., 2021). Several studies reported a drastic improvement in DO levels in river waters and thus improved water quality of the Yamuna River during the lockdown period where the values of dissolved oxygen (DO) were found to be in a range from 2.3 to 4.8 mg/L, which can be considered significant as compared to the previous year, 2019 (CPCB 2020; UPPCB 2020; Khan et al., 2021). A study conducted in the Ganga River reported a slight decrease in DO levels at all the monitoring sites in contrast to the present study, due to a significant increase in the turbidity and suspended solids which were contributed by heavy rain spells (60%) during the lockdown period (Dutta et al., 2020).

3.7 Total Suspended Solid Level in Yamuna River

The present study has found the average value of TSS to be 57.2, 30.33, and 60.40 mg/L for the pre-lockdown, the during the lockdown, and post-lockdown periods, respectively. The values of TSS varied from 6.0 to 178.0, 5.0 to 160.0, and 8.0–256.0 mg/L during these three time periods, respectively (**Figure 4B**). In the Damodar river, India, a study reported TDS values ranging from 665.6 to 806.4 mg/L and 480–563.2 mg/L for three comparable time periods (Chakraborty et al., 2021). TSS results indicated a sharp decline of 29.33% during the lockdown compared to the pre-lockdown period. A similar result was reported in the Ganga

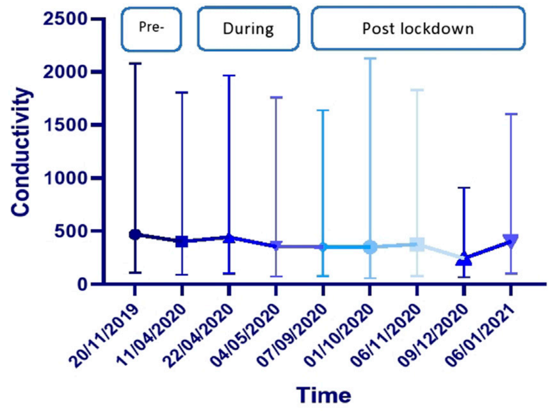

FIGURE 5 | Time series plot for the EC values during the pandemic in Yamuna river.

River where the TSS declined by 33.89% during the same period due to a decrease in industrial waste dumping (Ghildyal et al., 2020). However, the TSS value increased by 59.40% in the post-lockdown period compared to the lockdown period due to the opening of industrial and commercial activities.

3.8 Yamuna River's Electrical Conductivity Level

The average values of electrical conductivity of the Yamuna river water were detected to be 1743.01, 1500.24, and 1467.39 µS/cm for the pre-lockdown, the during the lockdown, and the post lockdown periods, respectively. The electrical conductivity levels in the Yamuna river water varied from 8.10 to 3310.0, 7.10 to 3020.0, and 7.20 to 3290.0 µS/cm for the pre-,during, and post-lockdown periods respectively (**Figure 5**). The values of EC in the Damodar river, India, were reported to be much lower than the present results, ranging from 1040 to 1260 µS/cm and 750 to 880 µS/cm for the during and post-lockdown periods, respectively (Chakraborty et al., 2021). In a study conducted in the rivers and canals of Rajasthan state, the electrical conductivity values ranged between 300 and 2100 µmho/cm and 230 to 1250 µmho/cm for the pre-lockdown and the post-lockdown periods, respectively (Chauhan et al., 2020). During the lockdown and the post-lockdown phase, the electrical conductivity has been observed to decline due to the reduction in industrial effluents' discharge into the river water. Furthermore, a decline in the electrical conductivity values implied a significant shutdown of industrial activities, which lowered the discharge rate of industrial effluents into the Yamuna River during the lockdown. In the pre-lockdown period, the higher electrical conductivity value in the pre-lockdown indicated a higher presence of chloride, phosphate, and nitrate emanating from the sewage systems flowing into the Yamuna River.

3.9 Hypothesis Testing (t-test)

We performed hypothesis testing (t-test) to understand any changes in the individual water quality parameters between the pre-lockdown and during lockdown periods. The results indicated that the t value was more significant than the alpha value at a 0.05% significance level. It suggested a significant reduction in concentrations of water quality parameters, thus rejecting the null hypothesis. Results indicated improved water quality during the lockdown period, which can be partly attributed to a significant closure of industries in the study area. Similar results were reported in the Damodar river during the same time periods (Chakraborty et al., 2021).

Table 3 depicted the correlation between the water quality parameters for the Yamuna river in the pre-lockdown, during the lockdown, and post-lockdown periods. A strong significant positive correlation between electrical conductivity and COD and TSS with COD was found, whereas a moderate correlation was observed between DO and COD and electrical conductivity for pre lockdown period. A strong significant positive correlation was observed between COD with BOD and TSS during the lockdown period, whereas moderate conductivity with pH, DO, BOD, COD, and TSS. A strong positive correlation was found between COD with BOD and conductivity, whereas moderate was shown between TSS with BOD and COD for the post lockdown period.

4 SUGGESTIONS AND RECOMMENDATIONS

The governments, both the Central and the State governments, have taken many steps to control pollution in the Yamuna river, for instance, the Yamuna Action Plan (YAP), whose first and second phases started in 1993 and 2004 with a total expenditure of Rs.682 crore and Rs.666.76 crore respectively. Building upon

TABLE 3 | Correlation coefficient matrix of Physico-chemical parameters for Yamuna River (Bold values indicate the strong correlation).

Pre-lockdown period

	pH	DO	BOD	COD	TSS	Conductivity
pH	1					
DO	−0.18	1.00				
BOD	0.06	−0.14	1.00			
COD	−0.16	−0.48	0.01	1.00		
TSS	0.11	−0.53	0.04	**0.73**	1.00	
Conductivity	−0.16	−0.48	0.01	**1.00**	**0.73**	1.00

During Lockdown Period

	pH	DO	BOD	COD	TSS	Conductivity
pH	1.00					
DO	0.09	1.00				
BOD	−0.64	−0.44	1.00			
COD	−0.67	−0.60	**0.76**	1.00		
TSS	−0.35	−0.72	0.59	**0.85**	1.00	
Conductivity	−0.61	−0.62	0.44	0.71	0.71	1.00

Post Lockdown Period

	pH	DO	BOD	COD	TSS	Conductivity
pH	1.00					
DO	−0.04	1.00				
BOD	−0.11	0.37	1.00			
COD	−0.11	0.37	**1.00**	1.00		
TSS	−0.11	−0.10	0.69	0.69	1.00	
Conductivity	−0.18	0.36	**0.78**	**0.78**	0.65	1.00

the success and lessons learned from YAP-1 and YAP-2, the Government of India has launched Yamuna Action Plan-3 (YAP-3) at an estimated cost of Rs 1656 crore with the assistance of Japan International Cooperation Assistance (JICA). From a policy point of view, the current study suggests that more efforts are required to improve the water quality of the Yamuna river. Some of the recommendations emerging from the current study are:

- Implementation of Growth Pole Strategies of economic development where decentralization of economic activities is advocated in a more emphatic manner.
- Close-knit collaboration with multiple stakeholders, where the industrial pollution from public sector enterprises must be minimized and shared with other stakeholders as industry best practices towards sustainable industrial development.
- Improvements of current sewage treatment plants (STPs), including automated river water quality monitoring.
- Formulation and strict implementation of regulations and laws to contain water pollution. Incentivizing the industries to use high-quality equipment resulting inefficient use of resources and reducing water pollution discharge.

Despite showing a strong correlation between the variation of water quality parameters and certain economic activities during the COVID-19 in Yamuna River, the current study has the following limitations. First, the current study only accounts for certain water quality parameters where data variability can be accurately measured. We do not account for other parameters such as metals loads and socio-economic indicators; future studies can research in this direction. Secondly, the inclusion of economic data for other sectors along the Yamuna river would provide more precise results and an interesting research contribution. However, we need to strengthen the real-time monitoring of water quality data for the river to accurately estimate the improvements or reduction in river water quality monitoring across all the rivers during and after any consequential events.

5 CONCLUSION

The impacts of the COVID-19 lockdown on the water quality parameters in the Yamuna river have been analyzed in the current study. The data on water quality parameters such as pH, BOD, COD, TSS, and EC were obtained from the Haryana Pollution Control Board between November 1 2019 to January 10 2021, and economic data were used from the economic survey of Haryana, 2019–2021. Overall, the discussion highlighted the dramatic effects of COVID-19 lockdown on economic activities and water quality parameters, such as 1) a significant improvement in water quality parameters in the Yamuna river due to COVID-19 lockdown that prevented the discharge of industrial effluent in the river, 2) a change in water demand and supply patterns in industrial and commercial sections, and 3) a disruption in agricultural activities near the Yamuna river bank which changed the agricultural water usage pattern.

The water quality parameters such as TSS, BOD, and COD witnessed a significant improvement during lockdown compared to the corresponding time period in 2019. This improvement in the water quality parameters of the Yamuna river was mainly due to a reduction in the effluent discharge into the river water as a result of the sudden lockdown.

Furthermore, the average concentrations of water quality parameters were 7.26 (pH value), 31.32, 136.07, 7.93, 30.33 mg/L, and 1500.24 μS/cm during the lockdown period, as compared to pre lockdown period values of 7.53 (pH), 39.62, 116.52, 6.1, 57.2 mg/L and 1743.01 μS/cm for BOD, COD, DO, TSS, and EC respectively. This indicated a drastic improvement and rejuvenation of the water quality of the Yamuna river due to restrictions in industrial, commercial, agricultural, and other anthropogenic activities near the Yamuna river bank.

The study has rejected the null hypothesis and has found a statistically significant impact of the lockdown period on the water quality parameters of the Yamuna river. The findings from the current study provide relevant insight to authorities towards the necessity of stringent environmental regulations to prevent the discharge of untreated municipal and industrial water waste into the Yamuna river.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

BS: Conceptualization, environment, analysis of the results and; discussion. PR: Procurement of data, Economics, framing the introduction section, preparing suggestions. NM: Data curation, Methodology, Economic section in results and discussion and Writing review and; editing. SK: visualization of graphs and; tables. MA: recommendations, and improving the overall quality of the current draft. ZA: Analysis of the statistical results and discussion. SR: Preparing the economic table from various sources.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.940640/full#supplementary-material

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BRIEF RESEARCH REPORT
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Fitness Culture and Green Space Equity: Accessibility Evaluation of Shanghai Communities

Tingting Qiu[1], *Daliang Zhou*[2] *and Wen Li*[3]*

[1]School of Physical Education, Huaqiao University, Quanzhou, China, [2]School of Physical Education, Nanjing Xiaozhuang University, Nanjing, China, [3]Basic Teaching Department, Wenzhou Business College, Wenzhou, China

In China, sports parks, and green spaces are often spatially integrated to realize the multiple functions of shared green spaces and play an important role in the production and living services of its residents. In this article, it is collectively referred to as green sport space (GSS). Whether the distribution of GSS is equal has an important impact on the sustainable lifestyle and the rehabilitation under the pandemic. Based on the POI data of the Shanghai urban area, it is preliminarily found that the areas with extremely high and high production and living densities are mainly distributed in downtown Shanghai. Polarization of the GSS distribution area and the high heat of points of interest can be seen. When the service radius of the GSS in Shanghai is 500, 750, and 1,000 m, the green space ecological service area can reach 2089.08, 3164.6^2, and 4469.75 km^2, covering 26.17, 39.64, and 55.99% of the total area, respectively. The coverage for walking accessibility of GSSs in Shanghai is extremely uneven. Based on network analysis, the overall accessibility of GSS under the walking mode in each residential district fails to meet the standard of a 15-min living circle, with an average of 15.37 min. The evaluation results of this plan demonstrate that Shanghai needs to further provide GSS space for the public in future to improve public wellbeing and diversify sports spaces.

Keywords: green sport space, equity, culture, Shanghai, planning, human geography, community

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Muhammad Kamran Khan,
Northeast Normal University, China

Correspondence:
Wen Li
liwenenglish@outlook.com
00201106@wzbc.edu.cn

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1 INTRODUCTION

Urban green space is an important part of urban public service facilities, and its layout is closely related to people's life and sustainable urban development (Wüstemann et al., 2017; Žlender and Thompson, 2017). Therefore, the layout of urban green spaces should reflect the concept of equity so that all classes of society have equal opportunities to enjoy urban green spaces (Haughton, 1999; Agyeman et al., 2002; Stessens et al., 2017). City Park was first born in the United Kingdom. It is not only an inevitable product of the progress of cities and human civilization under the background of industrialization but also reflects people's long-term pursuit of a better living environment and healthy lifestyle. The first city park in the world was Birkenhead Park in Liverpool, built by the British government in 1843. The birth of Birkenhead Park not only promoted the construction of parks in Britain but also affected places such as Europe and the United States. In addition to the first city park Birkenhead Park, Central Park in New York also has an important influence on the construction of city parks today.

The research on the spatial equity of urban park supply has always drawn the attention of Western academic circles, and accessibility analysis is a common method to measure spatial equity. In the 1990s, geographers first introduced the accessibility model to evaluate the rationality of public facility

distribution. Scott and Soja (1996) believe that there is a correlation between social interaction and the accessibility of green open space. They take socioeconomic status (income and education), block variables (block location and residence time), and leisure time (daily outdoor activities, marital status, and number of children) as parameters and apply the method of generalized estimation equation to analyze the relationship between social interaction and accessibility of the game field. Lee and Hong (2013) believe that urban accessibility is regional, and poor accessibility in many cities is due to the large population density and the small number of parks in the region. Through accessibility assessment, it is helpful for determining the location of people whose potential needs cannot be met and areas with poor accessibility, which will help city planners understand the service level and scope of the park in the planned area. Since the 21st century, with the development of measurement technology, research tends to adopt quantitative methods such as mathematical models and GIS spatial analysis to evaluate spatial equity. The literature on environmental justice from the perspective of sociology has also gradually increased. Boone et al. (2009) believe that the distribution of public service facilities needs to reflect the fairness of social distribution. Combined with the needs of users with different attributes, they analyze the fairness of the spatial distribution of urban parks in Baltimore, Maryland. It is found that within the 400-m buffer zone, White people have more opportunities to reach the park on foot than Black people. Scarcity of parks in black residential areas is higher than that in white residential areas. This phenomenon reflects the unfairness of the environment. Dadashpoor et al. (2016) believe that everyone in society should enjoy the services of public facilities fairly without being restricted by their identities and status.

The issue of fairness and justice of ecological services in China has gradually received attention. Meanwhile, China's discussion of green parks has focused on their fitness and athletic functions, while helping realize its National Fitness Program. For this, in China, green spaces and sports parks are spatially integrated to realize the multiple functions of shared green spaces and therefore play an important role in the production and living services of its residents. In this article, it is collectively referred to as green sport space (GSS). For example, in the master plans of major cities such as Beijing and Shanghai, it is required to achieve "a 15-min community fitness circle". As an important and basic public service facility in the community, the accessibility of green spaces with fitness facilities has become a significant improvement indicator. In addition, large-scale public green space is expected to meet the requirements of 5-min walk accessibility (Liu et al., 2008; Fan et al., 2016).

Fan et al. (2017) provided planning suggestions for Shanghai Xinhua Street in terms of accessibility, functionality, and sharing level with the goal of a 15-min living and fitness circle. At present, in many cities in China, the indicator system guiding urban GSS planning and construction still focuses on urban-scale equality, that is, the system uses four indicators: GSS rate, per capita green area, per capita GSS area, and urban–rural greening rate to guide urban greenbelt construction (Zhou and Rana, 2012; Shen et al., 2017). It can be found that although these indicators are conducive to the overall analysis of the quantitative characteristics of urban GSSs, they do not consider whether the service level of a park GSS can meet the actual needs of residents. If to only analyze the amount of GSS from a macro perspective without analyzing the rationality of the layout of urban GSSs based on the city's real economic conditions, traffic conditions, crowd characteristics, and social needs, the analysis results will be divorced from reality (Annerstedt van den Bosch et al., 2016; Gupta et al., 2016; Friedman, 2020). Therefore, to solve this problem, based on spatial analysis, this study selects Shanghai as a sample to explore the spatial layout of urban GSS and evaluates the fairness of the spatial distribution of urban GSSs in Shanghai, hoping to provide some reference value for the future location and construction of urban GSSs.

2 MATERIALS AND METHODS

2.1 Overview of Shanghai

2.1.1 Research Data

This study takes Shanghai as the research object because Shanghai has implemented a series of urban greening constructions since the 1980s. According to the 2020 Shanghai Municipal Statistical Yearbook, the current green area of Shanghai is 157,800 hm^2. By specifying parks with fitness facilities, there are 352 with an area of 21,400 hm^2. The green coverage rate of the built city is 39.7%, and the per capita GSS area reaches 13m^2. Two types of data are mainly used in this research. The first type is spatial data, including Shanghai administrative boundary, regional parks, GSS data, regional road traffic network data, and regional residential area data. All spatial data acquisition follows scientific and systematic methods, making full use of official portals such as Shanghai Urban Planning and Natural Resources Bureau, Shanghai Municipal People's Government, and electronic maps such as Gaode map. A unified spatial coordinate system is used to calibrate the data to ensure that all data are compatible. Urban economic data are also supplemented by reference to environmental economic studies (Islam et al., 2021; Khan et al., 2021; Zhang et al., 2021; Godil et al., 2022; Rehman et al., 2022). The spatial point data of all green parks in Shanghai and the descriptive text of relevant parks were crawled at the same time, and we screened out the parks with fitness facilities in the description by searching. Finally, 607 GSSs were found in Shanghai. In order to help analysis, the government statistical data were also used, which mainly come from the Shanghai Statistical Yearbook released by the Shanghai Municipal Bureau of Statistics in November 2020.

2.2 Research Methods

2.2.1 Kernel Density Estimation

Points of interest cover the location and attribute information of all facilities related to production and life in the city, which can provide decision-making services for urban planning and management and obtain the spatial distribution characteristics of urban facilities and events from a macro perspective (Bai et al., 2021; Guerrero et al., 2016). Generally speaking, the higher the concentration of points of interest, the more intensive the

production and living activities in the region and vice versa (Wang et al., 2018). Compared with methods such as the quadrant density and Voronoi diagram density, the kernel density method has more advantages in the expression of spatial features of points of interest (Bielecka et al., 2020). Therefore, this study uses the kernel density analysis method to simulate the heat map of the point of interest. The specific calculation formula is as follows:

$$f(x) = \sum_{i=1}^{n} \frac{1}{h^2} k\left(\frac{x - c_i}{h}\right). \quad (1)$$

In the formula, $f(x)$ represents the kernel density calculation function at the spatial location x; h is the distance attenuation threshold; h is the number of feature points whose distance from the location x is less than or equal to h; and the function k represents the spatial weight function. The geometric meaning of this formula is that the density value is the largest at each core element c_i, and it decreases continuously in the process of moving away from the core element c_i until the distance from the core element c_i reaches the threshold where the density value is 0.

2.2.2 Spatial Analysis of ArcGIS

The spatial analysis method is mainly applicable to the empirical analysis of the research on the fairness of urban public GSS. Urban public GSS has geospatial attributes. To reflect and display the spatial distribution pattern of urban public GSS, the GIS spatial platform is needed for multidimensional analysis (Sathyakumar et al., 2020). At the same time, combined with other spatial data and socioeconomic data with spatial attributes, overlay analysis, spatial statistical analysis, and other methods are adopted to further discuss the unfairness of public GSS. The accessibility of urban public GSS is drawn in the form of a map to accurately locate the areas of public GSS unfair. In this study, ArcGIS 10.2 is used as the operation platform, and the kernel density analysis tool in spatial analysis is adopted to analyze the points of interest in Shanghai. In practice, the setting of the search radius (related to the distance attenuation threshold) has an important impact on the results.

To scientifically reflect the heat of production and life in the region on a macro level, the natural grading method is adopted, dividing the kernel density values of points of interest in the study area into five grades from high to low: extremely high density, high density, medium density, relatively low density, and low density. Then, overlapped with the GSS entity, the spatial distribution of the GSS and POI dense area is preliminarily analyzed (Dong et al., 2018).

Generally speaking, public GSS can provide good ecological services for residents living within 500 m (walking time is less than 15 min), relatively good services for residents living within 500–750 m (walking time is about 15–25 min), average services for residents living within 750–1,000 m (walking time is about 20–30 min), and few services for those living beyond 1,000 m (Dong et al., 2018; Chen et al., 2020). Therefore, after a simple analysis of the spatial distribution characteristics of the GSS entity and POI heat zone, this study made three buffer zones with different radii of 500, 750, and 1,000 m for the GSS and coupled the analysis with the POI heat map. This article discusses relevant issues from the perspective of the supply of ecological services in GSS and the demand for ecological services in POI hot areas.

2.2.3 Multimode Two-step Floating Catchment Area Method

The two-step floating catchment area method is adopted to evaluate the accessibility of GSS from the perspective of GSS supply and population demand, that is, the more GSS the community residents can enjoy, the higher the GSS accessibility level. However, the two-step floating catchment area method based on ArcGIS network analysis cannot reflect the accessibility of GSS in multiple travel modes. Also, it is especially difficult to simulate and calculate the accessibility through public transportation and cannot reflect the real-time and objective road network conditions (Yang et al., 2021). Therefore, based on the traditional two-step floating catchment area method, combined with the application of TIQS, this study constructs and adopts a multi-mode two-step floating catchment area method (M2SFCA) to measure the accessibility of multi-scale GSSs in Shanghai, considering two travel modes of walking and cycling. The specific calculation process is as follows:

First, the travel time to reach grade c GSS and the number of people from a community in the two travel modes of walking (M_1) and cycling (M_2) are acquired. Walking and cycling are set as the priority as the resident choice of traveling. That is, if the residents can walk to this type of GSS within the predetermined time threshold, only the travel time to the GSS and the number of people from a community in the walking mode are acquired; otherwise, the travel time to the GSS and the number of people from a community in the cycling mode are acquired. The calculation process is as follows:

The first step is to calculate the supply-demand ratio of GSS, that is, the service capacity of GSS:

$$R_j = \frac{S_j}{\sum_{i\in_{ij}(M_1)\leqslant t_0(c)} r_{iM_1} \times G\left(t_{ij}(M_1), t_0(c)\right) + \sum_{i\in'_i(M_2)\leqslant t_0(e)} r_{iM_2} \times G\left(t_{ij}(M_2), t_0(c)\right)}. \quad (2)$$

In the formula, R_j is the service capacity of GSS; S_j is the area of GSS; r_{iM_1} and r_{iM_2} are the numbers of people that reach the GSS by walking and cycling within the time threshold, respectively; $t_{ij}(M_1)$ and $t_{ij}(M_2)$ are the travel time from the community to the GSS in the walking and cycling modes, respectively; and $t_0(c)$ is the time threshold for the grade c GSS. G is the time attenuation coefficient based on the Gaussian function. The calculation formula is as follows in walking mode (M_1) and cycling mode (M_1):

$$G\left(t_{ij}(M_1), t_0(c)\right) = \begin{cases} \frac{e^{-(1/2)*\left(t_{ij}(M_1)/t_0(c)\right)^2} - e^{-(1/2)}}{1 - e^{-(1/2)}}, & if\ t_{ij}(M_1) \leqslant t_0(c) \\ 0, & \text{if } t_{ij}(M_1) > t_0(c) \end{cases}. \quad (3)$$

$$G\left(t_{ij}(M_2), t_0(c)\right) = \begin{cases} \frac{e^{-(1/2)*\left(t_{ij}(M_2)/t_0(c)\right)^2} - e^{-(1/2)}}{1 - e^{-(1/2)}}, & if\ t_{ij}(M_2) \leqslant t_0(c) \\ 0, & \text{if } t_{ij}(M_2) > t_0(c) \end{cases}. \quad (4)$$

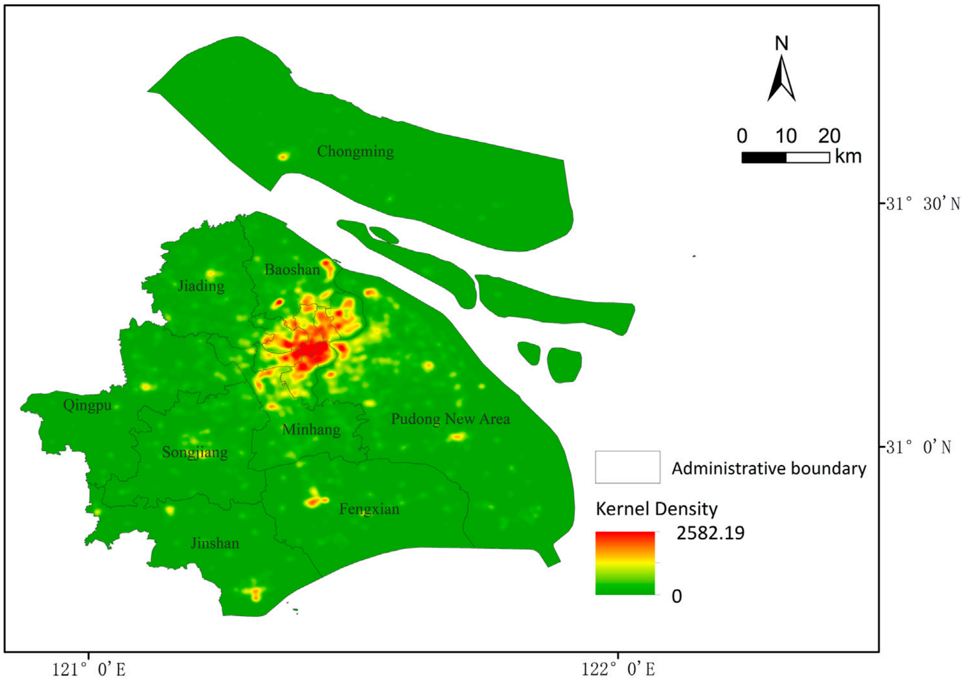

FIGURE 1 | Spatial distribution of POI kernel density in Shanghai.

The second step is to calculate the sum of the supply-demand ratio of the accessible GSS for each community within the time threshold, that is, the accessibility of GSS for community i.

$$A_i = \sum_{j \in t_i(M_1) \leqslant t_0(c)} R_j \times G\big(t_{ij}(M_1), t_0(c)\big) + \sum_{j \in t_i(M_2) \leqslant t_0(c)} R_j \times G\big(t_{ij}(M_2), t_0(c)\big). \quad (5)$$

In the formula, A_i is the GSS accessibility for community i. The larger the value, the higher the GSS accessibility level for the community.

3 RESULTS

3.1 Basic Characteristics of Green Sport Space Distribution

The patches of GSS in the urban area of Shanghai are relatively fragmented, and the green patches are distributed from the Bund in downtown Shanghai, and the density decreases successively. The green patches are most densely distributed between the inner ring and outer ring of the city. In Hongkou, Changning, and Xuhui districts, there are more green patches. The area of a single GSS is small, and the distribution is relatively scattered, showing bands, rings, and radials. Outside the urban core area, the green patches are mainly concentrated in the Shanghai Binhai Forest Park area, Jinqiao Park area, Chuansha New City area in Pudong New Area, Yangpu Xinjiangwancheng area, Gucun Park in Baoshan District, Dongtan Wetland Park area in Chongming District, and the Maqiao area of Minhang District. From the aspect of orientation, the GSS in Shanghai is characterized by more in the north and less in the south, more in the east, and less in the west. In the east of Xuhui District along the Huangpu River, Shanghai Botanical Garden, Longhua Park, riverside GSS, Houtan Park, and other public GSS resources are densely distributed, and financial services, business, and entertainment formats concentrate along the Huangpu River, with a relatively small residential population. Zhangjiang Science and Technology Park, as one of the important centers for the future urban layout of Pudong, is under development and construction. There has not yet been a large-scale concentrated population there. However, there are district-level parks such as Zhangjiang Theme Park, Guanglan Park, and Ziwei Park in the surrounding area.

3.2 Basic Characteristics of Point of Interest Heat Distribution

Through the kernel density analysis of POI in Shanghai, the kernel density distribution map of POI in Shanghai is shown in **Figure 1**. From the graph, the points of interest in Shanghai are mainly distributed in the city center. The closer to the city center, the higher the density of points of interest. In the area within the central ring road of Shanghai, the density of interest points is generally high. In the areas outside the central ring road of Shanghai, the density of points of interest gradually decreases with the increase of the distance from the city center, and the density of points of interest outside the outer ring road is generally low. From the aspect of orientation, as a whole, the

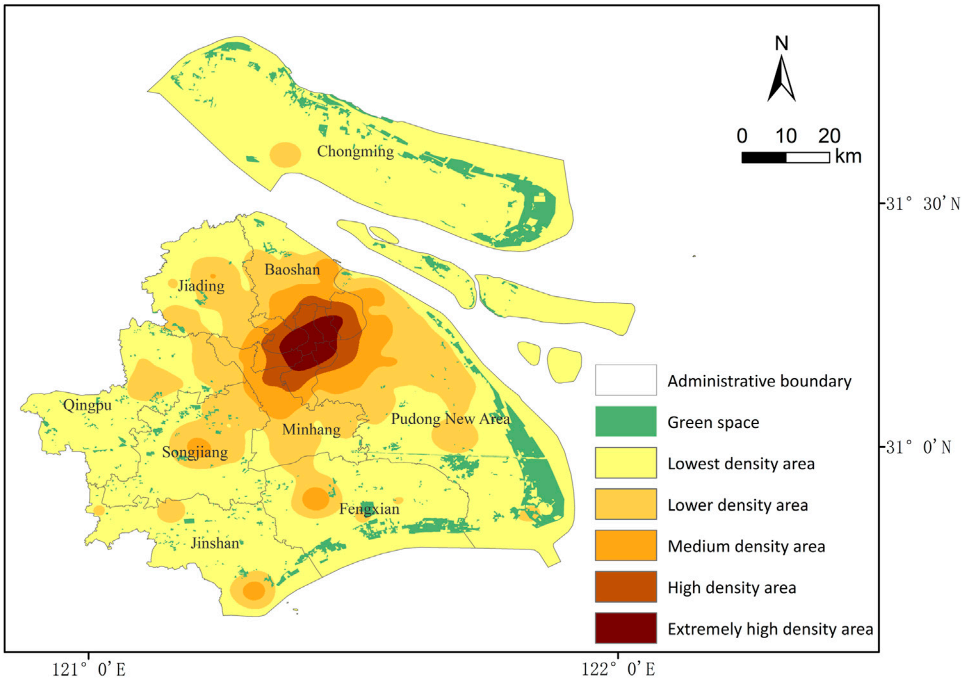

FIGURE 2 | Distribution of GSS overlapped by production and living density based on the POI.

central area has a higher density of points of interest than the surrounding areas in the four directions of east, west, south, and north, showing a trend of central agglomeration. On the other hand, the distribution of points of interest in the north is more concentrated, while that in the south is relatively scattered. Compared with the west of the city, the distribution of points of interest in the east is relatively concentrated, while that in the west is relatively scattered. As a social and economic complex, Shanghai's agglomeration effect and economies of scale are its most basic characteristics, which can be better reflected by the characteristics of POI kernel density.

3.3 Analysis of Different Service Radii of GSS Based on Point of Interest Heat Map

The spatial overlay of the POI kernel density grading distribution map in **Figure 1**, and the GSS is shown in **Figure 2**.

As can be seen from **Figure 2**, the areas with extremely high and high production and living density are mainly distributed in the south of Hongkou District, Jing'an District, the east of Changning District, and the northeast of Xuhui District. At the same time, there are some areas with low interest, where GSS has an advantage, such as Shenlong Ecological Park in Fengxian District, Shanghai Gulf National Forest Park, Binhai Forest Park in Pudong New Area, and Golf Park. In the extremely high-density, high-density, and medium-density areas, the urban GSS area is 28.71hm^2, accounting for 5.10% of the total GSS area; in the low-density area, the urban GSS has an area of 512.48hm^2, accounting for 91.13% of the total area of GSS, showing polarization of the GSS distribution area and the high heat of points of interest. Urban GSSs and intensive residential production and living areas inevitably overlap in space, but urban GSSs should be able to give full play to their effective service radius. Therefore, by further analyzing the buffer zones with different radii of urban GSSs (**Figure 3**), the study obtains the coverage of the buffer zones with a radius of 500 m (**Figure 3A**), 750 m (**Figure 3B**), and 1,000 m (**Figure 3C**) in POI heat areas in the study area, and the GSS service areas enjoyed by different levels of heat areas are as follows: 1) lowest density area: it has a total area of 5692.80 km^2, and its 500-, 750-, and 10,000-m ecological service areas are 1942.78, 2982.94, and 4205.62, respectively; 2) lower density area: it has a total area of 1562.36 km^2, and its service areas are 70.31, 86.68, and 105.12; 3) medium-density area: it has a total area of 433.69 km^2, and its service areas are 45.52, 52.16, and 76.52; 4) high-density area: it has a total area of 190.09 km^2, and its service areas are 21.02, 28.25, and 48.22; 5) extremely high-density area: it has a total area of 104.82 km^2, and its service areas are 9.46, 14.59, and 34.26.

When the service radius of GSS is 500, 750, and 1,000 m, the GSS ecological service area can reach 2089.08, 3164.6^2, and 4469.75 km^2, covering 26.17%, 39.64%, and 55.99% of the total area, respectively. From the perspective of the service supply of GSS, its spatial distribution pattern is relatively even. At the same time, within the 500 m service radius of GSS, only 9.02% of the extremely high-density area, 11.06% of the high-density area, and 10.50% of the medium-density area in the POI heat map are covered, which shows the uneven spatial distribution pattern of GSS from the perspective of service demand.

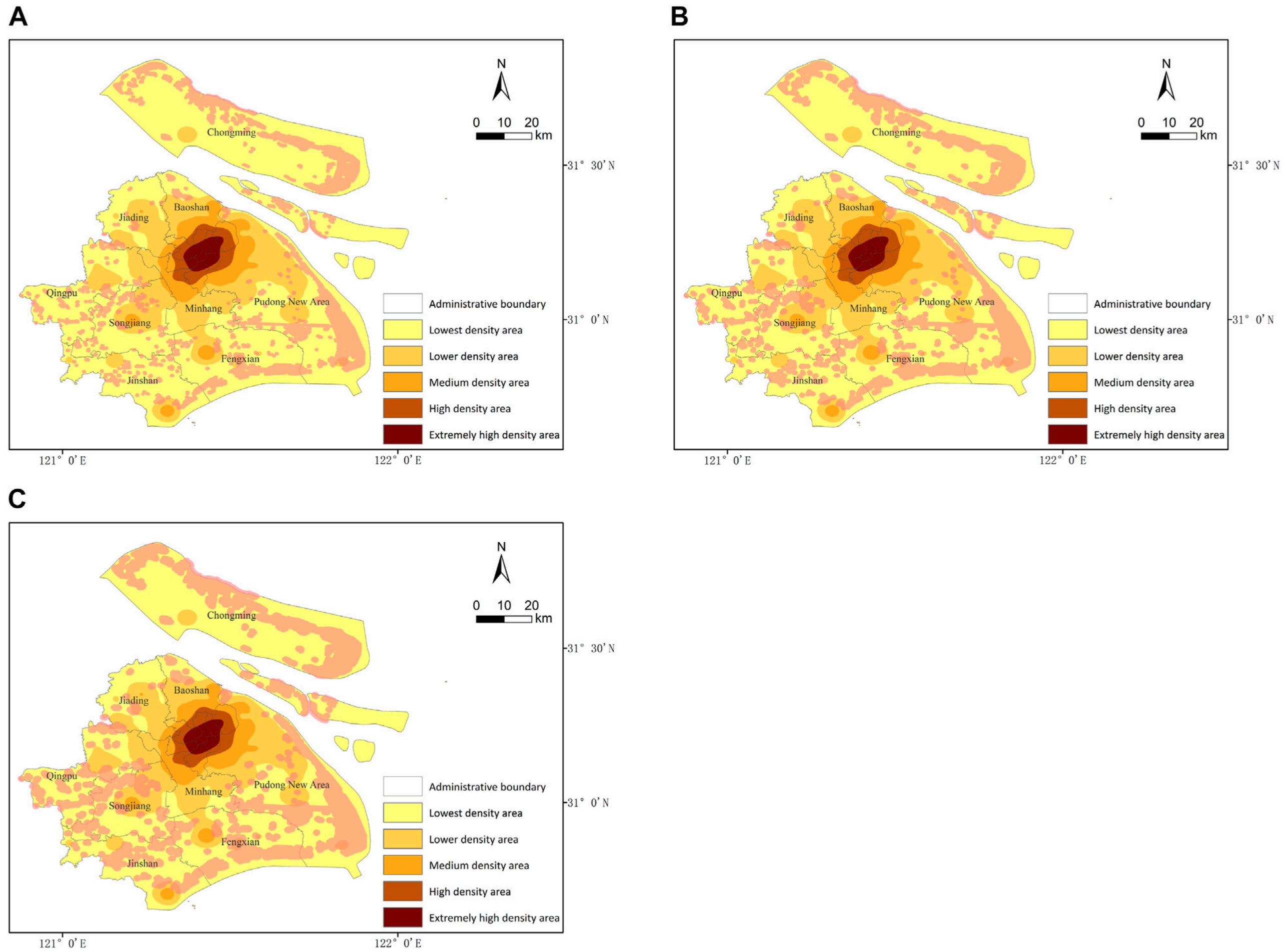

FIGURE 3 | Coverage of different radii ecological service areas of GSS. **(A)** 500 m, **(B)** 750 m, and **(C)** 1,000 m.

3.4 Analysis of Accessibility

3.4.1 Walking Mode

According to **Formula 3**, the accessibility evaluation results of public GSS in Shanghai in the walking mode are calculated, as shown in **Figure 4A**. According to the results, the walking accessibility of urban public GSSs presents a clear trend of agglomeration distribution with park GSS as the core. The areas with higher walking accessibility levels are mainly distributed in the surrounding area of urban public GSS and gradually expand outward with public GSS as the center, and the accessibility level decreases successively. The accessibility level in most peripheral areas tends to be zero. From the perspective of specific spatial distribution, the coverage for walking accessibility of public GSSs in Shanghai is extremely uneven. Based on network analysis, the overall walking accessibility of urban parks in each residential area is poor, with an average of 15.37 min. Among them, the residential area with the accessibility of over 30 min 1956) is the least, accounting for about 3.33% of the total residential area, and the residential area with the accessibility of less than 10 min (23,603) is the most, followed by those with accessibility between 10 and 20 min (22,180), accounting for 40.15 and 37.73%, respectively. From the spatial distribution, the accessibility of residential parks in the central level area of Shanghai presents a cobweb pattern. Although the surrounding large-scale comprehensive parks can guarantee service coverage, there is a lack of small parks as a supplement.

3.4.2 Cycling Mode

According to **Formula 4**, the accessibility evaluation results of public GSS in Shanghai in the cycling mode are shown in **Figure 4B**. Compared with the results of walking accessibility, the level of cycling accessibility in public GSS has significantly improved, and the distribution of high accessibility areas is irregular and diffuse. Compared with the results of walking accessibility, the riding accessibility level of public GSS has significantly improved, and the distribution of high accessibility areas is irregular and diffuse. Due to the high commuting efficiency of the cycling mode, the coverage of the high-value cycling accessibility area is much bigger than that of

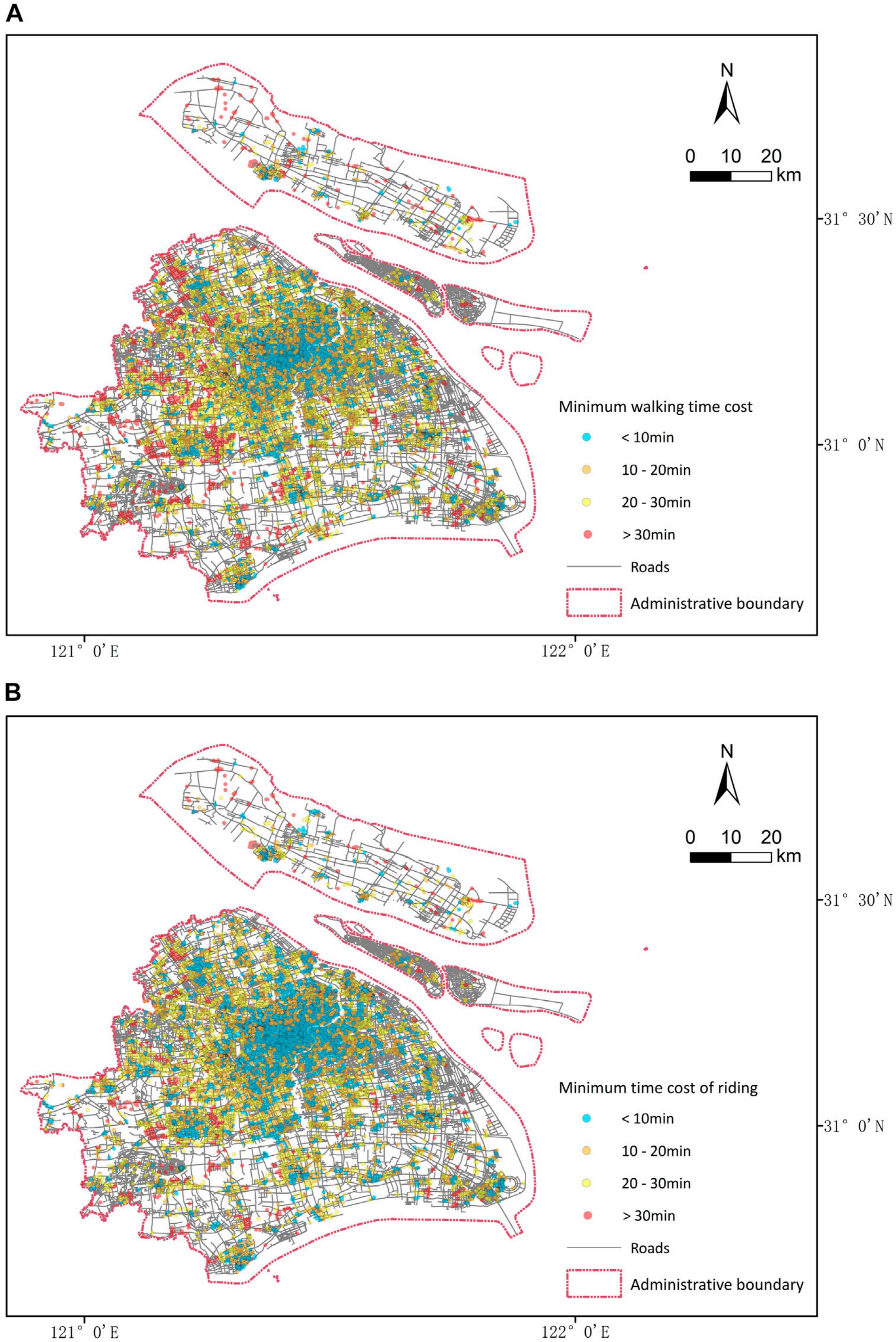

FIGURE 4 | Accessibility in residential areas. **(A)** walking mode and **(B)** cycling mode.

the walking accessibility area. Based on the network analysis method, the accessibility level of parks in each residential area in the cycling mode is obtained. Also, the overall accessibility is relatively high, with an average of 13.41 min. Among them, the residential communities with accessibility less than 10 min (32,962) accounted for 56.07% of the total residential communities, followed by the residential communities with the accessibility less than 10–20 min (32.63%), and the residential communities with accessibility greater than 30 min were rare.

4 CONCLUSION

From the view of orientation, the GSS in Shanghai is characterized by more in the north and less in the south, more in the east, and less in the west. The central area has a higher density of points of interest than the surrounding areas in the four directions of east, west, south, and north, showing a trend of central agglomeration.

The areas with extremely high and high production and living densities are mainly distributed in downtown Shanghai, which includes the south of Hongkou District, Jing'an District, the east of Changning District, and the northeast of Xuhui District. Polarization of the GSS distribution area and the high heat of points of interest can be seen.

When the service radius of the urban GSS in Shanghai is 500 m, 750 m, and 1,000 m, the GSS ecological service area can reach 2089.08, 3164.6^2, and 4469.75 km^2, covering 26.17%, 39.64%, and 55.99% of the total area, respectively.

As shown in the accessibility evaluation results of public GSS in Shanghai in the walking mode, the coverage for walking accessibility of public GSSs in Shanghai is extremely uneven. Based on the network analysis, the overall accessibility of urban parks under the walking mode in each residential district fails to meet the standard of a 15-min living circle, with an average of 15.37 min.

As shown in the accessibility evaluation results of public GSS in Shanghai in the cycling mode, compared with the results of walking accessibility, the level of cycling accessibility in public GSS has significantly improved, and the distribution of high accessibility areas is irregular and diffuse. Based on the network analysis method, the accessibility level of parks in each residential area in the cycling mode is obtained, and the overall accessibility is relatively high, with an average of fewer than 15 min.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by TQ and DZ. The first draft of the manuscript was written by TQ and WL, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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BRIEF RESEARCH REPORT
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A Pilot Assessment of New Energy Usage Behaviors: The Impacts of Environmental Accident, Cognitions, and New Energy Policies

*Jing Zhang and Weilun Huang**

School of Finance and Trade, Wenzhou Business College, Wenzhou, China

Literature reviews and interviews with experts showed that new energy would be the future way of life instead of traditional energy. In this study, a questionnaire survey and SPSS model are used to examine the impacts on people's new energy usage behavior (NEUB) by its cognitions of energy-related environmental accidents (CEREA) and new energy policies (CNEP), as well as other important factors affecting this behavior. The new energy usage behavior examines people's new energy usage behavior of product usage ($NEUB_{PU}$) and forecasted payment ($NEUB_{FP}$). Among the influencing factors, people's cognitions of energy-related environmental accidents (CEREA), people's cognitions of new energy policies (CNEP), new energy characteristics (CNEC), new energy advantages (CNEA), and new energy disadvantages (CNED) are examined, and the influence of personal factors on NEUB is also examined. People's new energy usage behavior of new energy stove ($NEUB_{NES}$), new energy car ($NEUB_{NEC}$), and $NEUB_{FP}$ are significantly positively correlated with CNEP; $NEUB_{NEC}$ is significantly positively correlated with CNEA, and $NEUB_{FP}$ is significantly positively correlated with CNEP and CNED. CNEC and CNEP significantly influence people's new energy usage behavior of household photovoltaic system ($NEUB_{HPS}$); CNEP significantly influences $NEUB_{NES}$; age, monthly income, CNEA, and CNEP significantly influence $NEUB_{NEC}$; age, monthly income, and CNEP significantly influence $NEUB_{FP}$.

Keywords: environmental accidents, new energy usage, cognitive behavior, policymaking, China

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Vishal Dagar,
Great Lakes Institute of Management, India

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Muhammad Imran Khan,
University of Agriculture, Pakistan
Muhammad Kamran Khan,
Bahria University, Pakistan

***Correspondence:**
Weilun Huang
drweilunhuang@126.com
huangwl@wzbc.edu.cn

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1 INTRODUCTION

The world is undergoing a transformation for a low-carbon future (Chishti et al., 2021; Oryani et al., 2021; Oryani et al., 2022). The United Nations Development Program (UNDP) classifies new energy into the following three categories: large and medium-sized hydropower; new renewable energy, including small hydropower, solar energy, wind energy, modern biomass energy, geothermal energy, and ocean energy (tidal energy); and penetrate biomass energy. More specifically, the transfer process of new energy includes primary and secondary energy, which is energy directly from nature and processed into electric energy. Among them, it is worth noting that although nuclear energy is one of the new energies, after the accident of the Fukushima Daiichi nuclear power plant, the government's initiative in the direction of nuclear energy research and development still plays an important role. The advantages and disadvantages of nuclear energy policies are correctly evaluated to gain the public's understanding and trust. Given a series of environmental accidents caused by

over-exploitation of traditional energy sources and the disastrous effects such as disease spread, in January 2006, China began to implement the *Renewable Energy Law of the People's Republic of China*, which showed the great significance of renewable energy for future social life, and pointed out a more precise direction for the future development of renewable energy and promoted the need of high-quality energy development. Most of the literature suggests that the new energy industry benefits the national economy by helping the development of the digital energy economy, improving environmental quality, and realizing sustainable energy development (Wang et al., 2021). In addition, the new energy industry has many characteristics of low carbon and environmental protection, which plays a positive role in the competitiveness, profitability, and enterprise performance of manufacturing enterprises. More specifically, the new energy industry can alleviate or even eliminate the tension between human behavior and the ecological environment by improving the utilization rate of energy resources, using low-carbon technology innovation, implementing green products, and controlling the cost of industrial waste treatment (Alvarado et al., 2018; Khan et al., 2021). With the green innovation characteristics of the new energy industry, it is helpful to help and consolidate the expectations of related enterprises in the overall competitiveness while improving profits and environmental performance (Bai et al., 2021). Not only that, but the new energy industry can also realize no pollutant discharge, which brings the energy social cost (health cost and climate cost) to zero, and at the same time reduces the demand for energy. In addition, creating long-term full-time jobs, realizing coordinated development of ecology and economy in power generation, and optimizing life cycle costs meet the needs of enterprises.

Our work collated the existing literature in China and found that there are a total of 577 articles on the new energy industry, and the research topics mainly belong to development research (or social research). The interests focused on the application and development of new energy. Among the articles published, 53% were on the new energy industry as the main theme. The second most frequent field is new energy, with 104 articles published, accounting for 19%. The main theme with the least publications is overcapacity, photovoltaic estate, and government subsidies, all accounting for 1.92%. Nonetheless, among these themes, few empirical studies have been conducted on the impact of environmental issues and policies on Chinese people's behavior toward new energy use, which shows that this theme is researchable. Wang et al. (2020) believed that the new energy policies implemented by the Chinese government have a significant positive impact on the "30–60" strategy based on the "five in one" perspective. Markard and Truffer (2006) indicated earlier that green power products involve many product fields, such as household photovoltaic systems and new energy cars. People can choose green power products voluntarily according to their preference for new energy. They can not only guide people to pay more attention to green consumption demand but also positively impact the promotion of new energy as one of the supplements of government energy policies (Chen and Zhang, 2021; Zhang et al., 2022). The present study found that the number of studies focusing on new energy policy increases over time. However, most studies focus on the relationship between new energy and low-carbon development (Xu et al., 2019; Chou et al., 2020; Su et al., 2022). Few studies focused on Chinese people's new energy usage behavior (NEUB) and not many studies discussed the impacts on Chinese NEUB by its cognitions of energy-related environmental accidents (CEREA) and people's cognitions of new energy policies (CNEP). For example, Caineng et al. (2021) pointed out that climate warming has become a global concern. Moving toward carbon neutrality is the consensus of human beings for green development, and new energy, as the main force of energy transformation, can effectively help low-carbon emissions. By using the financial statements of Chinese listed hydrogen-related companies from 2011 to 2019, Huang et al. (2021) analyzed the input-output relationship and found that location, equity owner, and equity concentration are significant factors can generate moderating effects on energy development Sun and Ren, (2021) discussed the relationship between energy consumption structure and carbon emissions by the SWI index and studied using the ARDL method that reducing coal consumption and expanding new energy investment can reduce carbon emissions. Sattler et al. (2018) analyzed the *Future Energy Employment Act of Illinois*, which showed that coal-fired power plants had a tremendous negative impact on public health. It was wise to accelerate the transition to clean energy resources. Although these studies acknowledged the importance of new energy but do not discuss the impact of existing renewable energy policies and environmental issues on Chinese people's new energy use behavior.

As a pilot study, the present study proposes the following research purposes:

1) Exploring the relationship between environmental accident cognition and people's new energy use behavior;
2) Exploring the relationship between new energy-related cognition and new energy use behavior;
3) Exploring the correlation between people's personal factors and people's new energy use behavior.

Based on the aforementioned research purposes, this study will achieve a preliminary understanding of which factors will promote and hinder people's new energy use behavior. First, based on the current energy situation, this study examines the driving factors of Chinese NEUB through the econometric model and provides targeted suggestions on energy policies and strategic ideas for future energy issues for the Chinese government in terms of industrial development. In addition, this study will help related enterprises to improve their management, speed up the adjustment of industrial structure, and then improve the level of new energy consumption. Second, although this study is based on the Chinese people's perspective, it has become a common challenge for humanity to cope with global climate change, and no one can be immune to the climate crisis. Therefore, from another angle, we try to help more people realize the significance of developing new energy in today's era, encourage and guide people to participate in the use of new

energy, and form green consumption to increase the promotion of new energy products.

2 METHODOLOGY

2.1 Descriptive Statistics

A questionnaire was designed to assess the impact of environmental accidents and new energy policies on people's new energy use behavior. The survey was carried out from 10 December 2021 to 12 February 2022 through a Chinese survey platform "Wenjuanxing". The final valid questionnaires were 373. The demographic description of respondents is as follows: (Alvarado et al., 2018): Gender: 54.69% male and 45.31% female (Bai et al., 2021); Age: the average is 40.07, the standard deviation is 10.51 (Caineng et al., 2021); Education: junior college or above accounted for 71%, senior high school or below accounted for 29% (Chen and Zhang, 2021); Region: 59% respondents were from urban area and 41% from non-urban; and Income: the average monthly income is RMB 8445.04, the standard deviation is 4,618.69.

The specific NEUBs surveyed were about people's new energy usage behavior of new energy stove ($NEUB_{NES}$), new energy car ($NEUB_{NEC}$), and household photovoltaic system ($NEUB_{HPS}$), the product usage ($NEUB_{PU}$), and forecasted payment ($NEUB_{FP}$) of these behaviors.

$NEUB_{PU}$ stands for people's new energy usage behavior of product usage, that is, respondents' preference for renewable energy products. The selected dimensions used to represent $NEUB_{PU}$ are as follows:

(1) $NEUB_{NES}$: $NEUB_{NES}$ refers to people's new energy usage behavior of new energy stove. It is expected that by 2050, domestic solar power generation will meet about 11% of global energy demand. This can address the energy access gap for those who are geographically restricted and have no or unreliable electrical service. However, among the types of green energy, the potential of solar energy in China is still unclear, which hinders the overall layout of energy planning to a certain extent, so it is worth further exploration. The public acceptance of household solar power generation was measured by asking participants whether they used solar water heaters, solar household lighting, and heating lamps.

(2) $NEUB_{NEC}$: $NEUB_{NEC}$ refers to people's new energy usage behavior of new energy car, that is, the acceptance of new energy vehicles under the new energy vehicle policy cognition. It was selected as the item to be measured because $NEUB_{NEC}$ shows great potential in reducing carbon emissions and pollution. Therefore, understanding the factors that affect the public's perception of $NEUB_{NEC}$ is crucial for the popularization of new energy vehicles. During the measurement, participants were asked whether the public would use new energy vehicles instead of traditional gasoline vehicles under the current preferential policies and tax incentives for new energy vehicles in China.

(3) $NEUB_{HPS}$: $NEUB_{HPS}$ is people's new energy usage behavior of household photovoltaic system, which means that people convert households to new combustion technologies with higher combustion efficiency and lower pollutant emissions, thereby replacing the use of traditional fuels. It was chosen as the item of measurement because the promotion of $NEUB_{HPS}$ offers a possible solution to achieve clean burning of residential solid fuels. During the measurement, participants were asked whether new energy fuel stoves were used as a substitute under the high emissions caused by traditional solid fuels.

$NEUB_{FP}$ represents people's new energy usage behavior of forecasted payment. It was selected as the measured item because when the public showed a positive attitude toward $NEUB_{FP}$, they were more concerned about the environment and more accepting of the low-carbon transformation of the energy structure. This can predict people's willingness to use renewable energy. The measurement was performed by asking participants how much they planned to pay for green energy products under the willingness-to-pay structure.

Based on causal logics, the NEUB is assumed here to be influenced by the CEREA, CNEP, CNEC, CNEA, and CNED. The items comprising these influencing factors which let participants show agreements were as follows: (Alvarado et al., 2018): CEREA agreed in the following order: the negative impact of climate change; increasing the demand for new energy (95.71%); China's "power cuts"; forming a low-carbon emission reduction consumption pattern (86.60%); and Japan's Fukushima nuclear accident, which affects the choice of new energy (49.59%) (Bai et al., 2021). CNEP agreed in the following order: providing preferential policies for new energy to the Chinese government, expanding the demand for new energy (92.23%), new energy policies promoted by the Chinese government (92.22%), and new energy promoted by the Chinese government (89%). CNEC agreed in the following order: technical level of products (65.68%), standards and specifications (65.68%), infrastructure construction (61.66%), and product pricing (45.58%). CNEA agreed in the following order: restoring environmental balance (67.02%), solving energy shortage (63.54%), lower cost (46.65%), and expanding employment (42.36%). CNED agreed in the following order: lack of core technology (44.50%), regional restriction (43.97%), immediacy (37.80%), and intermittence (37%).

2.2 Data Analysis

As the development of new energy is China's long-term development goal, the Chinese government and related enterprises need to understand the influencing factors of the NEUB. Therefore, this study uses a structural equation model to analyze the data and discusses the Chinese NEUB and the influence of various factors. Previous studies used the Tobit model, DID method, and panel data technology to explore the relationship between new energy and low-carbon development. However, no study used the binary Logistic model in SPSS to study Chinese NEUB by CEREA and CNEP. However, CNEP, CEREA, and social economy may influence NEUB. For example, Dagher and Harajli, (2015) used the Tobit model to analyze the relationship between Lebanese people's willingness-to-pay for new energy electricity and the social economy. Hossain et al. (2022) used the ARDL boundary test method to study the relationship between severe environmental problems caused by

TABLE 1 | Correlation between NEUB and its influencing factors.

		NEUB			
		$NEUB_{PU}$			$NEUB_{FP}$
		$NEUB_{HPS}$	$NEUB_{NES}$	$NEUB_{NEC}$	
Influencing factors	CEREA	0.00	–0.01	0.03	–0.09
	CNEP	0.10	0.12*	0.19***	0.20***
	CNEC	–0.06	–0.02	0.10	0.06
	CNEA	0.06	0.06	0.22***	–0.03
	CNED	0.02	0.03	0.09	–0.08

, **, *. The correlations are significant at 0.05, 0.01, and 0.001 levels (two-tailed).*

TABLE 2 | ANOVA analysis of NEUB on CEREA, CNEP, CNEC, CNEC, and CNED.

		NEUB			
		$NEUB_{PU}$			$NEUB_{FP}$
		$NEUB_{HPS}$	$NEUB_{NES}$	$NEUB_{NEC}$	
Influencing factors	CEREA	0.01	0.05	0.36	1.18
	CNEP	3.55	5.46*	13.31***	5.73***
	CNEC	1.15	0.15	3.50	1.64
	CNEA	1.23	1.50	18.08***	0.45
	CNED	0.130	0.26	3.18	3.33

, **, *. The correlations are significant at the 0.05, 0.01, and 0.001 levels (two-tailed).*

TABLE 3 | Independent sample *t*-test and ANOVA-check of gender, education, and region on NEUB.

		Gender (F(T))	Education (F(T))	Region (F(T))	Age (F)	Income (F)
NEUB	$NEUB_{HPS}$	4.27*(1.06)	3.77*(–1.36)	0.54 (–0.38)	0.52	0.43
	$NEUB_{NES}$	0.24 (0.24)	0.42 (–0.32)	0.02 (–0.07)	2.22	1.07
	$NEUB_{NEC}$	10.64***(–1.62)	1.37 (–0.56)	7.75**(–1.37)	1.57	2.30
	$NEUB_{FP}$	6.56**(–1.23)	4.76*(–0.97)	3.15 (–1.40)	2.53*	0.53
Influencing factors	CEREA	1.31 (3.68***)	0.00 (–0.07)	0.09 (–0.11**)	4.55**	1.46
	CNEP	0.77 (–1.32)	3.57*(–2.79**)	0.15 (–2.55**)	3.80**	1.07
	CNEC	2.06 (1.88)	4.39*(–1.37)	0.03 (–0.64)	1.44	1.07
	CNEA	0.30 (0.81)	4.05*(–0.86)	0.54 (–0.61)	0.85	4.66**
	CNED	0.59 (0.77)	6.37**(–2.14*)	0.00 (–0.93)	1.94	10.68***

, **, *. The correlations are significant at 0.05, 0.01, and 0.001 levels (two-tailed).*

chemical energy and the necessity of using new energy. Masrahi et al. (2021) used the research model of TPB to find the sensitivity of CNEP to the willingness to use new energy was significantly positively correlated. In a word, previous studies often used the ARDL method to explore the relationship between variables. To sum up, we used the likelihood ratio test, the most commonly used binary logistic regression model, to evaluate Chinese NEUB. The form of binary Logistic regression is as follows: $p = \frac{e^{\beta_0+\beta_1 x_1+\ldots\ldots+\beta_k x_k}}{1+e^{\beta_0+\beta_1 x_1+\ldots\ldots+\beta_k x}}$.

Among them, p is the probability of Chinese NEUB; x_1, x_2,. . ., x_k are the influencing factors; β_0, β_1,. . ., β_k are the regression coefficients; k is the number of samples; and β_0, β_1,. . ., β_k indicates x_1, x_2,. . ., x_k influence on Chinese NEUB. This can be regarded as the linear regression of p to k variables, and $0 \leqslant p \leqslant 1$. We can establish binary logistic regression models according to the differences between independent and dependent variables. The dependent variable replaces the value of p, the value of x_k (k = 1, 2, . . . m) is replaced by the independent variable, and the regression coefficient β_k (k = 0, 1, 2, . . . m) can be calculated the linear regression function through statistical software. This study collates CEREA, CNEP, CNEC, CNEA, and CNED. As shown in **Table 1**, the $NEUB_{NEC}$, and $NEUB_{FP}$ are significantly positively correlated with CNEP and $NEUB_{NEC}$ is significantly positively correlated with CNEA.

ANOVA analysis results of $NEUB_{PU}$ and $NEUB_{FP}$ of Chinese on CEREA, CNEP, CNEC, CNEA and CNED are shown in **Table 2**. $NEUB_{NES}$, $NEUB_{NEC}$ and $NEUB_{FP}$ are significantly positively correlated with CNEP, $NEUB_{NEC}$ is significantly positively correlated with CNEA and $NEUB_{FP}$ is only significantly positively correlated with CNEP.

In order to analyze the results of the questionnaire more profoundly, this article explores the impact of gender, age, education, region, and monthly income on CEREA, CNEP, CNEC, CNEA, and CNED. As shown from **Table 3**, gender

has a significant impact on the $NEUB_{HPS}$, $NEUB_{NEC}$, $NEUB_{FP}$, and CEREA; education has a significant impact on the $NEUB_{HPS}$, $NEUB_{FP}$, CNEP, CNEC, CNEA, and CNED; and the region has a significant impact on the $NEUB_{NEC}$, CEREA, and CNEP. As shown from **Table 3**, age has a significant impact on the CNEA, $NEUB_{HPS}$, and CNED and income has a significant impact on the $NEUB_{NEC}$ and $NEUB_{FP}$.

According to the regression analysis results of the $NEUB_{FP}$, the multiple of R is the correlation coefficient R between the independent variable X and the explanatory variable Y, which is 0.38, which is a low correlation. The R-squared indicates that the correlation coefficient R^2 between the independent variable X and the explanatory variable Y, which is 0.14, indicating a low degree of fit. The adjusted R^2 is 0.12, indicating a low fit. The standard error is 2,676.60, indicating a high degree of it. The ANOVA focuses on the p-value of Significance F, p = 0.000. Therefore, this statistical test is considered significant.

A binary logistic regression analysis of $NEUB_{HPS}$ was conducted. In the case handling summary, 373 cases are selected, and 0 cases are not selected. This result is obtained according to the set validate = 1. In the dependent variable coding, it can be seen that the values of "yes" or "no" of "$NEUB_{HPS}$" are 1 and 0, respectively. In the "Classification Table", it is predicted that there are 159 "No" (not $NEUB_{HPS}$) and 214 "Yes" ($NEUB_{HPS}$); In "Variables in the equation", the memory of "constant term" was initially assigned, with B being 0.297 and standard error being 0.105, then Wald = (B/S.E) = (0.297/0.105) = 8.0008, which is almost close to "8.0505" in the table because B and Exp(B) are logarithmic relations. After the logarithmic transformation of B, we can get Exp (B) = e + 0.297 = 1.346, in which the degree of freedom is one and sig is 0.005, which is very significant.

A binary logistic regression analysis of $NEUB_{NES}$ was conducted. In the case handling summary, 373 cases were selected, and 0 cases were not selected. This result was obtained according to the set validate = 1. In the dependent variable coding, it can be seen that the values of "yes" or "no" of "$NEUB_{NES}$" are 1 and 0, respectively. In the "Classification Table", it is predicted that there are 265 "No" (not $NEUB_{NES}$) and 108 "Yes" ($NEUB_{NES}$); In "Variables in Equation", the memory of "constant term" is initially assigned, with B being −0.898 and standard error being 0.114, then Wald = (B/S.E) = (−0.898/0.114) = 62.0502, which is the same as "61.8194" in table. B and Exp(B) are logarithmic relations. After the logarithmic transformation of B, we can get Exp (B) = e −0.898 = 0.408, in which the degree of freedom is one and sig is 0.000, which is very significant.

A binary logistic regression analysis of $NEUB_{NEC}$ was conducted. In the case handling summary, 373 cases were selected, and 0 were not selected. This result is obtained according to the set validate = 1. In the dependent variable coding, it can be seen that the values of "yes" or "no" of "$NEUB_{NEC}$" are 1 and 0, respectively. In the "Classification Table", it is predicted that there are 251 "No" (not $NEUB_{NEC}$) and 122 "Yes" ($NEUB_{NEC}$); In "Variables in Equation", the memory of "constant term" is initially assigned, with B being −0.721 and standard error being 0.110, then Wald = (B/S.E) = (−0.721/0.110) = 42.9621, which is the same as "42.7282" in table. B and Exp(B) are logarithmic relations. After the logarithmic transformation of B, we can get Exp (b) = e −0.721 = 0.486, in which the degree of freedom is one, and the sig is 0.000, which is very significant.

TABLE 4 | Regression coefficients analysis of $NEUB_{HPS}$, $NEUB_{NES}$, $NEUB_{NEC}$, and $NEUB_{FP}$.

	$NEUB_{HPS}$	$NEUB_{NES}$	$NEUB_{NEC}$	$NEUB_{FP}$
Intercept	0.50	−2.49*	−5.04***	1780.89
Gender	−0.31	−0.13	0.32	13.28
Age	−0.02	0.02	−0.03*	26.50*
Education	0.31	0.06	−0.11	115.07
Region	0.09	−0.01	0.06	−115.00
Income	$3.50*10^{-5}$	$-1.77*10^{-5}$*	$6.64*10^{-5}$**	0.17***
CNEC	−0.12*	−0.10	−0.07	74.33
CNEA	0.10*	0.07	0.23***	−76.08
CNED	0.01	0.02	−0.02	−84.50
CEREA	−0.03	−0.05	0.12	−169.59
CNEP	0.16*	0.20*	0.30***	388.77***

*, **, ***. The correlations are significant at 0.05, 0.01, and 0.001 levels (two-tailed).

According to **Table 4**, the regression coefficients of $NEUB_{HPS}$, $NEUB_{NES}$, $NEUB_{NEC}$, and $NEUB_{FP}$. This means that the regression equation of $NEUB_{HPS}$ is

$$NEUB_{HPS} = -0.12 * \text{CNEC} + 0.10 * \text{CNEA} + 0.16 * \text{CNEP} + \mu. \quad (1)$$

According to Alvarado et al. (2018), people's $NEUB_{HPS}$ can be zero, and the significant factors of the people's $NEUB_{HPS}$ are its CNEC and CNEP.

$$NEUB_{NES} = -2.49 \; - \; * \text{Income} + 0.20 * \text{CNEP} + \mu. \quad (2)$$

According to Bai et al. (2021), people's $NEUB_{NES}$ is significantly greater than zero, and the significant factor of people's $NEUB_{NES}$ is its CNEP.

$$NEUB_{NEC} = -5.04 - 0.03 * \text{Age} + * \text{Income} + 0.23 * \text{CNEA} \\ - + 0.30 * \text{CNEP} + \mu. \quad (3)$$

According to Caineng et al. (2021), people's $NEUB_{NEC}$ is significantly greater than zero., and the significant factor of people's $NEUB_{NEC}$ are its age, income, CNEA, and CNEP.

$$NEU_{BFP} = 26.50 * \text{Age} \; + 0.17 * \text{Income} + 388.77 * \text{CNEP} + \mu. \quad (4)$$

According to Chen and Zhang (2021), people's $NEUB_{FP}$ can be zero, and the significant factors of people's $NEUB_{FP}$ are its age, income, and CNEP.

3 CONCLUSION

Energy is a necessity for the survival and development of human society. In the era of high-quality growth, the new energy industry has become the commanding point of a new round of global economic development. Although the Chinese government has made fruitful work in the development of the new energy industry, the investment in domestic new energy needs to be strengthened. In addition, the Chinese people's cognitions of new energy are still partial, and related Chinese enterprises still lack key standard technologies in the "energy transformation". The purpose of this study is to explore the impacts on NEUB ($NEUB_{PU}$ and $NEUB_{FP}$) by its CEREA and CNEP, and other influencing factors (CNEC, CNEA, and CNED).

This study uses multiple regression models and ANOVA analysis to explore and analyses the impacts on NEUB by its CEREA and CNEP.

3.1 People's New Energy Usage Behaviors

According to the statistical results of the questionnaire analysis in this article, we found that the majority of people have some knowledge of the new energy industry, with male consumers dominating, accounting for 54.69%. In addition, 40% of people have a per capita monthly income below 5,000 yuan. In the $NEUB_{PU}$, $NEUB_{HPS}$ accounts for 57.37%, $NEUB_{NEC}$ accounts for 33.24%, and $NEUB_{NES}$ accounts for 28.69%, and 38.61% people are willing to spend less than RMB 2,500.

3.2 Factors Influencing the New Energy Usage Behavior

$NEUB_{NES}$, $NEUB_{NEC}$, and $NEUB_{FP}$ are significantly positively correlated with the CNEP, and $NEUB_{NEC}$ is significantly positively correlated with the CNEA. Furthermore, CNEC and CNEP significantly influence the $NEUB_{HPS}$; CNEP significantly influences the $NEUB_{NES}$; age, monthly income, CNEA, and CNEP significantly influence the $NEUB_{NEC}$; and age, monthly income, and CNEP significantly influence the $NEUB_{FP}$.

3.2.1 Optimize the Characteristics of New Energy Products

The government and related enterprises should provide targeted new energy products and services for people of different age groups and consumption needs, implement consumption subsidy measures, and find the combination point of comprehensively coping with the energy crisis and improving people's living standards. In terms of pricing, this study suggests that the government should implement the pricing in different wind resource areas in the on-grid tariff of wind power. The overall adjustment standard of photovoltaic power generation pricing is unreasonable. The pricing of biomass energy should be adjusted with time, market, and production conditions of enterprises so that supply and demand can play a full role.

3.2.2 Government has Increased the Support of New Energy Sources

Cultivating emerging industries is the key to coping with future competition and realize long-term development. Therefore, this study suggests that financial departments should innovate economic policies, further increase investment in new energy sources and emerging industries of energy conservation and environmental protection, especially the intensity of financial subsidies for new energy utilization enterprises, improve the implementation of preferential tax policies, and flexibly formulate different tax preferential forms, such as tax reduction and the exemption for critical materials used in manufacturing large-scale new energy resources, to support related enterprises to strengthen research and development and promote energy transformation.

3.2.3 Government Pays Special Attention to Publicity, Education, and Public Opinion Guidance

Environmental protection departments can use popular software, advertising, sending smart short messages, community propaganda, and other forms to popularize new energy culture knowledge to the public, actively guide people's behaviors of using new energy by policies, and establish people's concept of energy-saving life. In addition, teenagers are the main force of modern construction. While carrying out publicity and education on new energy culture for the whole people, we should focus on strengthening teenagers' education and jointly building the road of sustainable energy development in China.

3.2.4 Give Full Play to the Advantages of the New Energy Industry

Given the weak competitiveness of China's new energy market at present, relevant enterprises should make clear the critical strategic direction, take solving energy shortage and maintaining ecological balance as their responsibility, vigorously research and promote leading international technologies of new energy with the support of the government, and take the road of sustainable low-carbon development.

3.2.5 Strengthen the Environmental Awareness of the Government and People

There is a close relationship between environmental accidents and new energy use. According to our investigation, environmental accidents have not significantly affected Chinese people's new energy use behaviors. However, past research shows that environmental accidents are an unavoidable and important problem in the world, and the core of new energy is low carbon. Therefore, this study suggests that the government should intervene in environmental protection, focus on strengthening the control of environmental accidents, formulate energy development plans according to local conditions, guide and strengthen people's environmental awareness and energy awareness, and make environmental awareness universal.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethics review and approval/written informed consent were not required as per local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by JZ. The first draft of the manuscript was written by WH, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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EDITED BY
Fakhri J. Hasanov,
King Abdullah Petroleum Studies and Research Center (KAPSARC), Saudi Arabia

REVIEWED BY
Daniel Balsalobre-Lorente,
University of Castilla-La Mancha, Spain
Wasim Iqbal,
Shenzhen University, China
Qiang Wang,
China University of Petroleum, Beijing, China
Majed Alharthi,
King Abdulaziz University, Saudi Arabia

*CORRESPONDENCE
Gangyi Wang,
awgy@cau.edu.cn
Muhammad Irfan,
irfansahar@bit.edu.cn
Desheng Wu,
dwu@ucas.ac.cn
Jianhong Cao,
xiatiandeguoguo@gmail.com

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The effect of green finance and unemployment rate on carbon emissions in china

Yiniu Cui[1], Gangyi Wang[2]*, Muhammad Irfan[3,4,5]*, Desheng Wu[6]* and Jianhong Cao[7]*

[1]School of Economics, Yunnan University, Kunming, China, [2]School of Economics and Management, Northeast Agricultural University, Harbin, China, [3]School of Management and Economics, Beijing Institute of Technology, Beijing, China, [4]Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing, China, [5]Faculty of Management Science, Department of Business Administration, ILMA University, Karachi, Pakistan, [6]School of Economics and Management, University of Chinese Academy of Sciences, Beijing, China, [7]School of Business and Economics, University Putra Malaysia, Selangor, Malaysia

China's economy has developed rapidly since the reform and opening up, but under the long-term traditional extensive development model, energy consumption is excessive and carbon emissions rank first in the world. Therefore, how to reduce carbon emissions is a current hot issue in China. Although many scholars have found that green finance is the basic driving force to promote carbon emission reduction, its role path is diverse, and it still needs to be explored in width and depth. Especially in the green transformation stage of the economy, the potential unemployment risk is also a matter of concern. This study selects 30 provincial panel data from the Chinese mainland for the 2004–2019 years to investigate the impact of green finance on carbon emissions from the perspective of unemployment using ordinary least square (OLS), generalized method of moments (GMM), and mediating effect models. In addition, in order to avoid the bias of regression results caused by the cross-section dependence of the data, the feasible generalized least squares (FGLS) and the panel-corrected standard errors (PCSE) models are used for the robust test after correction. The findings show that 1) green finance has a significant inhibitory impact on carbon emissions; 2) green finance has significantly reduced the unemployment rate; 3) carbon emissions increase significantly with increasing the unemployment rate; and 4) there is regional heterogeneity in the effect of green finance on carbon emissions in eastern, central, and western China. Green finance in the eastern and central regions significantly inhibits carbon emissions, especially in the central region, while insignificantly in the western region. 5) According to the OLS and mediating effect regression results, economic growth and environmental regulation play a significant positive role in promoting carbon emissions. This study has theoretical reference significance for accelerating the realization of the dual carbon goal and alleviating phased unemployment.

KEYWORDS

mediating effect, regional heterogeneity, peak carbon emissions, green finance, the unemployment rate

1 Introduction

From the international context, in recent years, global attention to climate change has continued to increase (Anser et al., 2020a; Alharthi et al., 2021; Hua et al., 2022). To reduce global greenhouse gas emissions, countries around the world have carried out a series of measures to deal with climate change (Yang et al., 2021a; Balsalobre-Lorente et al., 2022; Usman et al., 2022). Through unremitting endeavors lately, China has largely accomplished the Millennium Development Goals and became the world's second-biggest economy and the top exporter (Zhao et al., 2020; Irfan et al., 2021a; Koondhar et al., 2021; Zhao et al., 2021). To better cope with climate deterioration and assume the responsibility of great powers, the Chinese government affirms at the 70th United Nations General Assembly and Climate Summit to improve the 2015 Paris Agreement's carbon reduction goals (Abbasi et al., 2022). Specifically, gross carbon emissions will peak in 2030 and achieve carbon neutrality in 2060 (Wu et al., 2020; Ren et al., 2021; Shen et al., 2022). While China affirms that carbon emissions will peak by 2030 is not surprising, the commitment to carbon neutrality is unexpected (Iqbal et al., 2021; Wen et al., 2022). Since China has far less time to achieve carbon neutrality and peak carbon emissions than developed countries, its economy, and energy mix need to adjust to low-carbon and decarbonization depth with unprecedented intensity (Al et al., 2019; Iqbal et al., 2019a; Khan et al., 2021; Rauf et al., 2021), thus facilitating an orderly peaking of carbon emissions across regions, sectors, and industries (Wu H. et al., 2019; Hao et al., 2020). Also, the achievement of carbon neutralization and peak carbon emission goals require a large amount of investment (Tang et al., 2022; Xiang et al., 2022). It is urgent to accelerate the construction of green finance and the national carbon emission trading market, guide the rational allocation of resources, leverage resources to lean toward green and low-carbon projects, and promote green and low-carbon development (Razzaq et al., 2021a; Qiu et al., 2021).

From the domestic environment, green finance is a wide conception (Ahmad et al., 2021; Ali et al., 2021). According to the definition in the Guidance on Building a Green Financial System issued by the Chinese government in 2016, green finance refers to economic activities that support environmental improvement, climate change, and the economical and efficient use of resources, that is, financial services providers for project investment and financing, project operation and risk management in the fields of environmental protection, energy conservation, clean energy, green transportation (Irfan and Ahmad, 2021), and green buildings (Jiang et al., 2020). Green finance not only involves investment and financing support services for various types of green projects such as clean energy and green materials, but also refers to financial services such as green credit, green bonds, green industry investment, green development funds, green insurance, and other financial services that support the transformation of the economy to green development (Taghizadeh-Hesary and Yoshino, 2019; Sun, 2021; Meo and Abd, 2022). As an emerging financial model, green finance provides powerful financial tools to support carbon emission reduction with the continuous enrichment and improvement of its product connotation and business types (Taghizadeh-Hesary and Yoshino, 2019; Hafner et al., 2020; Razzaq et al., 2020). Green finance is not only significant support for green enterprises through providing funds but can also significantly improve energy efficiency and ultimately achieve the vision of "carbon neutralization and peak carbon emissions" (Hou et al., 2019; Iqbal et al., 2019b; Shen et al., 2021). According to relevant calculations, China needs a huge amount of green financial investment of more than 100 billion yuan to achieve the goal of "carbon neutrality and peak carbon emissions". In addition to government funds, most of them need to be market-oriented to guide and encourage social capital through financial system investment and financing (Hao et al., 2021; Razzaq et al., 2021b; Ren et al., 2022b).

Green finance, with green credit, green securities, green assets, and green protection as the principle apparatuses, has grown quickly (Chandio et al., 2021; Tanveer et al., 2021; Fang et al., 2022). The "green capital" has extended its help for green ventures and sped up the green change of energy structure and modern construction (Irfan et al., 2021b). In this process, green finance indirectly affects carbon emissions by affecting the unemployment rate. With the green transformation of China's economy, some traditional polluting industries are bound to face structural upgrading (Zhu et al., 2014; Ren et al., 2022c). However, in the process of transformation from an extensive industry to a high-tech industry, a large number of low-level labor force members, including those in such enterprises, face the risk of unemployment (Sima et al., 2020). In addition, the traditional polluting enterprises are affected by the crowding-out effect in the development process of green finance, and their financing environment is squeezed, which may increase the unemployment rate due to the shortage of funds (Razzaq et al., 2021a; Ren et al., 2022a; Shi et al., 2022). However, green finance can further influence the allocation of resources and urge enterprises to invest more funds to cultivate green, scientific, and technological talents, to reduce the unemployment rate. In addition, green finance will inevitably drive the flow of talents under the influence of the financial spillover effect, to transport the labor force eliminated by traditional polluting enterprises to the green production sector (Dao et al., 2011; Hao et al., 2021). It is also worth noting that green finance would promote the increase of green entrepreneurship projects and create more jobs (Silajdžić et al., 2015). Therefore, in the green transformation stage of the economy, green finance contributes to reducing the unemployment rate and improving the employment rate. Meanwhile, the reduction of the unemployment rate is of great significance to carbon emission reduction (Islam et al., 2021). As mentioned above, green finance provides financial support for the improvement of labor quality

in the process of green transformation of traditional polluting enterprises through resource allocation, thus influencing the unemployment rate (Zhou et al., 2022). In addition, green finance also provides material conditions for the market labor force to flow from polluting enterprises to green production departments. This transfer of the labor force not only reduces the unemployment rate but also promotes the upgrading of industrial structures and green economic transformation, thus influencing carbon emissions (Wang and Li, 2021). Therefore, the decline in the unemployment rate is closely related to the increase in green talent and carbon emissions. However, few scholars currently conduct empirical research on the above issues. So what are the specific impacts of green finance and the unemployment rate on carbon emissions? This study has theoretical and practical significance and puts green finance, unemployment rate, and carbon emissions into a unified research framework for empirical research for the first time, which enriches the current basic research theory of carbon emissions. In addition, this study provides a new research path for carbon emission reduction and speeds up the realization of the dual carbon goal.

The contributions of this study are as follows: Firstly, it investigates the dynamic effect of green finance on carbon emissions, which enriches the existing literature for China to accelerate the realization of the double carbon goal and serves as some reference for developing economies similar to China to achieve their carbon reduction goals. Secondly, compared with previous scholars who studied the impact of green finance on carbon emissions from the perspective of industrial structure and technological innovation, this study examines the impact of green finance on carbon emissions by taking the unemployment rate as a mediating variable, complementing the existing research on green finance and carbon emissions. Finally, this study also conducts a regional heterogeneity in the effects of green finance and unemployment on carbon emissions, which formulate relevant policies depending on local differences in each area.

The structure of this study is organized as follows: Section 2 reviews the literature and research hypothesis; Section 3 gives the methodology and data; Section 4 proceeds with results analysis; and Section 5 summarizes the entire text and made important recommendations.

2 Literature review and research hypothesis

2.1 Green finance and carbon emissions

Financial development is an important indicator affecting carbon emissions (Shahbaz et al., 2013; Acheampong et al., 2020; Shahbaz et al., 2020). Some scholars have found that financial development could promote carbon emissions (Zhang et al., 2020). From the perspectives of the stock market, energy consumption, economic growth, and political system, these scholars use time series, spatial measurement, and other methods to prove that financial development can promote carbon emissions (Iqbal et al., 2020). Zhang et al. (2011) observe that monetary advancement was not just the primary justification for the increment in carbon emissions, yet in addition, different monetary improvement markers diversely affect carbon emissions. Among them, the effect of the financial mediating scale on carbon emissions is more noteworthy than other financial advancement pointers, for example, financial mediating effectiveness, securities exchange scale, and productivity. Adams and Klobodu (2018) added political elements to the investigation and discovered that financial improvement was the key component prompting the expansion of carbon emissions. Shen et al. (2020) support that a created financial system can diminish data deviation and make it more straightforward for organizations to fund. This will help enterprises expand production scale and lead to an increase in carbon emissions. Chen and Zhang (2014) find that the improvement of financial scale and efficiency would significantly improve the level of carbon emissions by using the spatial econometric model. Boutabba (2014) utilizes the time-series information from 1971 to 2008 to concentrate on the connection between carbon emissions, financial development, exchange receptiveness, and energy utilization. It is observed that finance improvement emphatically affected per capita carbon emissions.

However, different researchers argue that green finance has a conspicuous inhibitory impact on carbon emissions. Researchers who support this hypothesis have demonstrated that green finance has a huge inhibitory impact on carbon emissions through spatial panel models. Liu et al. (2015) find that the green credit policy will significantly reduce the production emissions of energy-intensive industries in the short and medium-term through the transmission path of green credit. He (2019) constructed a VAR model by estimating four components: green credit, green conservation, green protection, and green entrepreneurship, and observed that the development of green finance would radically reduce the level of national CO_2 emissions and promote sustainable economic development. Shao and Fang (2021) built an exhaustive record of green finance development through the entropy weight technique, and at this point not considered single factors, for example, green credit, protections, and venture, alone to make the general development of green finance more intuitive. Based on this, the following hypothesis is proposed in this study.

Hypothesis 1. Green finance has a significant inhibitory effect on carbon emissions.

2.2 Green finance and unemployment rate

In the green transformation stage of China's economy, green finance is closely related to employment. Finance could not only

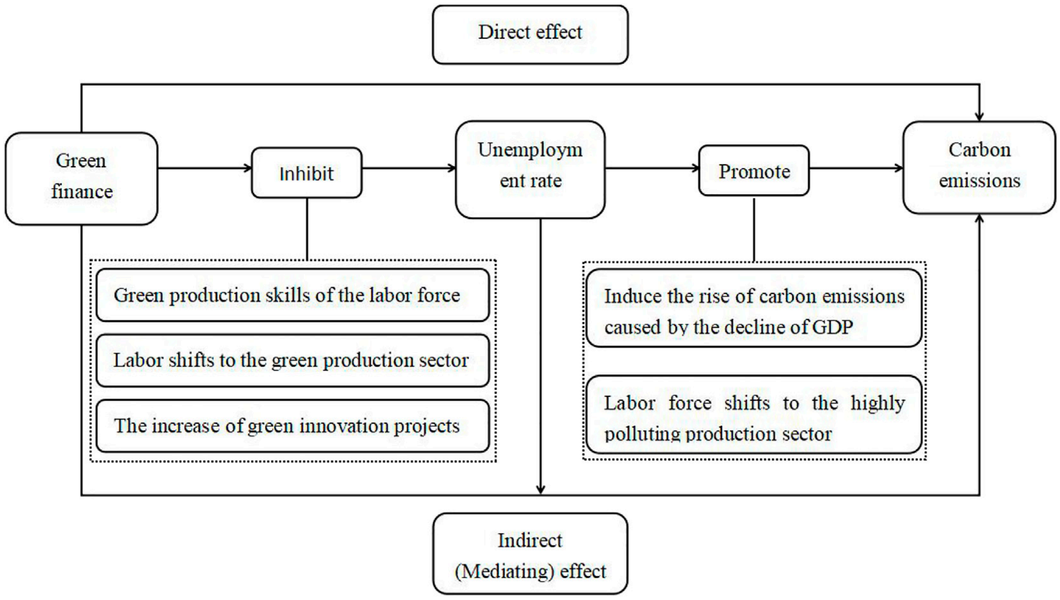

FIGURE 1
Role mechanism diagram.

support the labor–capital investment of enterprises and reduce the risk of unemployment but also promote labor market liquidity through the spillover effect. Since the unemployment rate is an indicator to measure the employment situation of a country, to more intuitively clarify the relationship between green finance and the unemployment rate. Ndubuaku et al. (2021) utilize the ARDL model and annualized time-series information from 1999 to 2019 to research the effect of financial development on the employment rate in Nigeria. The result shows that financial development altogether affects the employment rate. Alkhateeb et al. (2017) used the ARDL cointegration method to investigate the relationship between finance and employment in Saudi Arabia from 1980 to 2015. They found that financial development could assume an important part in economic development and occupation creation. Yang et al. (2015) revealed that the expansion of financial development scale restrained the employment of the primary and secondary industries, however, advanced the employment of the tertiary business and the improvement of financial productivity assumes a positive part in advancing the employment of the tertiary business. Besides, as macro-economic policies such as green finance are limited to green and low-carbon industries, China will create a large number of jobs in the future and promote the transformation of employment into technology-biased and environment-friendly jobs. At the same time, green finance provides financial support for the improvement of labor quality to adapt to the green economy model, which reduces the cost of the unemployment rate and other costs in the process of economic green transformation, and promotes the decline of the unemployment rate (Sun, 2021). In addition, the resource allocation function and spillover effect of green finance will optimize the distribution structure of the labor force in the market, promote the transfer of more labor force from the polluting production sector to the cleaner production sector, reduce the risk of some labor force, and thus hinder the rise of the unemployment rate. Lee (2020) believed that green finance could alleviate employment pressure and provide the impetus for economic development. Khobai et al. (2020) revealed that clean energy investment has improved the employment level in the long term, and has little impact on employment in the short term. He (2017) agreed that clean energy has increased the national employment and the employment of the clean energy industry, but it has a negative impact on the employment of the traditional energy industry. Therefore, the development of green and clean energy played a strong role in promoting green employment, while reducing carbon emissions. Based on this, the following hypothesis is proposed in this study.

Hypothesis 2. Green finance has a significant inhibitory effect on the unemployment rate.

2.3 Unemployment rate and carbon emissions

In the green transformation stage of the economy, it is inevitably accompanied by the transformation from high energy-consuming industries to green and clean energy

industries, and from traditional industries to green and low-carbon industries (Steward, 2012). In this process, the labor force will also undergo structural transfer between industries and industries; that is, the labor force will transfer from traditional industry, high energy, and high consumption industries to green and low-carbon industries. Green finance squeezes financial resources from the polluting production sector to the green production sector, while the labor force will also flow accompanied by financial resources (Wang, 2020). This kind of labor mobility can reduce the impact of economic transformation on the unemployment rate, to reduce it. In addition, green finance also promotes the green transformation of the labor force, cultivates more green talents, and alleviates the impact of economic green reform on employment stability. Meanwhile, a large number of green start-ups have sprouted with the support of green finance, and then more social unemployed people are absorbed by green environmental protection production enterprises, thus improving the reemployment rate of social unemployed people (Henzelmann et al., 2011). Therefore, in the context of "carbon neutralization and peak carbon emissions" goals, part of the reasons for the decline of the unemployment rate have to be attributed to the improvement of green production skills of the labor force, the structural transfer of labor force, and the increase of green innovation projects, which are closely related to carbon emissions. George et al. (2012) pointed out that large-scale development of electricity has a positive effect on reducing unemployment in Nigeria. Bulavskkaya and Reynès (2018) found that the clean energy industry has created thousands of jobs in the Netherlands and effectively promoted economic growth. Mu et al. (2018) confirmed that the improvement of clean energy has positively affected China's business level, especially the scale expansion of wind energy and solar energy industry, which can create employment. To sum up, it can be concluded that green talent training, industrial structure upgrading, and green innovation projects are conducive to improving production efficiency and energy efficiency, to reduce carbon emissions (Cheng et al., 2021).

Conversely, the rising unemployment rate may contribute to rising carbon emissions. Some scholars have conducted extensive research on the relationship between the unemployment rate and economic development, among which the most famous is the alternative relationship between the unemployment rate and GDP proposed by American economist Okun (1962). Besides, by studying a large number of developed and developing economies, Ball (2019) concluded that the coefficient of developing economies is on average lower than that of developed economies, and the effectiveness of Okun Law is different in different economies. Benos and Stavrakoudis (2020) concluded that the dependence between GDP and unemployment by using copula function analysis is only strong in the United States and France. That is, if the unemployment rate becomes higher, the economic level will decline. These research documents show that rising unemployment will lead to a decline in the level of the economy. Other scholars have found that the decline in the economic level will lead to an increase in carbon emissions. According to Wang et al. (2022c), when the level of GDP per capita is within a certain range, if the economic level decreases, to develop the economy rapidly, the government will take measures to stimulate the development of some high energy-consuming industries, so carbon emissions will rise. In addition, there are many reasons for the rise in unemployment. On the one hand, there is insufficient motivation for capital to stimulate employment and insufficient new jobs. On the other hand, the employment skills of the unemployed are not high. Under the background of carbon neutralization and peak carbon emission goals, some employees with low skill levels eliminated by the polluting production sector in the market in the process of transformation and upgrading cannot improve their skills and comprehensive quality in a short time, so the unemployment rate rises. On this basis, such displaced unemployed people are likely to enter the production sector with higher pollution levels under the condition of a lack of training capital, thus increasing the increase of total carbon emissions (Aceleanu et al., 2015).

Although the green finance development level has ranked first in the world, it is still being promoted in the form of the pilot in China, which still cannot meet the market demand. Therefore, the support of green finance to stabilize employment in green transformation is still insufficient, which makes the mobility of market labor in different sectors low and industrial structure upgrading less efficient, thus delaying the green transformation of the economy and detrimental to carbon emission reduction. It is also worth noting that most of the environmental protection, low-carbon, and green production departments in the market are science and technology-based, small and medium-sized enterprises, which have the characteristics of high investment, high risk, and long cycle (Machiba, 2011). Therefore, enterprises usually cannot fully absorb the unemployed, but control the development scale and reduce the employed due to capital constraints. In the short term, such unemployed people are likely to be squeezed out of highly polluting production sectors, which is not conducive to the improvement of industrial structure and energy structure, and finally stimulate the increase of carbon emissions (Zhou et al., 2013). Based on this, the following hypothesis is proposed in this study.

Hypothesis 3. The rise of the unemployment rate promotes carbon emissions.

Based on the above research, this study summarizes the following research gaps: firstly, the current literature pays more attention to the research on financial development and carbon emissions, while the research on green finance and carbon emissions stays at the theoretical level. Secondly, although some scholars study the relationship between green finance and carbon emissions, few scholars take the unemployment rate as a

TABLE 1 Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
$\ln CO_2$	480	1.030	0.783	−1.833	2.714
gfi	480	0.146	0.099	0.000	0.793
ur	480	3.449	0.741	0.000	6.500
open	480	0.268	0.304	0.010	1.457
lnpgdp	480	1.169	0.699	−0.864	2.799
eri	480	0.517	0.529	0.000	2.585
financeim	480	2.948	1.147	1.400	7.900

Note: CO_2, carbon emission; gfi, green finance; ur, unemployment rate; open, economic openness; pgdp, economic growth; eri, environmental regulation; financeim, financial development level.

TABLE 2 Cross-sectional dependence test results.

Variables	Pesaran CD-test	*p*-value
$\ln CO_2$	61.604	0.000
gfi	83.061	0.000
open	78.786	0.000
lnpgdp	80.145	0.000
eri	66.025	0.000
financeim	82.762	0.000

mediating variable to expand their research. Finally, the research on the regional heterogeneity of green finance on carbon emissions needs to be supplemented to promote the coordinated development of China's carbon emissions.

3 Methodology

3.1 Model establishment

3.1.1 OLS panel regression model construction

Under the premise that other variables are controlled for their effects on carbon emissions, following the study findings and empirical norms of Bai et al. (2022), this study examines the effects of green finance on carbon emissions. The model is set up in the following form:

$$\ln CO_{2it} = a_0 + \beta_1 gfi_{it} + \beta_2 open_{it} + \beta_3 \ln pgdp_{it} + \beta_4 eri_{it} + \beta_5 financeim_{it} + \varepsilon_{it} \quad (1)$$

where i represents the area and t represents the year; $\ln CO_{2it}$ refers to the explained variable and represents carbon emissions after taking the natural logarithm.; gfi_{it} is the core explanatory variable and represents the green financial level of the region i in the year t; a_0 is a constant, $\beta_1 \sim \beta_5$ are the coefficients of the relevant influencing factors; $open$ represents the degree of local openness; $\ln pgdp$ represents the local per capita nominal GDP; eri represents environmental regulation; $financem$ denotes financial development level; ε is the random error term.

3.1.2 Generalized method of moments

However, OLS is a static regression model and does not consider endogeneity among variables. To further explore the dynamic relationship between carbon emissions and green finance, this study lags carbon emissions by one period and applies a dynamic panel regression model. The specific model is as follows:

$$\ln CO_{2it} = a_0 + \beta_1 \ln CO_{2it-1} + \beta_2 gfi_{it} + \beta_3 open_{it} + \beta_4 \ln pgdp_{it} + \beta_5 eri_{it} + \beta_6 financeim_{it} + \varepsilon_{it} \quad (2)$$

Among them, $\ln CO_{2it-1}$ represents the one-period lagged term of the explained variable. Other variables are set as in Eq. 1.

3.1.3 Construction of mediating effect model

In addition, to verify the mediating effect of employment in green finance and carbon emission, this study sets the following model:

$$\ln CO_{2it} = a_0 + \beta_1 gfi_{it} + \beta_2 open_{it} + \beta_3 \ln pgdp_{it} + \beta_4 eri_{it} + \beta_5 financeim_{it} + \varepsilon_{it} \quad (3)$$

$$ur_{it} = a_0 + \beta_1 gfi_{it} + \beta_2 open_{it} + \beta_3 \ln pgdp_{it} + \beta_4 eri_{it} + \beta_5 financeim_{it} + \varepsilon_{it} \quad (4)$$

$$\ln CO_{2it} = a_0 + \beta_1 gfi_{it} + \beta_2 ur_{it} + \beta_3 open_{it} + \beta_4 \ln pgdp_{it} + \beta_5 eri_{it} + \beta_6 financeim_{it} + \varepsilon_{it} \quad (5)$$

In Eqs 4 and 5, $ur_{i,t}$ represents the level of unemployment in a region i in a year t. Figure 1 provides the role mechanism of green finance on carbon emissions from the perspective of the unemployment rate.

3.2 Variables description

3.2.1 Explained variable

The explained variable is expressed by carbon emission (CO_2). The measure of carbon emissions is determined by the utilization of 10 energy sources in every area, namely crude coal, coke, unrefined petroleum, gas, lamp oil, diesel, fuel oil, flammable gas, melted oil gas, and power (Chen, 2020; Jiang et al., 2022). The computation recipe is as per the following model:

$$\ln CO_{2it} = \sum_{j=1}^{10} \ln CO_{2itj} = \sum_{j=1}^{10} \ln E_{itj} \times Q_j \times \frac{44}{12} \quad (6)$$

In Eq. 6, CO_{2it} represents the total carbon emissions of a province i in a year t; $\ln CO_{2itj}$ represents the total carbon emission of the j energy in a province i in a year t. E_{itj} represents energy consumption for type j energy in i province

t year. Q_j is the carbon dioxide emission coefficient of j energy sources, where the carbon emissions coefficient adopts the IPCC standard, and $\ln CO_2$ is used to represent carbon emissions. To eliminate heteroscedasticity and reduce data fluctuation in empirical analysis, the logarithm CO_2 is adopted for analysis.

3.2.2 Core explanatory variable

Concerning Yin et al. (2021), this study constructs green finance (gfi) index system namely green credit, green securities, green insurance, green investment, and carbon finance indicators, and measures the green finance (gfi) index system using the entropy value method.

3.2.3 Control variable

1) Economic growth ($ln\, pgdp$): Economic development can contribute to an increase in the level of green technology, which can have an impact on carbon emissions (Anser et al., 2020b; Yang Z. et al., 2021; Jahanger et al., 2022; Wang et al., 2022a). Following Wang et al. (2022), this study uses per GDP to reflect the level of economic development. To eliminate heteroscedasticity and reduce data fluctuation in empirical analysis, the logarithm of $pgdp$ is adopted for analysis.
2) Economic openness ($open$): Referring to Yang et al. (2021b), the degree of economic openness selects the proportion of the total import and export trade of each province in the GDP of that year to measure the degree of local economic openness.
3) Environmental regulation (eri): Environmental regulation is the public authority's utilization of managerial orders to direct the creation conduct of undertakings, lessen the emission of pollutants, to accomplish the reason for environmental protection, and top-notch economic development. In this study, the complete index of environmental guidelines in every area is determined by the entropy technique from the release of modern wastewater, modern SO_2, and modern residue.
4) Financial development level ($financeim$): Following Cao et al. (2021), the financial development level is estimated by the extent of the harmony between stores and credits of financial organizations in every area in the neighborhood GDP.

3.2.4 Mediating variable

In this study, the mediating variable is measured by the unemployment rate (ur) of each province.

3.3 Descriptive statistics

This study selects 30 provincial panel data of the Chinese mainland from 2004 to 2019 as the research objects. The original data come from the China Statistical Yearbook, China Financial Yearbook, China Environmental Statistical Yearbook, China Industrial Statistics Yearbook, China Insurance Yearbook, China Environmental Statistics Yearbook, the Statistical Yearbook of each province, and Wind database. Descriptive statistics are shown in Table 1.

4 Results and discussion

4.1 Discussion on cross-sectional dependence and slope heterogeneity tests

As marketization continues to increase as well as economic interactions among various areas intensify in frequency, correlations among areas are increasingly significant. Consequently, inconsistency and bias in the estimates arising from the cross-sectional dependence formed by the various areas may occur when examining some economic stories by using the panel data of the composition of the above-mentioned area as methodologically (e.g., Baltagi, 2008; Pesaran, 2015b) and empirically shown (e.g., Baltagi, 2008; Hasanov et al., 2016; Hasanov et al., 2021; Hasanov and Mikayilov, 2021; Liddle and Hasanov, 2022). Referring to Pesaran (2015a) and Hasanov and Mikayilov (2021), the Pesaran test with weak exogenous cross-sectional dependence is examined for the study sample in this study. The test results are shown in Table 2.

However, the FGLS estimation method is able to correct for the heteroscedasticity, cross-sectional correlation, and sequence-correlation problems due to the cross-section data, improving the consistency, and effectiveness of the panel regression. Therefore, this study uses the feasible generalized least squares (FGLS) to substitute the residual vectors of each individual cross-section into the covariance matrix of cross-section heteroscedasticity and uses GLS to obtain the parameter estimates. It is worth noting that when the number of times T in the panel data model is less than the section number N, the standard deviation of the FGLS estimation parameters cannot fully reflect the variation, so the panel-corrected standard errors (PCSE) should be considered to deal with the complex panel error structure. The PCSE method substitutes the residual term into the diagonal matrix by retaining the OLS estimation parameters and correcting its standard deviation, which is an alternative to FGLS and enables a more accurate regression estimation of the panel data. Therefore, to solve the complex panel error structure, the FGLS and PCSE estimates were used to correct the model. Test results are presented in Table 3. The results show that the FGLS and PCSE estimates are essentially the same and are generally consistent with the benchmark regression results, so the benchmark regression results in this study are robust.

TABLE 3 Test results after the correction.

Variable	FGLS	PCSE
gfi	−1.544*** (0.109)	−1.415*** (0.208)
open	−0.133*** (0.014)	0.094 (0.075)
lnpgdp	0.549*** (0.012)	0.183*** (0.053)
eri	0.993*** (0.007)	0.030 (0.019)
financeim	−0.059*** (0.005)	0.021 (0.019)

Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.
Note: gfi, green finance; open, economic openness; pgdp, economic growth; eri, environmental regulation; financeim, financial development level.

TABLE 4 Panel unit root test result.

Variables	Level	First difference
$lnCO_2$	−2.415*	−3.817*
gfi	−1.777	−3.057*
open	−1.415	−3.095*
lnpgdp	−0.743*	−2.596
eri	−1.845*	−3.875*
financeim	−1.608	−2.671

The symbols * refer to the level of significance at 10%.

TABLE 5 Pedroni test for cointegration.

		Statistic	*p*-value
Pedroni	Modified Phillips-Perron t	6.6334	0.0000
	Phillips-Perron t	−8.0345	0.0000
	Augmented Dickey-Fuller t	−6.9990	0.0000

TABLE 6 Cointegration results for Westerlund (2007) test.

Statistic	Value	Z-value	*p*-value
Gt	−3.120	−5.212	0.000
Ga	−13.180	−1.056	0.146
Pt	−17.222	−6.580	0.000
Pa	−20.372	−10.470	0.000

TABLE 7 OLS panel regression result.

Variable	(1)	(2)	(3)	(4)	(5)
gfi	**−1.686*****	**−1.780*****	**−1.641*****	**−1.570*****	**−1.520*****
	(0.173)	(0.191)	(0.183)	(0.177)	(0.190)
open	—	−0.093	−0.121	−0.095	−0.113
	—	(0.087)	(0.084)	(0.083)	(0.082)
lnpgdp	—	—	0.206***	0.212***	0.271***
	—	—	(0.058)	(0.059)	(0.075)
eri	—	—	—	0.083***	0.082**
	—	—	—	(0.032)	(0.032)
financeim	—	—	—	—	0.042 (0.028)
_cons	0.703***	0.720***	0.752***	0.719***	0.642***
	(0.037)	(0.040)	(0.037)	(0.038)	(0.066)
N	480	480	480	480	480
adj.R-sq	0.971	0.971	0.972	0.972	0.972
AIC	−526	−525.1	−539.8	−544.6	−545.2
BIC	−334	−328.9	−339.5	−340.1	−336.5

Standard errors in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.
Note: gfi, green finance; open, economic openness; pgdp, economic growth; eri, environmental regulation; financeim, financial development level.

4.2 Discussion on panel unit root test and cointegration test results

The variables used in the analysis are often drifting and hence their mean, variance, and covariance change over time (e.g., see Pesaran, 2015b). Therefore, in order to maintain the validity of the econometric test and estimation results the panel data should be subjected to a unit root test to check whether they have stationarity (Baltagi, 2008; Pesaran, 2015b). Following Meo et al. (2020), and Hasanov et al. (2021), the cross-section dependence unit root test proposed by Pesaran (2007), is employed in this study to verify whether there is a unit root for the dataset (see Table 4). Pesaran (2007) suggests that most of the variables are stationary and most of them become stationary after the first difference. After finding the order of integration in the panel, this study also attempts to investigate whether there is a cointegration relationship between the variables (see Tables 5 and 6). Table 5 that Pedroni test is rejected at the 1% level, so there is a cointegration among them, which also implies that the benchmark regression model can be used for the estimation. Besides, Table 6 demonstrates that a null hypothesis of no cointegration cannot be rejected for the results of the Westlund (2007) test that Gt, Pt, and Pa variables are cointegrated, while the remaining one cannot reject the null hypothesis of no cointegration. As Hasanov et al. (2021), the Westlund (2007) test causes under-rejection in small samples.

4.3 Discussion on OLS panel regression result

To add to the robustness of the regression result, this study utilizes the stepwise regression method of progressively expanding the control factors, and increasing the robustness and validity of the results. The time and individual effects were fixed to reduce the impact on estimated results (see Table 7). Table 7 reveals that the coefficients of the core explanatory variable (gfi) are significantly negative at the 1% level; that

TABLE 8 Results of stepwise regression of GMM model.

Variable	(1)	(2)	(3)	(4)	(5)
L1. $lnCO_2$	0.788*** (0.102)	0.776*** (0.118)	0.629*** (0.107)	0.602*** (0.102)	0.574*** (0.112)
gfi	**−12.293** (4.929)**	**−12.520*** (4.890)**	**−12.671*** (4.630)**	**−14.162** (5.804)**	**−15.517** (6.920)**
open	—	−0.239 (0.211)	−0.276 (0.200)	−0.294 (0.209)	−0.392** (0.191)
lnpgdp	—	—	0.129 (0.313)	0.052 (0.353)	0.199 (0.428)
financeim	—	—	—	−0.033 (0.190)	−0.281 (0.033)
eri	—	—	—	—	0.143* (0.081)
AR(2) *p*-value	0.242	0.246	0.230	0.237	0.195
Hansen	0.201	0.267	0.238	0.252	0.232

Standard errors in parentheses; $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

is, the development of green finance has a huge inhibitory effect on carbon emissions. Hypothesis 1 is confirmed. Our results provide similar evidence for the findings of Sun (2021) and Xiong and Sun (2022). It is not difficult to understand that, due to the nature of green finance, it strictly restricts the financing support for high pollution and high energy-consuming enterprises, such as the high-interest rate for loans, so that the expansion of the production scale of such enterprises is restricted, and then through the market mechanism, it forces enterprises to transform and upgrade to reduce the pollution emissions caused by the original production mode (Shen et al., 2021; Meo and Abd, 2022). In addition, by increasing financial support for the development of environmental protection and energy-saving industries, such as the implementation of preferential interest rates on green credit for such industries, capital support for their expansion and reproduction cannot only strengthen the production scale of the original enterprises in the market but also attract other enterprises to enter the industry, reducing carbon emissions from the source (Bai et al., 2022).

4.4 Discussion on panel regression model result

To further verify the dynamic relationship between green finance and carbon emissions, this study introduces the GMM model to alleviate the endogenous problem. Some necessary tests should be required before using the GMM model (see Table 8). Table 8 reports that according to the *p*-value of AR(2), there is no second-order autocorrelation in the random disturbance term. Hansen test results show that there is no over-identification problem of instrumental variables, indicating that the estimation results are effective. The lagged period of the explained variable is significantly positive at the 1% level, implying that carbon emissions in the earlier period will have a positive impact on carbon emissions in the later period. Besides, the core explanatory variable (gfi) is significantly negative at least 1%. Hypothesis 1 is once again tested.

4.5 Discussion on robustness test result

To additionally demonstrate the robustness of the above results, a two-stage least squares test (2SLS) is conducted, and the outcomes are displayed in Table 9. It can be seen that in the process of stepwise 2SLS regression, the contribution of green finance to carbon emissions is significantly negative at the level of 1%. The significance and indication of the core explanatory variable have not changed except for the little difference in the regression coefficient. The openness, per capita GDP, financial development, and environmental regulation are significant at the level of 10%, which is consistent with the results of OLS panel regression and dynamic panel GMM regression. The results of stepwise OLS panel regression, GMM dynamic panel regression, and 2SLS robust regression show that the results of empirical regression are reliable and have good stability. Therefore, the research results of this study are robust.

4.6 Discussion on mediating effect regression result

According to the mediating effect of the unemployment rate on the impact of green finance on carbon emissions, the next test is carried out according to the mediating effect test process. As shown in Table 7, in the bootstrap test, the direct effect and mediating effect are significantly negative at the level of 1%, that is, the direct effect and indirect effect of green finance on carbon emissions are negative, while the Sobel test is significantly negative at the level of 1%, which proves the stability of the mediating effect.

As shown in Table 10, the impact of green finance on carbon emissions in path 1 is significantly negative at the level of 1%, that is, it has a significant inhibitory effect. The indirect regression results of path 2 show that the impact of green finance on the unemployment rate is significantly negative at the level of 1%, therefore, Hypothesis 2 is verified. It can be seen from path 3 that

TABLE 9 Results of robustness test.

Variable	(1)	(2)	(3)	(4)	(5)
gfi	**−1.526*** (0.168)**	**−1.745*** (0.199)**	**−1.713*** (0.193)**	**−1.659*** (0.186)**	**−1.588*** (0.206)**
open	—	−0.175** (0.078)	−0.200*** (0.075)	−0.179** (0.073)	−0.182** (0.073)
lnpgdp	—	—	0.135** (0.055)	0.136** (0.056)	0.181** (0.070)
eri	—	—	—	0.061** (0.030)	0.060** (0.030)
financeim	—	—	—	—	0.029 (0.024)
_cons	1.681*** (0.049)	1.736*** (0.544)	1.525*** (0.106)	1.586*** (0.106)	1.317*** (0.190)

Standard errors in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

TABLE 10 Results of mediating effect regression analysis.

Variable	Path 1	Path 2	Path 3
	$lnCO_2$	ur	$lnCO_2$
ur	—	—	**0.145*** (0.396)**
gfi	**−1.555*** (0.403)**	**−3.247*** (0.462)**	**−1.085** (0.418)**
open	−0.136* (0.781)	0.256*** (0.895)	−0.173** (0.078)
lnpgdp	0.546*** (0.044)	−0.574 (0.050)	0.554*** (0.049)
eri	1.001*** (0.046)	−0.162*** (0.053)	1.024*** (0.046)
financeim	−0.567* (0.031)	−0.157*** (0.358)	−0.340 (0.031)
_cons	0.286*** (0.794)	4.514*** (0.091)	−0.367* (0.195)

Standard errors in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

TABLE 11 Bootstrap and Soble test.

_bs_1	**−0.470*** (0.156)**
_bs_2	**−1.085*** (0.402)**
Soble	−0.470*** (0.145)
Goodman-1 (Aroian)	−0.470*** (0.146)
Goodman-2	−0.470*** (0.144)

Standard errors in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

the unemployment rate and carbon emissions show a significant positive effect at the level of 1%, that is, the increase in the unemployment rate will increase carbon emissions. Therefore, Hypothesis 3 is verified. Therefore, combining the results in Tables 10 and 11, it is clear that green finance can significantly reduce carbon emissions by diminishing the unemployment rate. One potential explanation is that, ceteris paribus, the financing constraints induced by green finance will raise firms' production costs, thereby reducing their production size and the number of employees they can absorb. However, Porter's hypothesis confirms that in this case, the polluting firm may have a comparative advantage due to the impact on competitors in terms of production process transformation and products. Moreover, the green financial tools currently adopted by China do not directly constrain total carbon emissions, but rather attempt to reduce them by financing adjustments and technological advances. Therefore, if the "use of new technologies" is implicit in this process, then the carbon abatement technology itself generates job creation and thus reduces unemployment. For instance, green finance stimulates the R&D and application of emission reduction technologies, which require additional labor input in the process and thus create some employment opportunities. Also, these abatement technologies may convert by-products (e.g., residues) generated in the production process into commodities, thereby increasing corporate profits and corresponding employment opportunities. This not only further reduces unemployment but also curbs carbon emissions.

In addition, it can be seen from Tables 5 and 6 that a open has a significant inhibitory effect on carbon emissions, but it has a significant promoting effect on *ur*. The reason is that trade opening is conducive to the introduction of foreign advanced technology, which drives domestic technological progress, leads to reduced energy consumption, and ultimately suppresses carbon emissions. However, the improvement of the opening level will promote the import of a large number of foreign talents, thus squeezing the domestic labor market and leading to the rise of *ur*. Economic growth will significantly aggravate the increase of carbon emissions but will not significantly inhibit the rise of *ur*. Because economic growth will promote energy consumption and increase carbon emissions (Li et al., 2022; Wang et al., 2022b). However, economic growth will promote the increase of jobs, thus reducing *ur*. *eri* has a significant positive impact on carbon emissions, but has a significant negative impact on *ur*. When *eri* is at a low level, the production department will follow the cost principle and purchase cleaning equipment, but it also inhibits the development of technological innovation and will eventually promote an increase in carbon emissions. When *eri* is at a high level, the production department will transfer industries with high energy consumption and high pollution

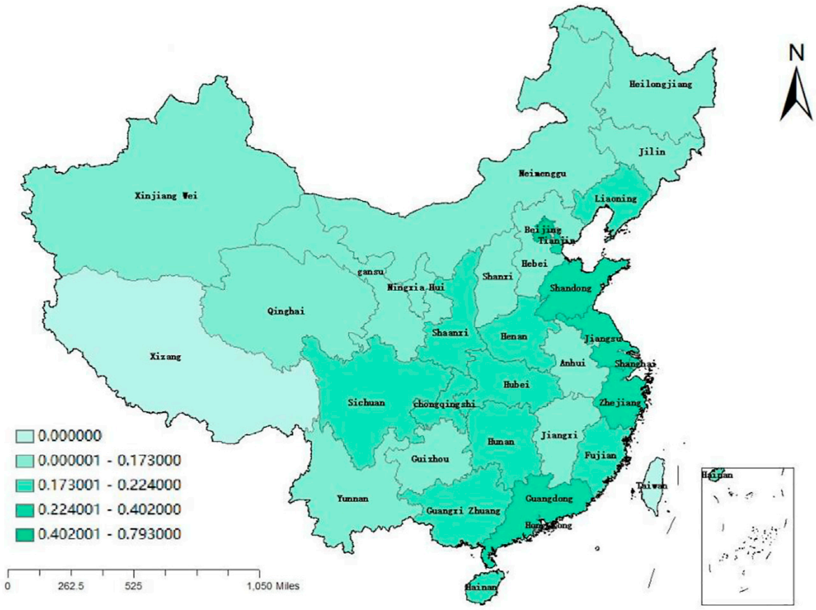

FIGURE 2
2019 Green finance index distribution map.

to areas with preferential policies, thus reducing the constraints of environmental regulation (Wang et al., 2022c). Even in some regions, government departments are engaged in "bottom-by-bottom competition" in order to chase GDP growth, which is not conducive to carbon emission reduction.

4.7 Discussion on regional heterogeneity result

There may also be significant regional heterogeneity in the impact of green finance on carbon emissions in different regions due to their different natural endowments, economic levels,

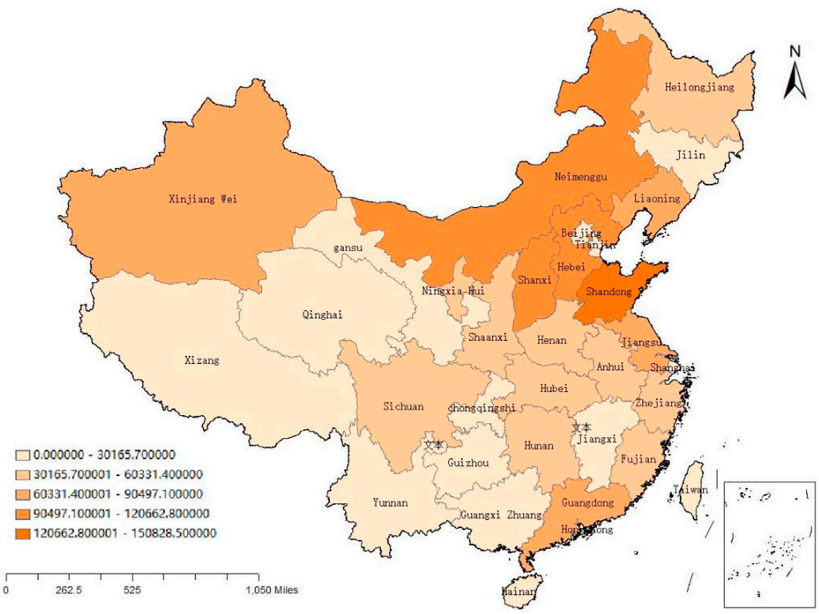

FIGURE 3
2019 Carbon emissions distribution map.

TABLE 12 Regional heterogeneity result.

	Eastern	Central	Western
gfi	**−1.394*** (0.181)**	**−5.259*** (1.040)**	**−1.959 (1.480)**
open	0.253** (0.114)	1.105*** (0.357)	−0.9026*** (0.294)
lnpgdp	0.777*** (0.147)	0.753*** (0.107)	−0.503*** (0.140)
eri	−0.003 (0.037)	0.093** (0.046)	−0.038 (0.083)
financeim	0.064 (0.039)	0.158* (0.076)	−0.137*** (0.048)
_cons	−1.233** (0.487)	0.682*** (0.179)	0.283 (0.208)
N	196	128	176
adj.R-sq	0.990	0.974	0.958
AIC	−310.6	−270.1	−143.9
BIC	−212.3	−190.2	−45.6

Standard errors in parentheses; $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

industrial structures, and policy preferences (Islam et al., 2022; Yang et al., 2022). This study divides China's 30 provinces (cities) into three parts according to the level of economic development: eastern, central, and western (Yang et al., 2021c). The eastern region includes Beijing, Tianjin, Shandong Province, Hebei, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan; The central region includes Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, and Guangxi; the western region includes Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. As shown in Figure 2, there are extraordinary contrasts in the development level of green finance in the eastern, central, and western, and the essential development status shows a pattern of slow decrease to the inland. The development of green finance in the eastern coastal regions is relatively high. The development of the central region is relatively deficient except Hubei Province, Henan Province, and Hunan Province, and the development of green finance in the western region is relatively deficient except Sichuan Province and Chongqing. However, there are differences in carbon emissions. According to Figure 3, carbon emissions are relatively high in the central region, especially Shanxi Province and Inner Mongolia in the central region, Hebei Province, and Shandong Province in the eastern region, and moderate in some eastern coastal provinces and developed regions such as Beijing, Shanghai, Zhejiang Province, and Fujian Province.

On this basis, this study uses the OLS model to analyze the regional heterogeneity of the impact of green finance on carbon emissions in eastern, central, and western regions. Table 12 shows that green finance has a significant inhibitory effect on carbon emissions in the eastern and central regions at the level of 1% but insignificant in the western region. One potential reason is that the eastern region mainly gathers political, economic, and cultural centers, and the economic level is relatively developed (Yan et al., 2021). Therefore, the development of green finance can be better supported in the eastern region. However, the local industrial structure is biased toward the tertiary industry, with the majority of high-tech industries, a high level of technological innovation, high energy efficiency, and low carbon emissions compared with the central region (Baloch et al., 2020). Therefore, the inhibitory effect of green finance on carbon dioxide emission is less than that of the central region. Besides, the central region has a relatively dense population, high pressure of employment competition, and many high energy-consuming industries, such as coal, steel, and other industries. Therefore, green finance has a greater impact on the industries in the central region to promote the green transformation and upgrading of industries. With the support of green financial development, the employment pressure can also be better alleviated, to reduce the unemployment rate in the central region, and further curb carbon emissions. Therefore, it has a stronger effect on restraining carbon emissions. Finally, the development level of green finance in the western region is relatively low, coupled with its vast territory and sparse population, the energy demand is relatively low compared with the eastern and middle regions, and the ecological environment is high. Therefore, the inhibitory effect of green finance on carbon emissions is insignificant.

5 Conclusions and policy recommendations

Using the panel data of 30 provincial administrative regions in China from 2004 to 2019, this study investigates the impact of green finance on carbon emissions based on an unemployment rate perspective. This study takes the unemployment rate as the mediating variable to study the impact of green finance on carbon emissions for the first time, which enriches the current research path and theoretical basis and provides more empirical reference evidence for realizing the dual carbon goal. The statistical results found that green finance has a significant inhibitory impact on carbon emissions. Green finance has significantly reduced the unemployment rate. The unemployment rate has a significant positive effect on carbon emissions. Green finance can reduce carbon emissions by diminishing the unemployment rate. There is regional heterogeneity in the effect of green finance on carbon emissions in eastern, middle, and western China. Specifically, green finance in the eastern and central regions significantly inhibits carbon emissions, while in the western region not significantly. In response to the above findings, the study draws corresponding strategic recommendations.

First, speeding up the improvement of the green finance standard framework and motivation and limitation instrument. Policymakers should continue to establish a more effective green financial incentive system, and guide financial resources to green and low-carbon projects. Besides, policymakers should accelerate research on the establishment of emission reduction support tools and encourage the financial sector to increase support for green and low-carbon projects with significant emission

reductions. Through innovation sharing, policymakers can actively cultivate green finance, speed up the reform of energy-intensive industries, and achieve carbon emission reduction.

Second, policymakers should utilize the green finance funding leverage and channeling effect to drive the rapid development of low-carbon, zero-carbon, and carbon-negative industries to develop a scale effect to expand employment. Furthermore, policymakers should play the substitution effect of green finance to accelerate the migration of workers from coal, steel, oil, and other industries to low-carbon industries to optimize the labor market and thus achieve stable employment rates. Finally, policymakers shall employ green finance to increase wages and subsidies for those employed in low-carbon industries, thereby promoting employment for the purpose of indirectly reducing carbon emissions.

Third, policymakers should find out the development process of green finance according to local conditions, formulate green financial development plans accurately according to the actual situation of each region and the attributes of industrial construction, and implement financial and industrial policies following local conditions. Economically developed areas should make use of their developed financial level to vigorously develop green finance and infiltrate into areas, where the green financial level is underdeveloped to achieve the role of a bellwether. While implementing green finance, the central and western regions should optimize the existing green finance development policies by drawing on the advanced experience of the eastern regions, thereby maximizing carbon emission reduction.

However, this study still has some limitations. Firstly, it is only based on China's inter-provincial panel data, and other countries may have the same problems, so future research can be expanded to international research samples. Secondly, it lacks case analysis. Future research can further support the research conclusion of this study by investigating the pilot efficiency of green finance policy. Finally, the impact of green finance on carbon emissions may have a nonlinear relationship, so future scholars can deepen this research by adding threshold variables.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

YC: Conceptualization, Project administration, Formal analysis, Writing—review and editing, Data curation, Writing—original draft. GW: Software, Visualization, Conceptualization, Methodology. MI: Writing—original draft, Writing—review, and editing, Formal analysis, Validation. DW: Writing—review and editing, Validation. JC: Writing—review and editing, Writing—original draft, Conceptualization, Methodology, Funding acquisition, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Evaluating Barriers on Biogas Technology Adoption in China: The Moderating Role of Awareness and Technology Understanding

Shahid Ali[1], *Qingyou Yan*[1,2], *Muhammad Irfan*[3,4,5†] *and Zhenling Chen*[6,7]*

[1]School of Economics and Management, North China Electric Power University, Beijing, China, [2]Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Beijing, China, [3]School of Management and Economics, Beijing Institute of Technology, Beijing, China, [4]Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing, China, [5]Department of Business Administration, Faculty of Management Science, ILMA University, Karachi, Pakistan, [6]School of Economics, Beijing Technology and Business University, Beijing, China, [7]Institute for Carbon Peak and Neutrality, Beijng Wuzi University, Beijing, China

Biogas technology adoption is a challenge in developing countries like China. The primary objective of this study was to explore the major issues for farmers in adopting biogas plants. The sample size was identified through the snowball sampling method. A total of 51 respondents of biogas plant adopters participated in this study. The structured questionnaire was used to collect primary data through respondents. The formulated suppositions were assessed by partial least square structural equation modeling (PLS-SEM). The results indicated that all independent variables are significant and positively correlated with adopting biogas technology, reducing energy crises, and attaining cost-saving purposes. The results further indicated that the low cost and clear policy positively and significantly attract farmers to adopt biogas plants. The selected variables and their adopted moderation have a significant and positive impact on this conceptual model. The findings further indicate that major maintenance and day-to-day operations of biogas plants are expensive due to a lack of skilled operators, untrained or partially trained owners, and the unavailability of technicians. The results suggested that the government needs to plan a clear policy, provide short operation courses and technical support with skilled technicians to biogas plant owners, and launch a media campaign about maintenance to develop biogas plants.

Keywords: renewable energy, biogas resources, biogas power plants, trade using biogas technology, potential and barriers

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Yunpeng Sun,
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Tayyaba Rani,
Xi'an Jiaotong University, China

Correspondence:
Zhenling Chen
chenzhenling2008@163.com

†ORCID:
Muhammad Irfan
orcid.org/0000-0003-1446-583X

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INTRODUCTION

In the present world, human activities, including burning fossil fuels (coal and oil), are known as the primary causes of global warming (Xie et al., 2022). Like an underdeveloped world, China needs substantial energy to support its population and industry (Fang et al., 2022). China has abundant potential in the geographical location of all types of renewable energy sources like bio-energy, solar energy, and wind energy (Jinru et al., 2021). The country has the massive potential for biomass generation to produce bio-energy by applying combustion, trans-esterification, gasification, and pyrolysis (Wu et al., 2021). Modern technology can play an important role in sustainable economic

TABLE 1 | Factors motivating farmers' attention.

Reason	Case (%)	Response (%)	Frequency
Motivation by the construction body	32	11	18
Motivation by existing plants	42	15	22
Subsidy	42	14	22
Unavailability of alternative fuels	21	8	11
Environmental advantages	19	6	8
Health advantages	15	5	10
Time-saving benefits	30	11	16
Energy-saving ability	31	10	15
Social reputation	32	11	17

development in the country (Irfan and Ahmad, 2022). The fact about social niche starts with the behavior of individuals, and existing social practices are connected with it. **Table 1** indicates the reasons for inspiration to adopt biogas plants from plant users.

Some barriers and important factors closely discourage the country's acceptance rate of biogas technology. Biogas technology is still not socially acceptable in China, even though this technology has economically attractive features, is technically possible, and is environmentally sustainable. The existing literature has shown a significant gap in knowledge concerned with critical influence factors due to dependencies such as market, institutional, and family choices for a fuel source. Biogas adoption negatively impacts the collection time and fuel-wood expenditures, but it has a positive and significant impact on crop revenues and income (GoP, 2020).

In China, all previous research studies concerning the energy sector mainly included 1) demand and supply–based energy gap, 2) energy generation sources, 3) future of the energy sector, 4) assessment of the energy sector of the country, and 5) energy mix. Regardless of the previous researcher's long-standing interest, all these studies have specific gaps, i.e., 1) there is a need to find out significant barriers and reasons compelling farmers to desolate the use of biogas technology; 2) the lack of technical barrier analysis and critical social factors on adopting biogas-installed plants discourage the investors and all types of investment; 3) financial planning for realizing economic benefits of biogas-installed plants to the farmers and investigating the critical factors due to which the farmers left biogas technology; 4) making the effective and efficient performance of biogas plants by highlighting and removing the installing and operating barriers of biogas plants in China. For contributing to the existing research gaps, the current study will address the following research questions: 1) investigate the main barriers and critical factors of biogas-installed plants for the sustainable development of biogas technology in China; 2) highlight the installing and operating barriers for removing these barriers to attract biogas plant investors for sustainable development of biogas energy and empirically evaluating the moderating role of awareness and understanding of the adopting biogas technology for sustainable improvement. The results of this research study will support government institutions, competent authorities, and NGOs to condense the weak process. The purpose of biogas plants is to produce low-cost RE to reduce greenhouse gas emissions through biogas and adequate waste management for the farmers of rural areas. Furthermore, the purposes of the present study are to provide awareness to the farmers for biogas plant adoption, build-up skills, and upgrading installation due to low capital investment and long-term benefits. The current study aimed to reduce financial risks, minimize the farmer's biogas plant investment barriers, create costless energy production through small-scale biogas plants for the farmer's self-consumption, and increase the biogas plant competencies. Additionally, ensuring the biogas industry coordination among knowledge centers, government institutions, and municipalities is the purpose of the present study. Hence, the primary purpose of conducting this study was to explore and discuss the major factors that encumber farmers from adopting the biogas technology. The further objective of this study was to attract investors to invest in biogas plants for the sustainable development of biogas energy by releasing biogas potential in China. As a step further, this study aimed to investigate the critical factors of biogas-installed plants for the sustainable development of biogas technology in China. The next section discusses the literature review then the research methodology with research design and formulation of hypotheses and describes the literature review and conceptual model. The data analysis and results section describes the testing of hypotheses. The discussion section explains the findings, implications, and conclusion, including the important limitations to the study.

LITERATURE REVIEW

Energy generation from fossil fuels is a worldwide issue. Current lifestyle and economic growth are impossible without a continued energy supply worldwide. Consistent availability of energy is highly required for modern life. The nation's economic growth and success greatly depend on the proper use of energy resources. Energy plays a fundamental role in improving the standard of living and economic development of any country or nation (Callegari et al., 2020). Energy worked as a vital building block for developing countries' economic and social development (Carmona et al., 2021). It saves an average of USD 214,406 (PRs, 37.925) million per month in different terms such as liquefied petroleum gas, wood, kerosene oil, and bio fertilizer (Arshad et al., 2018). The current most promising emerging

biogas technologies in terms of their potential uses, environmental benefits, and public acceptance give a picture of the current conditions on the adoption of a biogas road map in the various EU Member States with an analysis of the status and gaps in the implementation of incentive and support policy, a discussion of non-technological barriers, and a summary of proposed solutions to increase the use of biogas energy (Capodaglio A et al., 2016). Biogas is a low-cost energy source critical for any country's sustainable development. But at present, energy generation is a challenging job using modern technology. The increasing population and current economic development are the reasons for the country's extreme demand for energy. The energy demand and supply gap create issues in almost all country sectors, including sustainable development, prosperity, development of other sectors, and economic growth. These issues are considered harmful to human health, water resources, agricultural productivity, and environmental activities (Amir et al., 2019).

Many research studies have discussed that biogas provides energy to specific rural areas and fills the different types of the gap, such as reducing poverty, creating local jobs, and improving health for economic growth. Biogas production provides several environmental benefits such as power generation and sustainable energy, waste treatment, and bio-slurry as organic fertilizer to improve stamina in crops. Many reasons for deforestation are explored in rural areas of low-middle-income countries, such as energy shortage, sluggish growth, and lack of biogas production. Hence, women of rural areas tolerate the burden of burning and woodcutting for cooking and heating. Biogas production and bio-slurry collection were effectively supported by biogas for soil fertility. Developing countries are facing a severe economic burden in importing gas and oil. Conversely, biogas adoption is financially feasible and environmentally friendly. Most portion of the power is generated from fossil fuels in China. Conversely, these energy generation sources have opposing environmental impacts and are also high-priced. The government of China has decided to eliminate the major energy crisis by using alternative, clean, and cost-effective energy sources. Modern RE methods justifiably address environmental problems and provide solutions for all energy issues (Jan and Akram, 2018). The biogas policy field is fraught with incoherence and dispersion. As a result, there is a clear possibility that the responsibility for biogas policy is dispersed and does not have a clear owner among the relevant actors. The framework of biogas regulations is inconsistent and inefficient (Gustafsson and Anderberg, 2021). However, the government of China has decided to enhance the share of RE by 5% until 2030, but biomass energy plays a vital role in achieving this target. China consumes a sizeable national treasury to import gas and oil to reduce the temporary energy shortage.

The current shortfall of energy in the country can be overcome by the effective and efficient use of biogas as an alternative energy source. China has prodigious potential to produce energy from biogas, the sixth-largest livestock-based economy globally. China meets 28.12% of its energy needs through imported gas and oil. For the last 2 decades, private contractors have installed biogas plants, international non-governmental organizations (INGOs), non-governmental organizations (NGOs), and the government sector. China has a huge animal-based population and production of biogas potential by using animal dung. In light of the findings, the system drivers can be classified into four categories according to their interrelationships. These categories are proactive answers to challenges, policy support, cooperative efforts, and technology capabilities. A recent study conducted a comprehensive literature review of seven established biogas markets, including Austria, France, Germany, Italy, Sweden, the Czech Republic, and the United Kingdom. The purpose of the study was to assist policymakers and practitioners who want to begin using biogas technology or expand their current use of it (Nevzorova and Karakaya, 2020). The biogas plant is economical due to its installation cost and also beneficial in minimizing eye and respiratory contaminations.

Biogas provides practically 14% of primary energy because it is the fourth most important energy source worldwide (Abbas et al., 2017). Many countries worldwide, including low-middle income countries, have invested in renewable energy technologies such as solar thermal, biomass, and hydro to generate reliable, indigenous, and affordable energy (Marion et al., 2017). Policies and policy instruments about biogas that are successful in one nation may not necessarily result in the same outcome in another nation because they are dependent on the larger context and the policy and economic framework (Gustafsson and Anderberg, 2022). Social reputation and time-saving attributes are also considered motivational factors and account for 33.5% each. Technology progress in low-middle income countries with social acceptance is highly linked. The primary reason for installing and constructing biogas plants in China is the inspiration of energy, saving time, and subsidy. The 42.5% of key motivational and subsidy factors included support, tax, and finance for cleaner fuel adoption (Capodaglio A. G et al., 2016; Puzzolo et al., 2016). The adoption of biogas technology provides health advantages and financial benefits with the lowest cost at 13.7%, but it depends on the awareness level of adopters (Capodaglio and Callegari, 2016; Pilloni et al., 2020). Biogas generation through organic waste has been acknowledged as a sustainable energy source (Afridi et al., 2019). On the contrary, biogas plants are successful, running with a higher number in South Asian countries such as China, Bangladesh, India, and Nepal (Wang Z et al., 2020).

THEORETICAL BACKGROUND AND FORMULATION OF HYPOTHESES

Availability of Technicians for Biogas Plants

To overcome the blamed economic conditions due to energy inefficiencies, biogas technology establishes dominance over energy decisions in rural areas in China. The supremacy is necessary to analyze the durables prevailing in energy efficiencies and the implications of biogas technologies with durable investments. The country requires experienced technicians for biogas plants. The government has rich biogas resources, including agricultural residues, fuel wood, municipal solid waste, and animal dung. Due to being an agricultural

country, China has a considerable quantity of animal-based biogas resources. The functional implementation of these biogas resources can return fruitful outcome to rural areas. The proper use of manure and straw biogas resources can play a vital role in reducing emissions and increasing economic advantages (Nevzorova and Kutcherov, 2019). Small-scale anaerobic digestion, often known as SSAD, applies to the agricultural sector in Europe. The size and productivity of individual farms, on average, are insufficient to supply the feedstock requirements of medium- and large-scale operations. Even though there is clear evidence that SSAD is beneficial, the technology is still not utilized to its full potential. Most of the research conducted in the past has been on the study of large-scale systems. The current state of the SSAD technology in Europe includes identifying the process design, operational features, and influential EU policies. The most recent advances connected SSAD and the challenges met (O'Connor et al., 2021). Since incentives are structured right now, the energy goals set by the EU at the local level are impossible to achieve. To accomplish this goal, the policy mix of the EU will need to be rethought to take into account regional disparities. Even though there are certain compromises to be made in terms of socioeconomic and environmental factors, the generation of energy through agriculture can stabilize farmers' income and maintain the viability of rural communities (O'Connor et al., 2021). The biogas plants produce electricity, reduce emissions, and increase economic development by increasing profit, and their upgrading can increase environmental performance (Iqbal et al., 2018). Its parallel situation positively depicts the biogas adoption of sites and projections to increase economic growth. We formulated the first hypothesis in light of these findings as follows:

Hypothesis 1. (H1): there is a positive association between the availability of technicians for biogas plants and the adoption of biogas social projects in China.

Low-Cost and Clear Policy

The established portable biogas plants are advantageous due to abundant production of methane gas, low cost, clear policy, and lightweight. This type of biogas plant can produce for the prosperity of rural areas and fulfill domestic requirements (Capodaglio and Dondi, 2016; Wang Z et al., 2020). The prosperity of the rural areas is correlated with the adoption of biogas plants. Prosperity and biogas development include household biogas digesters, biomethane plants, biogas grid plants for electricity generation, the development of large-scale biogas plants, and small-scale biogas digesters in rocky areas: the incentives, digested biogas integration, various capital investment mechanism construction, and improvement for the biogas sector (Iqbal et al., 2018). The influence of the production of biogas and the generation of energy in rural and urban areas, as well as the assistance it provides for implementing Brazilian environmental and social policies (Freitas et al., 2019). These findings are consistent with the development of biogas plants initiated in China. This importance elaborates on the significance of biogas for individual investment and its association with economic prosperity. Biogas is the best RE option for the region's development and prosperity regarding a professional management unit. Finally, commercial biogas is considered the direction of revolution in rural areas and provides social, economic, and environmental benefits (Zemo et al., 2019). Overall, the conceptual model of this study is helpful to solar biogas plant issues and for the prosperity of rural people in China. These arguments lead us to the formulation of the second hypothesis as follows:

Hypothesis 2. (H2): there is a positive association between China's low-cost and clear policy to adopt biogas plants.

User Satisfaction and Biogas Plant Quality

Recently, electricity has been produced with the use of biogas. The feedstock material is a sustainable source of RE (Luyer et al., 2021). Experiments with the production of biogas and biomethane on a big scale across European nations' policy tools, agricultural intensification, and supply chain dangers are all factors that come into play while figuring out the future course of policy for particularly important countries (Zhu et al., 2019). The use of biogas potential to produce electricity can mitigate power crises, be helpful for feedstock material management, and solve the environmental issues in China. Feedstock materials such as plant, agricultural, and food waste are the best energy sources and essential components for a sustainable transition. It helps raise people's livelihood but could also denote positive impacts on their lives. The biogas potential of China is required for the appropriate use of the country's economic development. The biogas support program (BSP) is needed to be spread in rural areas all over the country (Jan and Akram, 2018). Benefits gains are more extensive in the coming years than benefits gains in the first year of the biogas plant due to the fixed installation cost. According to benefit-cost analysis, using rice husk to install a biogas plant with poultry waste is feasible in China. We proposed the third hypothesis by keeping in view these findings as follows:

Hypothesis 3. (H3): there is a positive association between user satisfaction and plant quality and the adoption of biogas in China.

Operational and Maintenance Government Support and Adoption of Biogas Plants

The biogas sector of China has enormous potential and needs appropriate utilization with relevant information to the local farmers. The issues of the biogas sector can be removed with the investment of foreign investors if operational and maintenance government support is provided to the biogas plant users in China. Operational and maintenance costs vary from installation scales. The adopted biogas plant's technical and operational design should be considered for similar projects. The government can play a primary role in promoting the biogas sector in the country by offering subsidies, incentives, and current policies to attract stakeholders and investors (Jarrar et al., 2020). The fixed dome biogas plants show excellent financial performance due to low capital costs (installation and reaction), lower maintenance and operational costs, and rapid

payback (Yasar et al., 2017). The thermal energy produced with biogas positively affects evaluation outcomes. The RE policy incentives can attract investors for biogas and improve biogas plants' viability if the policy is amended and independent projects are allowed as a renewable plug-in (Govender et al., 2019). In China, the biogas power plant can be benefited from the economic conditions. These conditions are potential impacts of some elements of operation and maintenance and close associations of improvement toward biogas power projects. In the light of these arguments, we proposed the following hypothesis as follows:

Hypothesis 4. (H4): there is a positive association between operational and maintenance government support and adopting biogas in China.

Moderating Role of Awareness and Understanding Between the Availability of Technicians and Biogas Plants

Awareness and understanding of biogas technology to the farmers of the rural regions are associated with positive and significant feedback toward the economy. The contribution, local experts' availability, and attractiveness of biogas technology's increasing RE market are the essential factors in adaptation to climate change (Hasan et al., 2020). A clear picture is depicted in developing countries like China, where biogas production can improve with biogas technology adoption. The failed ratio of productive biogas installation is 50% due to technological and logical issues within 2 years after contracting. Due to the poor quality of digester feed, the lack of awareness and understanding of the facilities failed to sustain biogas production. During the shortage of primary feedstock, the local technical data to use alternatives also failed to maintain biogas production (Tumusiime et al., 2019). The current position states the evaluation is based on awareness and understanding of biogas plants, which describes the broader geographical region view. These elements are linked significantly with biogas installation and production. Some factors played a role in delaying specific biogas plants, but developing countries positively associated services with biogas plants. Acknowledging responsibility, consumer effectiveness, environmental concern, and awareness of consequences ultimately and significantly affect the farmer's norms. Subsequently, the farmers' intentions are affected by personal criteria to adopt biogas technology in China (Wang Z et al., 2020). In light of these arguments, we proposed the following hypotheses as follows:

Hypothesis 5. (H5): the project's awareness and understanding positively moderate the association between the availability of technicians and the adoption of biogas in China.

Hypothesis 6. (H6): the project's awareness and understanding positively moderate the association operation and maintenance of government support and adoption of biogas in China.

Hypothesis 7. (H7): the project's awareness and understanding positively moderate the association between the low-cost and clear policy and the adoption of biogas in China.

Hypothesis 8. (H8): the project's awareness and understanding positively moderate the association between user satisfaction and plant quality and adoption of biogas in China.

In this study, energy choice theory is on a theoretical basis. This study can apply the energy choice theory in a specific area. Depending on the gas connection availability, an investigation will be conducted where it has the potential to choose between connecting with a Sui gas national or biogas from agriculture waste or other alternative energies. The energy ladder model defined that any household can choose a specific fuel. Different types of fuels can be changed with this linear process. Traditional fuels like dung cake, shrubs, and firewood are used on the bottom level in China. Still, modern fuels such as electric stoves and methane gas depend on the household's average income. This model explicitly highlights the individual pay for the explained energy choice (Gautam et al., 2020). Countries worldwide face challenges by using conventional energy sources to meet their people's clean energy demands and exploring new RE sources. This theory has two main factors: economic and wealth status (Ozoh et al., 2018). In China, this study was conducted based on the theoretical background to determine the adopting factors for biogas energy plants. The assumed environmental, social, and technical factors could not be excluded from the failure or success of the biogas energy plants through consumers or society. The reflection of consumer perception can deliver through the conceptual model shown in **Figure 1** to the choice of energy source for living. The conceptual model shows the expected relationship between the independent variables (IVs) and dependent variables (DVs). The current model also shows the expected moderation between the IV and DV.

RESEARCH METHODOLOGY

This research has used non-probability (snowball) sampling questionnaires and mobile applications to improve existing biogas plants and check the potential of biogas in China. This sampling technique has not provided an equal chance for all the population members to participate in the research study. This sampling technique is used for specific population characteristics and to conduct pilot studies, qualitative research, or exploratory research. The common non-probability sampling techniques include quota sampling, snowball sampling, purposive sampling, voluntary response sampling, and convenience sampling. Working biogas plants were selected for research to improve their service and quality. Specific biogas plants were adopted when the snowball sampling technique was employed to present our sample from biogas plants throughout the country. To fulfill this purpose, the researchers surveyed from March to September (2021); when the fourth wave named delta variant virus, a type of coronavirus (COVID-19), was at its peak in China, it was a high risk of approaching relevant respondents (the biogas plant owners).

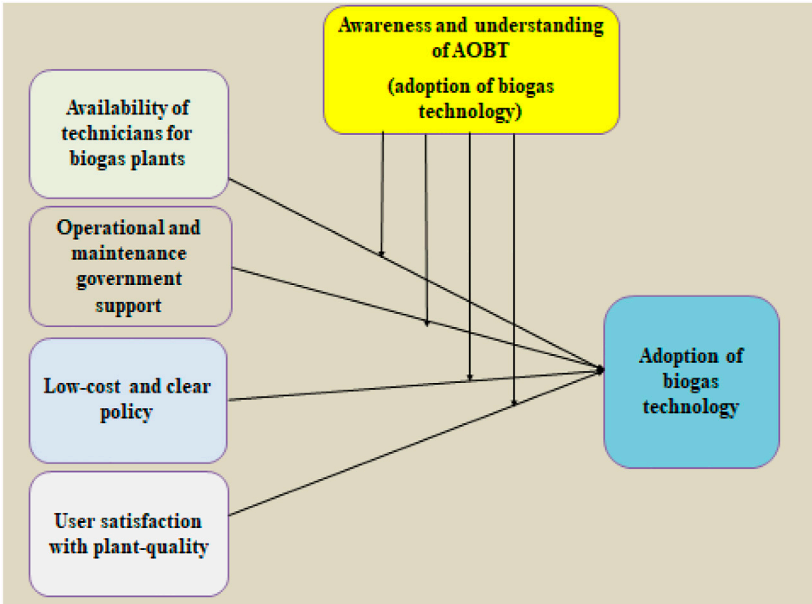

FIGURE 1 | Conceptual model.

Moreover, all representatives have a heterogeneous background in biogas plants and demographic measures (see **Supplementary Appendix Tables A1, A2**). Furthermore, snowball sampling was employed to select respondents (biogas plant owners) with diverse behaviors. Snowball sampling is unsuitable for theoretical generalization, primarily when randomization cannot be performed but a participant is referred to another participant (Ozoh et al., 2018). The ongoing research goal is to examine the potential and barriers to adopting biogas technology and assess satisfied owners of biogas plants with their financial performance. The moderating role of awareness and understanding in adopting biogas plants is among the nexus of satisfaction and reduces the barriers. The present study has adopted the quantitative approach of data collection and the questionnaires to collect the data from the respondents.

Our research employed structural equation modeling (SEM) for data analysis objectives (Irfan et al., 2021). The study adopted this method to analyze the relational dimensions because it is a component-focused method (Urbach and Ahlemann, 2010). The extensive use of PLS-SEM in subsequent studies is evidence of its appropriateness (Ying et al., 2020). It is a component-focused strategy used to assess the relationship characteristics of the research (Urbach and Ahlemann, 2010; Ahmad et al., 2021). PLS-SEM was selected over all other covariance-based methods because it enables researchers to assess both computations and factor structures. PLS-SEM's robustness and usefulness in the researched domain have been shown by its expanding application. PLS-SEM was chosen by the authors due to its popularity and suitability, as proven by the following research (Hair et al., 2019b; Raza et al., 2020). In addition, the statistical power of partial least square route modeling is greater than that of covariance-based structural equation modeling. This shows that PLS-SEM is more useful for detecting links between the variables under study.

On the other hand, an appropriate statistical process is most important for management and social science research (Ramayah et al., 2010). Measurement and structural models are two-stage analysis approaches of PLS-SEM that include measurement results in two steps (Osborne et al., 2010). Convergent validity was measured over the average variance extracted (AVE), internal consistency reliability was measured over composite reliability (C.R), and item reliability was measured over outer loading using measurement analysis. Reliability and validity tests or the assessment of the inner model is included in the measurement assessment model. Hypothesis/relationship testing or the evaluation of the outer model is included in the structural assessment model. The present research used PLS 3.0 software for primary data analysis and examined the links among the variables under study. Additionally, partial least square path modeling has higher statistical power than covariance-based structural equation modeling. PLS-SEM is more advantageous for intercepting relationships among the variables.

In addition, the smart-PLS for VB-SEM uses the PLS-SEM path modeling method to examine the nexus among the variables (Solangi et al., 2019). The purpose of smart-PLS is hypothesis testing, and the complex model research has adapted to it. The smart-PLS have two approaches: measurement assessment and structural models for the analysis. The assessment measurement model includes the reliability and validity of the constructs checked with convergent and discriminant validity. The convergent validity related to the correlation among the items was examined using Cronbach's alpha, composite reliability, and items loading. However, the discriminant validity is associated

with the correlation among variables examined using Fornell-Larcker criteria, cross-loading, and heterotrait–monotrait ratio. Moreover, the assessment of the measurement model includes the testing of hypotheses that are reviewed using path analysis—the analysis of the study discussed in the findings section. The path analysis has shown the links among the variables.

Sample and Procedure

This study was conducted based on presently working biogas plants. We contacted 79 biogas plant users from 35 villages, of which 63 agreed to participate in the survey. The data collection process started with a few numbers of biogas plants. After that, it increased progressively. After getting the consent of biogas plant owners, the researchers provided opened and closed-hand questionnaires using a smartphone to each biogas plant owner *via* LinkedIn and WhatsApp. This research questionnaire was applied after initial site visits, interviewing biogas plant owners, considering the existing literature, and discussing with an expert. Last, 56 filled questionnaires were returned from the total sample size of the questionnaire survey. However, the researchers discarded five questionnaires due to unmatched and inadequate responses. There were a few participants in this study; hence, the snowball sampling technique was used. This process led the researcher to attend to the still undiscovered respondents. Finally, the sample resulted in 51 usable responses from the overall sample size, and the response rate was 80.95%. The finding is generated based on a fair sample representation, and PLS-smart was used for data analysis.

The demographic features of the respondents include gender, age, and owner's experience, the owner's education, and the biogas plant names currently working. The respondents were given the proper response (see **Table 1**). The present research followed the standard 5-category scale in which one always symbolizes and five expresses as never. The questionnaire covers the personal detail of biogas plant owners and features of biogas plants, like quality, user satisfaction, biogas plant cost, and energy supply. The present study adopted six predictors of availability of technicians for biogas plants (AT) with six items, the operational and maintenance government support (OMGS) with five items, the user satisfaction and plant quality (USPQ) with five items, the low-cost and clear policy (LCCP) with seven items, adoption of biogas technology (ABT) as a dependent variable with eight items and finally awareness, and understanding of the adoption of biogas technology (AUAOBT) as a moderator variable with six items. The data analysis and results section tables show these variables with links. The goal was to gather responses from the biogas plant users on three critical points at the time of investment in a biogas plant, i.e., operational matters and maintenance, technical and skilled labor, and day-to-day operational tools used in biogas plants. In this study, a new research questionnaire was developed with three questions and tested before the author's application; some questions covered the satisfaction of biogas plant users. Some online questions are related to the investment in biogas plants and the most favorable scenario for the satisfaction of biogas plant users. Some online questions are asked from the owners of biogas plants with enough knowledge about biogas plants' operation. These questions include the operational and maintenance cost of biogas plants and day-to-day plant expenses. Finally, some questions are related to the technical and skilled laborers and trained owners of biogas plants.

Instrument and Variable Measurement

Researchers have adopted all items from different previous literature reports in this research. Items based on the availability of technicians for biogas plants were constructed from the study (January 2017). Things regarding the operational and maintenance of government support were adopted from the research study (Shah and Sahito, 2017). Items related to the low-cost and clear policy were assumed (Ozoh et al., 2018). Objects related to user satisfaction and plant quality were constructed (Chin and Newsted, 1999). Items that belong to the awareness and understanding of adopting biogas technology (AOBT) were adopted (Wang Z et al., 2020). Finally, items related to the adoption of biogas technology were adopted from this study (Hair et al., 2014).

DATA ANALYSIS AND RESULTS

All verified validity and reliability values in this measurement model are given below in relevant tables. The measurement assessment model shown in **Figure 2** indicates the factor loading of the variables. All the factor loading values are more significant than 0.50, so the convergent validity of all items is valid in the measurement assessment model. The path analysis has been shown to test the hypotheses, and the results have shown that AT, AUAOBT, and LCCP are positive. In contrast, OMGS negatively affects ABT and accepts AT, AUAOBT, LCCP, and USPQ. In addition, the results also show that AUAOBT significantly moderates the links of AT, AUAOBT, LCCP, USPQ, and ABT and accepts AT, AUAOBT, LCCP, and USPQ. This section analyzes convergent validity that shows the correlation among items. The results and links reported in **Table 2** indicate the loadings and AVE values are higher than 0.50, while alpha and composite reliability (C.R) values are more significant than 0.70. These values have indicated that convergent validity is the valid and high connection among the items. AVE values are also higher than 0.50, and composite reliability (C.R) values are greater than 0.70. These values have indicated a high correlation among items and valid convergent validity.

Measurement Assessment Model

The measurement model confirms the reliability and validity of the constructs, and the factor loadings of all items were approved by the model (Hair et al., 2019a). The measurement evaluation model is consistent on reliability tests (item reliability and internal consistency reliability) and validity tests (convergent validity and discriminant validity) (Hair et al., 2011). All item loadings are well upstairs with the threshold value of 0.5 (Hair et al., 2014) (**Table 2**). The study analysis verified that all the averaged factor loadings were greater than 0.50, and each observation contributed to the constructed variable (Arbuckle, 2011). AVE exceeds the suggested value of 0.5. The composite

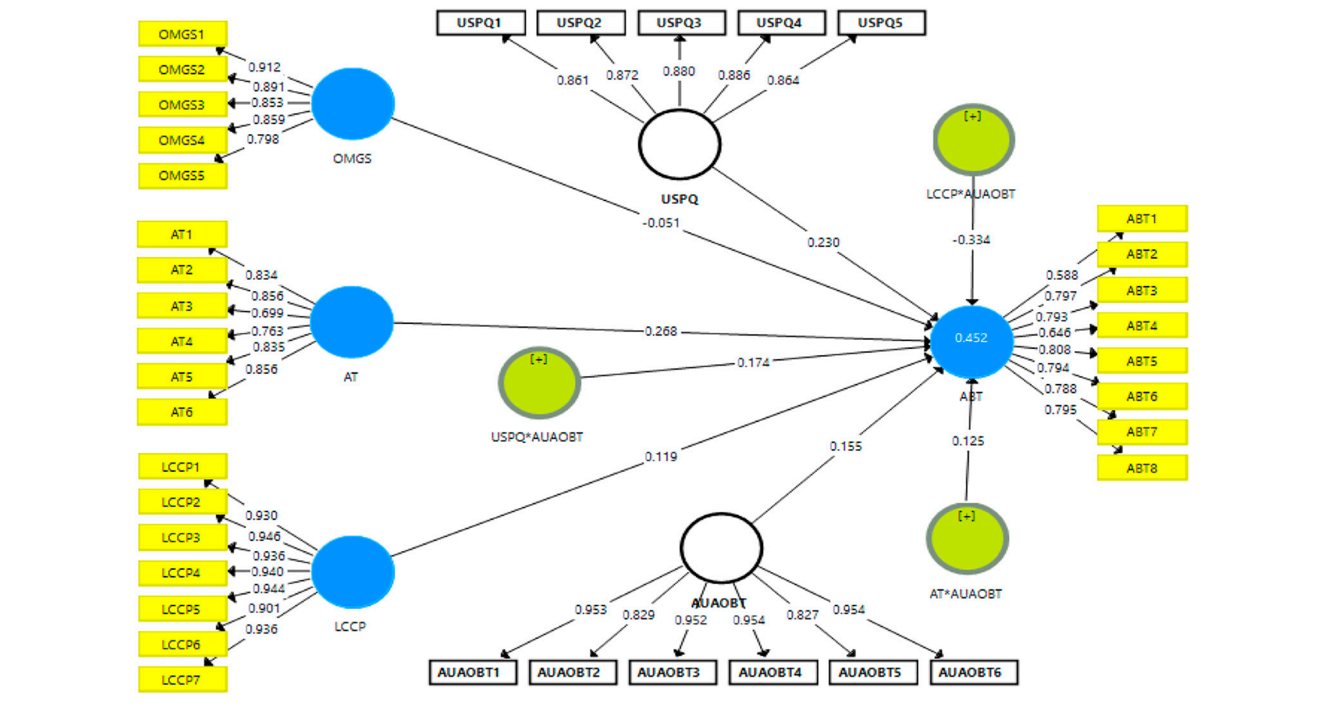

FIGURE 2 | Measurement model assessment.

reliability value for each standard exceeds the cut-off point of 0.70, indicating that the measurements are reliable (Anderson and Gerbing, 1988). The results of the present research designate that all the values of AVE are between 0.570 (adoption of biogas technology) and 0.871 (low-cost and clear policy), and C.R values are between 0.913 (adoption of biogas technology) and 0.979 (low-cost and clear policy). The values of all additional loadings are between 0.5 and 0.946.

The research findings also include the correlation assessment among variables named discriminant validity. The cross-loading was used to test the discriminant validity. These values have indicated a low correlation among variables and verify discriminant validity. The findings section also shows in **Table 3** the discriminant validity through the Fornell–Larcker criterion about the nexus among the variables. The bold values in **Table 4** show that the factors have a strong relationship, while others have weak ones. The bold values of the cross-loadings are compared with other factors row-wise to check discriminant validity. The variable values have shown that the values indicated the nexus with the variable itself are higher than those with other variables. These values explored that discriminant validity is the valid and low connection among the variables. The measurement assessment model is shown in **Figure 2**, indicating the variables' factor loading. All the factor loading values are more significant than 0.50, so the convergent validity of all items is valid in the measurement assessment model.

The heterotrait–monotrait ratio of correlations (HTMT) for the discriminant validity measure is considered more suitable due to different researchers' criticism of the criteria of Fornell–Larcker (Akbar et al., 2019). The value of discriminant validity is confirmed if it is less than 0.85 (Cohen, 1988) or 0.90 (Ali et al., 2021). All values are less than 0.90, as shown in **Table 5**. The findings section has also shown the variables' discriminant validity. The variable values have shown that the values indicated the nexus with the variable itself are higher than those with other variables. This research also used the HTMT ratio to examine the correlation among variables. The statistics of HTMT have shown that the values are less than 0.85.

Structural Assessment Model

First, we evaluated the measurement model, and then the structural assessment model was evaluated, which checked the relationship between exogenous and endogenous variables. The assessment of the structural model is based on different types of statistical values, including effect size (f^2), t values, predictive relevance (Q^2), coefficient of determination (R^2), and path coefficient (β values). The study evaluates hypotheses and estimates the significance of path coefficients using the criteria provided in the PLS-SEM literature. The bootstrapping process was employed with 5000 sub-samples with a 5% significance level (one-tailed) to test the significance of the hypotheses. Results indicate that all hypotheses are accepted except H6. Availability of technicians for biogas plants ($\beta = 0.268$; $t = 2.909 > 1.64$; $p < 0.05$), availability of technicians for biogas plant relationship (moderator), ($\beta = 0.230$; $t = 4.050 > 1.64$; $p < 0.05$), awareness and understanding through AOBT ($\beta = -0.125$; $t = 1.870 > 1.64$; $p < 0.05$), low-cost and clear policy, ($\beta = 0.155$; $t = 1.874 > 1.64$;

TABLE 2 | Convergent validity analysis.

Item	Loading	Alpha	CR	AVE
ABT1	0.588	0.890	0.913	0.570
ABT2	0.797			
ABT3	0.793			
ABT4	0.646			
ABT5	0.808			
ABT6	0.794			
ABT7	0.788			
ABT8	0.795			
AT1	0.834	0.893	0.919	0.655
AT2	0.856			
AT3	0.699			
AT4	0.763			
AT5	0.835			
AT6	0.856			
AUAOBT1	0.953	0.959	0.968	0.834
AUAOBT2	0.829			
AUAOBT3	0.952			
AUAOBT4	0.954			
AUAOBT5	0.827			
AUAOBT6	0.954			
LCCP1	0.930	0.975	0.979	0.871
LCCP2	0.946			
LCCP3	0.936			
LCCP4	0.940			
LCCP5	0.944			
LCCP6	0.901			
LCCP7	0.936			
OMGS1	0.912	0.920	0.936	0.745
OMGS2	0.891			
OMGS3	0.853			
OMGS4	0.859			
OMGS5	0.798			
USPQ1	0.861	0.922	0.941	0.762
USPQ2	0.872			
USPQ3	0.880			
USPQ4	0.886			
USPQ5	0.864			

Notes: N = 51; AT, availability of technicians for biogas plants; OMGS, operational and maintenance government support; LCCP, low-cost and clear policy; USPQ, user satisfaction, and plant quality; AU, awareness and understanding of AOBT; ABT, adoption of biogas technology.
Bold values show that the factors have a strong relationship.

TABLE 4 | Cross-loading.

Item	ABT	AT	AUAOBT	LCCP	OMGS	USPQ
ABT1	**0.588**	0.305	0.278	0.354	0.206	0.187
ABT2	**0.797**	0.456	0.493	0.397	0.124	0.319
ABT3	**0.793**	0.459	0.446	0.426	0.095	0.359
ABT4	**0.646**	0.261	0.244	0.330	0.145	0.233
ABT5	**0.808**	0.447	0.382	0.398	0.144	0.315
ABT6	**0.794**	0.358	0.398	0.304	0.124	0.284
ABT7	**0.788**	0.373	0.359	0.319	0.090	0.340
ABT8	**0.795**	0.351	0.377	0.305	0.146	0.297
AT1	0.400	**0.834**	0.663	0.388	0.180	0.327
AT2	0.453	**0.856**	0.731	0.450	0.134	0.355
AT3	0.364	**0.699**	0.536	0.317	0.104	0.341
AT4	0.394	**0.763**	0.663	0.398	0.124	0.348
AT5	0.396	**0.835**	0.662	0.382	0.179	0.330
AT6	0.450	**0.856**	0.723	0.455	0.134	0.363
AUAOBT1	0.457	0.766	**0.953**	0.457	0.172	0.330
AUAOBT2	0.470	0.720	**0.829**	0.442	0.134	0.372
AUAOBT3	0.460	0.759	**0.952**	0.460	0.168	0.333
AUAOBT4	0.448	0.774	**0.954**	0.461	0.175	0.331
AUAOBT5	0.466	0.718	**0.827**	0.444	0.126	0.372
AUAOBT6	0.450	0.764	**0.954**	0.456	0.165	0.327
LCCP1	0.425	0.456	0.465	**0.930**	0.335	0.383
LCCP2	0.446	0.472	0.457	**0.946**	0.312	0.403
LCCP3	0.423	0.476	0.450	**0.936**	0.300	0.410
LCCP4	0.436	0.463	0.473	**0.940**	0.332	0.379
LCCP5	0.450	0.468	0.462	**0.944**	0.313	0.398
LCCP6	0.467	0.447	0.471	**0.901**	0.288	0.359
LCCP7	0.434	0.456	0.469	**0.936**	0.317	0.378
OMGS1	0.225	0.213	0.199	0.331	**0.912**	0.173
OMGS2	0.145	0.162	0.162	0.293	**0.891**	0.162
OMGS3	0.111	0.069	0.102	0.301	**0.853**	0.110
OMGS4	0.091	0.123	0.096	0.275	**0.859**	0.118
OMGS5	0.081	0.129	0.122	0.208	**0.798**	0.118
USPQ1	0.338	0.309	0.292	0.354	0.126	**0.861**
USPQ2	0.351	0.389	0.342	0.357	0.130	**0.872**
USPQ3	0.329	0.373	0.306	0.351	0.146	**0.880**
USPQ4	0.318	0.376	0.345	0.370	0.189	**0.886**
USPQ5	0.370	0.403	0.361	0.375	0.136	**0.864**

Notes: N = 51; AT, availability of technicians for biogas plants; OMGS, operational and maintenance government support; LCCP, low-cost and clear policy; USPQ, user satisfaction and plant quality; AU, awareness and understanding of AOBT; ABT, adoption of biogas technology.

TABLE 3 | Fornell–Larcker criterion.

Variable	ABT	AT	AUAOBT	LCCP	OMGS	USPQ
ABT	0.755					
AT	0.508	0.809				
AUAOBT	0.504	0.823	0.913			
LCCP	0.472	0.496	0.498	0.933		
OMGS	0.173	0.176	0.172	0.336	0.863	
USPQ	0.393	0.425	0.378	0.415	0.166	0.873

Notes: N = 51; AT, availability of technicians for biogas plants; OMGS, operational and maintenance government support; LCCP, low-cost and clear policy; USPQ, user satisfaction and plant quality; AU, awareness and understanding of AOBT; ABT, adoption of biogas technology.

TABLE 5 | Discriminant validity using the heterotrait–monotrait ratio (HTMT).

Variable	ABT	AT	AUAOBT	LCCP	OMGS	USPQ
ABT						
AT	0.559					
AUAOBT	0.535	0.786				
LCCP	0.504	0.528	0.514			
OMGS	0.172	0.176	0.167	0.342		
USPQ	0.427	0.468	0.400	0.437	0.170	

Notes: N = 51; AT, availability of technicians for biogas plants; OMGS, operational and maintenance government support; LCCP, low-cost and clear policy; USPQ, user satisfaction and plant quality; AU, awareness and understanding of AOBT; ABT, adoption of biogas technology.

TABLE 6 | Structural model results (hypothesis testing).

Hypothesis	Relationship	Beta	S.D.	T-statistics	*p*-value	Supported	R^2	Q^2	f^2
H1	AT–>ABT	0.268	0.092	2.909	0.002	Yes	0.478	0.248	0.093
H2	AUAOBT–>ABT	0.125	0.067	1.870	0.032	Yes		0.167	0.037
H3	LCCP–>ABT	0.155	0.083	1.874	0.032	Yes			0.110
H4	USPQ–>ABT	0.119	0.070	1.695	0.047	Yes			0.017
H5	OMGS–>ABT	–0.051	0.046	1.090	0.139	No			0.019
H6	LCCP *AUAOBT–>ABT	–0.334	0.066	5.077	0.000	Yes			0.021
H7	AT *AUAOBT–>ABT	0.230	0.057	4.050	0.000	Yes			0.013
H8	USPQ *AUAOBT–>ABT	0.174	0.056	3.125	0.001	Yes	0.489		0.016

Notes 1: N = 51; AT, availability of technicians for biogas plants; OMGS, operational and maintenance government support; LCCP, low-cost and clear policy; USPQ, user satisfaction and plant quality; AU, awareness and understanding of AOBT; ABT, adoption of the biogas technology.
Notes 2: (*), the moderating relationship indicated by the asterisk among the variables.

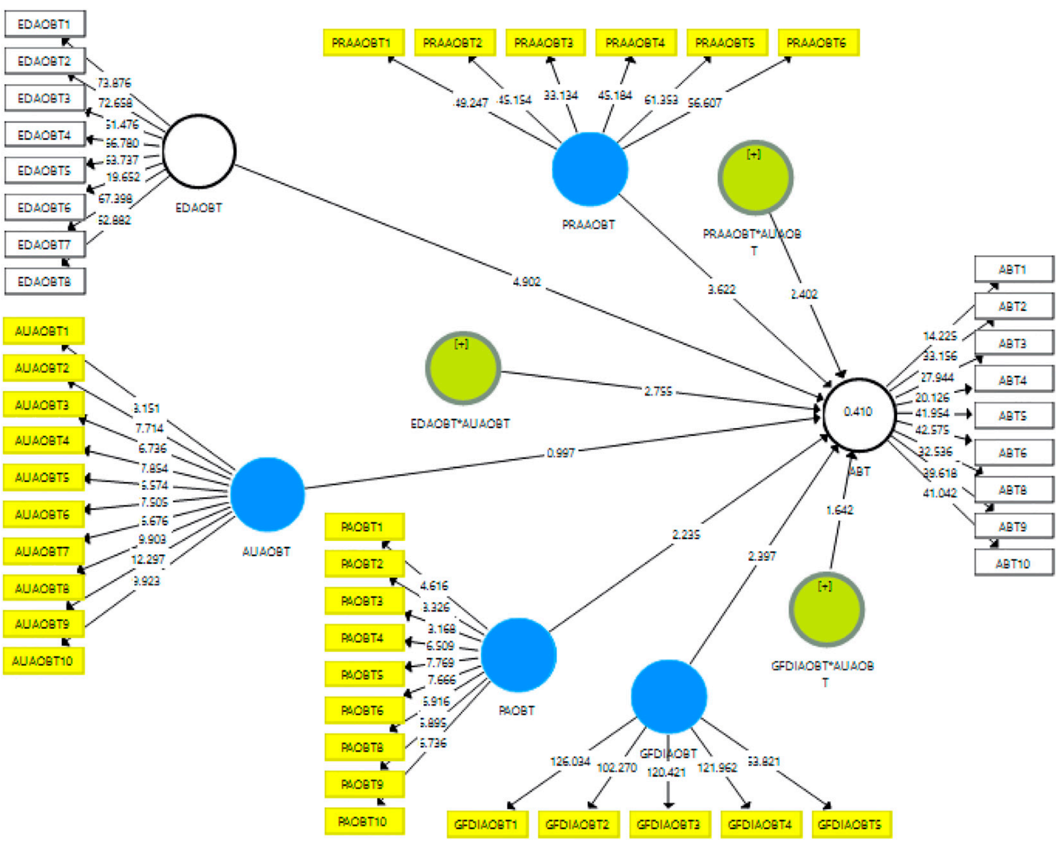

FIGURE 3 | Structural model assessment.

$p < 0.05$), low-cost and clear policy relationship (moderator), (β = 0.334; t = 5.077 > 1.64; p < 0.05), user satisfaction and plant-quality, (β = 0.119; t = 1.695 > 1.64; p < 0.05), user satisfaction and plant-quality relationship (moderator), (β = 0.174; t = 3.125 > 1.64; p < 0.05), and operational and maintenance government support (β = –0.051, t = 1.090 > 1.64, p < 0.05) have a positive significant for adoption of biogas technology.

The R^2 value of the availability of technicians for biogas plants through AOBT is 0.478, which displays that the model has substantial explanatory power for adopting biogas technology in China. However, only based on the value of R^2 is not considered a suitable and effective method to assist a model. Consequently, the measurement of predictive relevance Q^2 of the model is the best way. The latent exogenous standards have excessive predictive relevance, which shows that the value of Q^2 is more sophisticated than zero. The model has significant predictive relevance because the results show that the value of Q^2 is 0.248, which suggests increasing the small-scale industry's

TABLE 7 | Satisfaction and views of biogas plant users.

Description	Case (%)	Response (%)	Frequency
Food is cleaner and tastier using biogas	10.8	6.4	6
Preparation of appliances	4.9	3.2	3
Workload reduction	8.9	5.3	5
Cooking made easy	6.1	4.2	4
Easy biogas plant operation	12.8	7.3	7
Food preparation and lighting (sufficient gas)	14.7	8.5	8
Technicians' availability	20.6	11.6	11
Advantages of health	6.9	4.3	4
Advantages of economics	12.9	7.4	7
Advantages of the environment	8.9	4.3	5
Reputation in the society	10.9	6.4	6
Others	12.9	7.4	7

TABLE 8 | Barriers and challenging factors.

Variable	Description	Case (%)	Response (%)	Frequency
Reasons through which users are not fully satisfied with biogas plants	Insufficient gas to prepare food/lighting	7	9	12
	Unavailability of technicians	9	11.7	16.7
	Technical problems encounter frequently	7	9	8
	Through extra workload	5	6.3	8.8
	Biogas plant operational difficulty	3	3.7	4.9
	Prepared food (not pleasant)	7	8	11.9
	Others	5	6.3	8.9
Uncontrolled reasons for biogas plants	Complete work stops occasionally	7	6.5	12.8
	To prepare food/lighting gas is insufficient	8	8.4	14.7
	Unavailability of technicians	9	9.5	16.7
	Technical problems encounter frequently	11	11.5	19.8
	Through extra workload	8	8.4	14.5
	Food is not tasty using biogas	7	7.5	12.5
	Gas leakage difficulty	7	8	11.9
	Stove's malfunctioning	5	5.3	8.7
	Others	9	9.5	16.8
Main problems or common reasons for a biogas plant work failure	Poor material applied for construction	9.5	7.5	18.5
	Poor installation service quality	5	3.4	8.7
	Old/outdated design	10	7.6	18.7
	Bio-slurry mismanagement	4	3.2	6.9
	Workload increasing	8	5.2	14.7
	Poor maintenance	14	10.5	26.5
	Spare parts unavailability	11	8.4	20.7
	Stove's malfunctioning	5	5.3	8.7
	Empower local gas distribution authority in case availability of natural gas	7	5.4	12.8
	Unavailability of the skilled operator of biogas plants	12	9	22.7
	Poor operation with unbalanced feed of water and dung	20	15.6	40.3
	Natural disaster	10	7.7	18.7
	Un-sacred attachment toilet	3	2.5	4.9
	Bio-slurry obstruction in the pipeline	11	8.4	20.7
	Blockage of the pipeline caused by condensed water	10	7.7	18.7
	Others	16	16.9	30.5

performance through SHS. These are the typical values of f^2, including 0.02, 0.15, and 0.35, which indicate small, medium, and large effects in three categories, respectively. Thus, the value of f^2 assumed that the effect size differs from medium to large (see **Table 6**). **Table 6** has several kinds of statistical techniques. The structural assessment model is shown in **Figure 3**, which indicates the significant relationship among the variables because the T-values are greater than 1.64. All hypotheses are accepted except H5. All the values of moderated variables are positive signs and indicate an entirely significant relationship in the structural assessment model for adopting biogas technology in China.

The structural assessment model indicates the relationship of the variables because the T-values are more critical than (1.64). The adoption of biogas technology is positive and significant for the availability of technicians for a biogas plant in China. All the values of moderated variables have positive signs. They indicate an entirely substantial relationship in the structural assessment model for adopting biogas technology to attract green FDI in China. Second, to explore the actual issues of biogas plant owners and collect practical experience knowledge about the maintenance and operations hindrances, we conducted semi-structured interviews about various operational aspects of biogas plants with illiterate (those who cannot fill the questionnaires) biogas plant owners. The aspects include maintenance and operation costs of biogas plants, availability of technicians, cost of capital, initial installing cost, and technology awareness. We have 43 biogas plant owners interviewed from rural areas of China. Finally, all the parameters considered for biogas plants and the response of biogas plant owners are revealed in **Tables 7**, **8** and are shown in (%). All % figures are the division of responses collected from (illiterate) biogas plant owners. **Table 7** demonstrates the satisfaction and views of respondents (biogas plant owners) from China for their biogas plants. The primary reasons are the easy operation of the biogas plant, availability of technicians, economic advantages, sufficient gas collection for food preparation, gas used for lighting, and social reputation. Countries such as India, Nepal, and Bangladesh generally have technical service availability as a sufficient driving force for social project development (Breitenmoser et al., 2019). A total of 64% of respondents said that adopting biogas technology needed user satisfaction with a biogas plant in China. About 21% of respondents expressed that a lower cost and straightforward policy are required for biogas technology, but 15% disclosed that user satisfaction and plant quality are also necessary. Additionally, half of the biogas plant user respondents reported that their plants are functional and serviceable.

Important Barriers and Inspiring Factors

The partial adoption of biogas plants is facing a list of various discouraging factors. Unavailability of technicians has the highest response attributed to 16.8%, whereas frequent operational problems were 13%, and low biogas pressure is another problem. Many operational problems are faced by the biogas plants, such as deterioration of the steel parts, roof and wall crack development of the biogas plants, and leakages of the gas pressure (Zemo et al., 2019; Scheutz and Fredenslund, 2019). The lowest pressure recorded for biogas was 4.9%, a severe issue for properly cooking food. Poor mixing in feed is the main reason for the low pressure or biogas inside the reactor. The proper stirring mechanism in biogas plants is required to improve the gas pressure for the end-user (Nsair et al., 2019). The frequent technical problems are the reasons for the delay in the operation of the biogas plant, about which 21% of the owners complained. Correspondingly, to handle the biogas plant, the extra workload was 15%, gas leakages were 13%, and technical support was equal to zero for biogas consumers. The users of biogas plants feel failure and discouragement due to the contribution of these factors, and the weak approval of technicians is attributed to the policy framework of the project. The sustainability of a biogas plant project is negatively affected without a supporting system and technical assistance running in the background (Pandyaswargo et al., 2019). Barriers and challenges of currently working biogas plants in China are shown in **Table 8**.

DISCUSSION AND IMPLICATIONS

The present research has both theoretical and empirical implications. The current significant literary work contributes to the biotechnology and socioeconomic literature. This study presents the influence of four factors such as AT, OMGS, LCCP, USPQ, AUAOBT, and ABT, to attract the farmers to biogas plant adoption and sustainable development of biogas technology in China. The study provides guidelines to the policymakers and higher management of the government sector and private NGOs to facilitate farmers adopting biogas plants and improving biogas technology. The present study conveys extreme importance for policymakers, economists, and competent energy sector authorities to remove the major barriers and provide financial assistance to the farmers for adopting biogas technology plants. The best planning of the top management can reduce critical factors and barriers to biogas plants, contributing to biogas-related awareness and understanding. Therefore, biogas technology adoption can reduce the energy crisis and improve the financial position of the farmers. Still, government support can enhance the biogas plant adoption and motivational level among the rural areas and new investors.

The results indicate that the low-cost and clear policy significantly relates to adopting biogas plants and attracting new investors due to expenditure saving and mechanism satisfaction. The low-cost and clear biogas technology policy increases farmers' confidence in adopting biogas plants and provides better living standards for rural areas. A past study has supported these results (Garfí et al., 2019). This study also discussed that awareness and maintenance of biogas plants is not a perfect moderator between operating and upkeep of biogas plants and adopting biogas technology. The study reveals that awareness and understanding of biogas plants affect the adoption capacity of biogas technology in rural areas of China. The current results agree with Luo et al. (2021). The past studies indicate that awareness and understanding of biogas plants affect installation factors and adoption of biogas technology. This study has also noted that awareness and understanding of biogas plants is a considerable moderator between low-cost and clear policy and adoption of biogas technology in China. The results are in line with the results of the previous study (Havrysh et al., 2020), which show that the awareness and understanding of biogas technology affect the low-cost and clear policy of the government and attract the farmers of rural areas to adopt biogas plants and save money (Winquist et al., 2019).

The current study suggested that the availability of technicians proves the adoption of biogas plants and socially and economically benefits the farmers of selected rural areas. The low-cost and clear policy has a high-performance turnover to

attract farmers and new investors to invest in biogas plants. The study also indicates that operational and maintenance government supports positively correlate with attracting biogas plant users and the social-economic benefit of biogas plants. User satisfaction and plant quality are a progressive way to attract farmers and new investors to adopt biogas plants and reduce the energy crisis overall and improve domestic prosperity on their own. The analysis of the study proves that user satisfaction and plant quality can play a major role in attracting local area farmers, private NGOs, and new investors to invest in biogas plants and earn economic and social benefits in China. The findings of this study offer practical guidelines for policymakers, experts, institutional bodies, regulators, the ministry of water power, and the higher management of the alternative energy development board (AEDB) to adopt these factors for a high level of former satisfaction, attracting rural farmers of selected areas for the sustainable development of biogas technology. The competent institutional authorities need to consider AT, OMGS, LCCP, and USPQ to save farmers' time, reduce cost and energy crisis, and provide better living standards for rural farmers who provide low-cost biogas energy mechanisms.

Second, the financial benefits of biogas technology are also evaluated from the interviewees' responses in this study. About 58% of respondents agree that they saved fuel expenditure, whereas 42% of respondents (biogas plant owners) did not agree. Recent studies have reported fuel cost savings (Negri et al., 2020). Additionally, 38% of respondents reported a positive change in their household financial status after biogas plant installation. In comparison, 53% of respondents had no change in their financial situation. So here this change is a feature of the number of family members and their expenditures. Joint families save less, while nuclear families are kept more in rural China and supported by contributing equally. About 53% of families could not hold their money due to aforementioned reasons. The present study's results match the past (Akter et al., 2021). Moreover, the current study results show that the availability of technicians for biogas plants assessing the adoption of biogas technology has a significant and positive relationship with the sustainable development of biogas plants. The present study results verify the past study results, underlining the impact of the availability of technicians for biogas plants on farmers adopting biogas technology (Mengistu et al., 2016). The current research suggests that the availability of technology for biogas plant elements helps attract the former to adopt biogas plants and assists the top management in removing the installation barriers of the biogas plant. Additionally, the study results explore that operational and maintenance government support positively affects the adoption and motivation of the farmers for biogas plants. The present study shows that operational and maintenance government support significantly impacts biogas plants and indicates social and economic benefits. These results approve the results of the past research (Wang X et al., 2020). This study implies that providing government support for operating and maintaining biogas plants improves the adoption of biogas and increases the attraction for new farmers to adopt this technology.

The fully satisfied users have significantly reduced their expenditures after installing a biogas plant. The reduction of expenses is considered a primary adaptive reason for the satisfaction of partially satisfied users at a specific point. Biogas plants can solve and improve a household's financial status, as indicated by this variable. Advantages include, from the environmental perspective, cleanliness, and safety after installing biogas plants, a substantial drop in fire accidents, and less smoke production attributed to better health and a clean kitchen. A total of 33% of respondents highlighted a significant decrease in fire accidents. Freedom from sickness was reported in 15%, which correlated with deficiency and smoke of black dirt in kitchen and house, and 9% decided to reduce everyday expenditures associated with fitness in response to the question. But the main benefits of biogas plants are connected with cleanliness and health. A total of 43% did not answer the questions during interviews.

Managerial Implications

Our research findings offer valuable insights into rural people and government/NGOs working in China. The study suggests that biogas plants are very suitable for the rural areas of China to save their expenditures and make prosperous economic development. With the simultaneous implementation of biogas plants, the government and NGOs should begin with motivation and complete information about the installation process to encourage rural people and their prosperity. The results also suggested that adopting biogas plants has positive and significant relationships with the availability of technicians and user satisfaction with plant quality in China. The owners of biogas plants are required to complete operational guidelines for biogas plants to reduce their financial expenditure from the output of plants. Moreover, the study findings demonstrate that skilled and trained owners get more financial and maintenance benefits than non-skilled/untrained owners. The study also explored that biogas plants are more beneficial if technicians and equipment are fully available. We also suggest that the government of China INGOs/NGOs should improve the potion of subsidies for biogas plants and economic development for the home-grown farmers. Most of the problems can be solved if one individual from the family of biogas plant owners is trained and can handle the maintenance issues to save their day-to-day expenditures. The study suggested that biogas plants should be spread to other provinces rather than Beijing, Tianjin, and Hebei with the support of the government INGOs/NGOs.

CONCLUSION AND LIMITATIONS

Biogas is considered a powerful source to produce energy worldwide. The increasing rate of biogas plants is the primary issue in adopting modern biogas plants in China and other low-income countries. Although the government of China and some relevant INGO/NGOs are trying to make acceptable said technology by giving subsidies for biogas plants to home-grown farmers, the acceptance ratio is very low in rural areas and village communities. According to the choice theory of

energy, the population of this research area expressed their interest in utilizing the biogas in native farms instead of in modern ways. Conversely, the main issue of biogas plants was maintenance and operation. The major inspiring causes behind the installation and construction of biogas plants include motivation from structure, social subsidy advantages, cases of existing biogas plant owners, and energy protection, although the significant reasons commonly include extra workload, gas leakages from connections, insufficient gas to prepare food/ lighting, complex biogas plant operations, technical problems, and unavailability of technicians.

Consequently, the present study indicates that all independent variables are significant and positively correlated with adopting biogas technology, reducing energy crises, and attaining cost-saving purposes in rural China. The current study has explored that removing the selected barriers is better and more significant for sustainable green energy generation, financial management, cost-effectiveness, return on capital investment, and assessing the fixed factors before adopting biogas plants in rural China. The outcomes of this study will also identify to the government that it is highly required to take appropriate actions to spread information and awareness on adopting biogas technology and start its development programs in the future. The value of R^2 in **Table 6** for AT is 0.478, which shows that the present conceptual model has extensive explanatory power to attract farmers to adopt biogas plants in rural China. The Q^2 value is 0.248, which indicates that the conceptual framework has significant and positive predictive relevance, which recommends that the selected barriers should be removed to increase the likelihood of adopting biogas plants in the rural areas of China. The chosen variables express their meaningful relationship to an LCCP in **Figure 1** in the model; the values of t statistic are result-oriented and more critical than 1.64, and the low-cost and clear policy positively and significantly impacts attracting farmers to adopt biogas plants in the rural area of China. In the structural assessment model, the moderated variable's importance has positive signs and indicates an exclusively substantial relationship in the structural assessment model. The present study has also displayed that selected variables and their adopted moderation in this conceptual model have a significant and positive impact on the structural assessment model on adopting biogas plants in the rural areas of China.

Finally, the buyers did not facilitate the services after sale from the construction and installation organizations or bodies. Therefore, some recommendations are given to the Chinese government to develop and promote biogas technology in rural areas of China. The government should be planning a clear policy for RE projects for operation and maintenance, capacity building sessions, technical support, and launching a media complaint about maintenance to develop biogas plants. The rural area of China has great potential for biogas technology to overcome domestic energy shortages. Consequently, some training steps should be taken by the relevant NGOs/INGOs and the government of China for sustainable project development, maintenance, and smooth operation of biogas plants in rural areas. Hence, government institutions of China and relevant INGO/NGOs should arrange skilled technicians' technical centers and provide the appropriate installation of biogas plants to the consumer after-sales service. In this current position, the other variables such as poverty, biogas plant owner literacy, the quantity of the animals, the required area for biogas plants, and other social and economic factors affecting the adoption of biogas plants have been entirely ignored. Hence, interested researchers must also identify the rest of the elements to adopting biogas plants while considering the results of this study. We have selected to adopt a biogas plant in the rural areas of a developing country such as China. Thus, the current study results are not equally valid for developed and underdeveloped countries. So the authors in the future must investigate the encouragement to attract the farmers to adopt biogas plants in developed countries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by This research study was conducted according to the Declaration of Helsinki guidelines. The Institutional Review Board of North China Electric Power University has approved the study. (protocol code 926- on 27 November 2021). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SA: writing—original draft, formal analysis, data handling, variable construction, and methodology. QY: supervision. MI: conceptualization, software, writing review, and editing. ZC: funding acquisition, writing review, and editing. All authors have read and agreed to the published version of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.887084/full#supplementary-material

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How Green Organizational Strategy and Environmental CSR Affect Organizational Sustainable Performance Through Green Technology Innovation Amid COVID-19

Maoran Ye[1], Feng Hao[2], Mohsin Shahzad[3] and Hafiz Waqas Kamran[4]*

[1]School of Economics and Management, Southeast University, Nanjing, China, [2]School of Economics, Tianjin University of Commerce, Tianjin, China, [3]School of Economics and Management, Dalian University of Technology, Dalian, China, [4]Department of Business Administration, Iqra University, Karachi, Pakistan

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***Correspondence:**
Feng Hao
hbhjhf@126.com

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The growth of green-oriented businesses for sustainable development (SD) is no longer optional in the current dynamic world, especially for manufacturing businesses in general. Accordingly, the present study investigates the interlinkages between green organizational strategy (GOS), environmental corporate social responsibility (ECSR), and organizational sustainable performance (OSP) by exploring the key mediating role of green technology innovation (GTI). This study uses a quantitative method to gather data from Chinese manufacturing industries, employing a well-structured questionnaire. Senior and middle-level managers were the intended respondents. From the primary survey, 264 valid responses were gathered. The final data were analyzed using SmartPLS (version 3.3.9) by adopting structural equation modeling (SEM) to examine the associations between the targeted constructs, and the results add to the recent literature by offering a cohesive model of GOS, ECSR, GTI, and OSP. The findings revealed that GOS has a strong positive effect on ECSR, GTI, and OSP. Further, ECSR has a strong positive impact on GTI and OSP. Meanwhile, GTI is a key mediating variable in these relationships, which previous studies have not explored. This study innovatively integrates the three green traits, namely, GOS, ECSR, and GTI, into a comprehensive model that is understudied in existing literature in order to help businesses improve their sustainable competitive advantage. The ultimate aim is to help businesses improve their environmental performance and achieve solid sustainability over the long term.

Keywords: green organizational strategy, environmental CSR, organizational sustainable performance, green technology innovation, structural equation modeling

1 INTRODUCTION

Economic growth and development are inextricably related to social and environmental challenges (Chen et al., 2021). In the context of current fast-paced development, corporate stakeholders are increasingly concerned with societal and environmental emergencies (Le, 2022). A variety of harmful human actions and changing climatic circumstances pose a substantial hazard, resulting in various ecological repercussions (Yang et al., 2022). Further, the environmental regulation issue puts additional pressure on firms to take appropriate and timely steps to control the impact on the environment, economy, and society (Fernando et al., 2019). Environmental penalties for breaking environmental laws also affect environmental development and the community (Ding and Shahzad, 2022a). Against this backdrop, the United Nations (UN) developed the 2030 Agenda for Sustainable Development program, which discusses the multiple ongoing concerns connected to ecological degradation, climate change, zero hunger, and other adverse impacts of various manufacturing operations (Kumar et al., 2020). People have witnessed and uploaded blue sky pictures via social and print media due to the suspension of industrial activity during COVID-19 lockdowns, indicating that these lockdowns improved air quality worldwide. However, we cannot reduce or eliminate industrial operations; we can only encourage green manufacturing practices that adhere to sustainable development (SD) goals (Novitasari et al., 2022).

Despite the issues and concerns mentioned above, the corporate world's recent significant efforts toward socially responsible activities are noteworthy. Organizations are increasingly becoming extremely concerned with their ecological and sustainable performance; according to Shahzad et al. (2021), they can reduce the potential adverse effects of their operations on the natural environment by enhancing socially responsible behavior, innovation, and green organizational strategies. However, more efforts are required regarding environmental concerns such as "climate change," "pollution," and "glasshouse gas emissions," which have not been adequately addressed at the corporate level (Li et al., 2020). An individual or an organization cannot handle the environmental problem in the short term; it necessitates a synchronized shift of environmental awareness and policies (Kumar et al., 2020). In this regard, organizations play a critical part in this process since they must be able to translate an idea into an actual plan to tackle this matter. As a result, a green organizational strategy (GOS) has been proposed as a strategic resolution to position and then drive enterprises towards sustainable initiatives based on environmental and social challenges (Le, 2022).

GOS is described as a complementary approach to operational business strategies, designed to assist enterprises in decision-making that protects the natural environment (Olson, 2008). GOS helps keep businesses on track, remain ethical, and fulfill their commitments to meet their stakeholders' expectations. According to stakeholder theory (ST), environmental and social advantages and economic interests must be considered (Freeman et al., 2020). Therefore, GOS is critical both for organizations and stakeholders. However, GOS alone is insufficient for the firm to be sustainable; to achieve organizational sustainable performance (OSP), practices and actions aligned with the green strategic direction are required. Environmental corporate social responsibility (ECSR) and green technology innovation (GTI) are of the utmost importance in their association with GOS. ECSR and GTI are believed to be well-integrated with GOS in providing OSP as the business paradigm is shifting from a profit-oriented to a triple bottom line (TBL) approach, centered around the social, environmental, and economic dimensions of SD (Shahzad et al., 2020a). Given the worldwide concerns regarding achieving SD, world-renowned organizations such as DuPont Sorona have successfully transformed their conventional production into sustainable and innovative polymer production using renewable plant-based ingredients. Now they are using 40% less energy and releasing 56% less gas emissions (Dupont, 2019). Further, Google, Apple, and Accenture have started to prioritize green and sustainable business activities, as "more than 84% of S&P 500 executives" trust that their innovation is a precondition for the success of their corporation (Khalil and Nimmanunta, 2021; Le, 2022). These examples highlight the importance and understanding of environmental issues and their relationship with SD.

Despite its importance, no empirical study in the current literature has examined the impact of GOS, ECSR, and GTI on long-term business success (Sun and Razzaq, 2022). These features are currently being investigated in the prevailing literature in a non-collective manner, and combined research on GOS driving ECSR and GTI to realize OSP is noticeably lacking (Ding and Shahzad, 2022b; Jin et al., 2022; Le, 2022; Wang et al., 2022). Shahzad et al. (2020a) investigated the influence of various dimensions of CSR on environmental sustainability and GI in the manufacturing industry. The results highlighted that ECSR is the stronger predictor of ecological sustainability and GI. Wang et al. (2022) also identified that green strategies and sustainable decision-making help promote CSR and sustainable goals. Shahzad et al. (2020b) further highlighted that sustainable practices (environmental, economic, and social) also significantly impact corporate green innovation. In the study of Jin et al. (2022), the researchers explored how sustainable and green practices, including information and communication technology, positively affect GTI. Shahzad et al. (2022) acknowledged the critical role of ethical motives for green management practices in manufacturing organizations. Therefore, the present study intends to fill this gap by examining the relationship of GOS and ECSR in encouraging GTI towards attaining OSP, where GTI plays an interceding role in the GOS to OSP and ECSR to OSP relationships. In this context, manufacturing industries in evolving economies are considered for many reasons. First, the manufacturing sector is strongly associated with environmental problems and creates a very high proportion of countries' GDP (Sun et al., 2022). Subsequently, sustainability stimulates manufacturing in general, especially in emerging economies. This is because they generally have limited knowledge and resources (Bouzon et al., 2018; Shahzad et al., 2020c). Following the above discussion, the goal of this innovative work is to fully comprehend how GOS promotes ECSR and GIT

in organizations in order to achieve OSP in harmony with the TBL. These linkages are examined in this context using resource-based theory (RBV) and ST. In order to achieve this objective, this study aims to answer the following questions:

1) How do GOS and ECSR promote GTI to achieve OSP?
2) How does GTI mediate the relationship among GOS, ECSR, and OSP?

This research will supplement the literature regarding the association among GOS, ECSR, GTI, and OSP and provide significant implications and novel findings for business leaders to promote green and sustainable organizational strategies in an all-encompassing model. This research also emphasizes the key interceding role of GTI among the targeted constructs, which is still limited in prior works. Furthermore, the empirical analysis is performed using an innovative structural equation modeling (SEM) approach and the results have significant implications. The remainder of this study is structured as follows. Section 2 presents the theoretical basis and the development of the hypotheses. The research technique is described in **Section 3**. Section 4 details the data analysis procedures, and the results and implications, including future research directions, are discussed in Section 5.

2 THEORETICAL BACKGROUND AND HYPOTHESES DEVELOPMENT

2.1 Theoretical Background

RBV has been persistently utilized in the sustainable management context to define internal organizational virtues and shortcomings and their relationship with a competitive edge and performance (Barney et al., 2011). RBV is a harmonizing theory that could help an organization to comprehend the most appropriate means and technologies to advance specific production and process efficiency (Savino and Shafiq, 2018). These resources include all skills, processes, tools, knowledge and information, organizational qualities, and other resources that enable a corporation to conceive and deploy plans that advance its effectiveness (Barney, 1991). Furthermore, Barney (1991) highlighted that these physiognomic resources are VRIN ["(a) valuable, (b) rare, (c) inimitable, and (d) non-substitutable"]. In contrast, RBV is restricted to unraveling firm-level repercussions and ignores the impact of SD on the environmental conditions (Andersén, 2021). In response, Hart (1995) developed natural RBV (NRBV). NRBV widens the scope of RBV by acknowledging the significance of the environment. It is further described as "a theory of competitive advantage based on the firm's relationship with the natural environment" (Hart, 1995). This theory further examines how organizational green resources might lead to competitive advantages and sustainable outcomes. By adopting NRBV, environmentalists and ecologists have claimed that GTI would make a business more affluent and boost its long-term success (Shahzad et al., 2020b).

Similarly, ST hypothesizes that diverse stakeholders' pressure and involvement encourage companies to advocate for sound ecological practices to realize sustainable and green development (Sarkis et al., 2011; Forcadell et al., 2021). If a company wishes to succeed, it should consider the benefits of all of its shareholders: every stakeholder is critical to the company's success (Freeman et al., 2020). In this study, GOS and ECSR initiatives are viewed as business endeavors to satisfy the concerns of many stakeholders, particularly those with a focus on the global environmental and societal crisis. Diverse stakeholders pressure businesses to develop green and sustainable strategies, policies, and activities aligned with the ecological goals to promote OSP (Fernando et al., 2019; Guo et al., 2020). RBV and ST support the theoretical framework that an organization employing GOS and ECSR has a high chance of adopting GTI to manufacture green products to promote OSP. Further, current research argues that GTI plays a magnificent role in enhancing OSP. The framework of the study is provided in **Figure 1**.

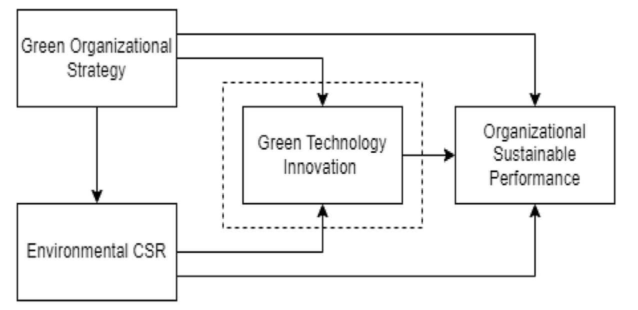

FIGURE 1 | Conceptual framework of the study.

2.2 Hypotheses Development

2.2.1 Green Organizational Strategy (GOS)

GOS is well-defined conceptually as a coordinated plan for the business, operation, and resource strategies. It assists industries in making decisions that have the most significant favorable influence on nature and the environment (Olson, 2008; Le, 2022). It incorporates environmental considerations and hazards into decision-making to achieve ecological sustainability. Notably, such actions are applied voluntarily and willingly as a corporate responsibility to society and the environment and to provide long-term advantages to stakeholders (Chang, 2016). GOS is tackled in a different way than the traditional strategy: the traditional approach focuses solely on the economic, social, and political settings, ignoring the natural environment and environmental threats (Jin et al., 2022). Irrespective of the many tactics to achieve the objective of GOS, in this setting, it is viewed as actual CSR to stakeholders by including ecological challenges into company culture and commercial decision-making for long-term sustainable goals (Arfara and Samanta, 2020). Increased stakeholder knowledge the ecological emergency has acted as a driver for firms to respond quickly to address stakeholder demands in support of ecological issues (Ding and Shahzad, 2022b; Ding et al., 2022). GOS is commonly regarded as a complementary business strategy (public or private) that serves as a guide for resolving the ecological emergency in the best possible way. Previous studies

TABLE 1 | Demographic details.

	Frequency	Percent (%)
Gender		
Male	156	57.58
Female	108	42.42
Education		
Bachelor's	114	43.18
Master's	105	39.77
Others	45	17.05
Job title		
Coordinator	96	36.36
Supervisor	79	29.92
Senior Manager	67	25.38
CEO/Directors	22	8.33
Experience (years)		
<10	143	54.17
10 to 15	78	29.55
>15	43	16.29

have highlighted that adopting green and sustainable practices allows firms to differentiate themselves from their competition. As a result, the business gains a competitive edge, improves market performance, and increases efficiency, leading to improved economic and non-economic performance (Arfara and Samanta, 2020).

Furthermore, Le (2022) acknowledged the positive association between green strategy, CSR, and firm performance. According to Barney et al. (2011), GOS is viewed as a strategic enterprise resource crucial in boosting ECSR activities and GTI application to gain a sustainable competitive edge and attain OSP. Given the preceding rationale, the following hypotheses regarding the linkage between GOS, ECSR, GTI, and OSP are proposed:

H1. GOS has a favorable effect on ECSR.
H2. GOS has a favorable effect on GTI.
H3. GOS has a favorable effect on OSP.

2.2.2 Environmental CSR (ECSR)

In the current situation, where various socio-environmental concerns are threatening humanity, CSR has emerged as one of the rising areas in the literature on management, and its importance to the community is growing (Skarmeas et al., 2014). Carroll (1979) asserted that the "social responsibility of organizations includes the legal, economic, ethical, and philanthropic expectations that society has of businesses at a given point in time." Farooq et al. (2014) classified the four main dimensions of CSR as environmental, consumers, employees, and community. Further, ECSR revolves around organizational obligations for ecological protection, climate change, accountable industrial waste management, and emission reduction, among other things (Turker, 2009; Farooq et al., 2014; Shahzad et al., 2019). Previous research has identified that CSR positively affects sustainable performance in Asian countries. For example, Shahzad et al. (2019) claimed that more responsible firms outperform others in terms of sustainable performance. Moreover, Shahzad et al. (2020a) acknowledged that ECSR has a more substantial positive effect on environmental SD and green innovation than other CSR dimensions (consumers, employees, and community) using a novel second synthetic grey relational ranking approach. Integrating green initiatives into CSR activities is critical for improving enterprises' competitiveness in the marketplace and assisting enterprises in accumulating a competitive edge, reducing ecological costs via waste minimization, energy conservation, and revenue growth, improving company reputation and customer loyalty, and cultivating economic performance (Pan et al., 2020; Le, 2022).

Further, CSR also promotes green technology adoption. Environmental performance is also linked to business performance (Farooq et al., 2014). In the current setting, let us assume that ECSR is best suited for GTI to encourage the implementation of green innovation, ultimately facilitating OSP. Based on the above considerations, the following links between ECSR, GTI, and OSP are hypothesized:

H4. ECSR has a favorable effect on GTI.
H5. ECSR has a favorable effect on OSP.

2.2.3 Green Technology Innovation (GTI)

Green technologies that are energy effectual are predicted to become a leading factor in mitigating environmental problems resulting from the industrial revolution, effectively reducing targeted carbon emissions by over 60% (Jin et al., 2022). Monitoring pollution, waste management, and clean technology are examples of GTI (Chen and Lee, 2020). Furthermore, GTI may be contingent on the specific social, environmental, and economic aspects related to the TBL (United Nations, 2018) as GTI is way of developing new ideas, items, services, and processes that could be applied to address environmental issues (Sun et al., 2021). Understanding the inclusive relationship between TBL and GTI, on the other hand, is critical to achieving the UN's Sustainable Development Goals (SDGs). GTI implementation can increase competitive advantages through green product quality and cost reduction, enhance productivity and profitability, and simultaneously improve sustainable performance and growth (Shahzad et al., 2021; Sun et al., 2021; Jin et al., 2022). Furthermore, the degree of GTI favorably influences OSP in such a way that it improves product distinctiveness based on market trends (Ong et al., 2019). As a consequence, the business's market efficiency and environmental performance increase. Jum'a et al. (2022) also identified that sustainable-oriented innovation has a strong positive impact on all dimensions of sustainability, namely, social, environmental, and economic. Chang (2016) underlined that environmental and green technological abilities, ecological regulations, and market and customer green demands are also central elements of GTI. GTI also helps to save costs related to the amendment of products, operations, and processing (Novitasari et al., 2022).

As per the above discussion, the direct link between green innovation and operational performance is well-established; however, the research on GTI and OSP is still in its infancy. Furthermore, this study also proposes the key mediating role of

TABLE 2 | Fornell-Larcker criterion.

	ECSR	GOS	GTI	OSP
ECSR	0.833	-	-	-
GOS	0.666	0.807	-	-
GTI	0.572	0.720	0.812	-
OSP	0.544	0.689	0.665	0.814

ECSR, environmental CSR; GOS, green organizational strategy; GTI, green technology innovation; OSP, organizational sustainable performance.

TABLE 3 | HTMT ratio.

	ECSR	GOS	GTI	OSP
ECSR	-	-	-	-
GOS	0.615	-	-	-
GTI	0.793	0.772	-	-
OSP	0.564	0.762	0.718	-

ECSR, environmental CSR; GOS; green organizational strategy; GTI, green Technology Innovation; OSP, organizational sustainable performance.

GTI among ECSR, GOS, and OSP. Hence, the following hypotheses are proposed:

H6. GTI has a favorable effect on OSP.
H7. GTI partially mediates the relationship between GOS and OSP.
H8. GTI partially mediates the relationship between ECSR and OSP.

3 MEASURES AND VALIDATION

ISO-certified manufacturing industries listed on the Shanghai Stock Exchange comprise the target population. The focus of this study is on China for cross-sectional analysis, considering that Chinese manufacturing industries comprise over 90% of the overall business establishment, along with a considerable contribution to GDP. Chinese manufacturing industries contribute 56% to the annual GDP and create 75% of employment opportunities (Waheed and Zhang, 2020). Manufacturing has enormous potential to create economic growth and prosperity in developing countries (Shahzad et al., 2022). The number of workers working in the manufacturing industry is unclear because the analysis unit is individuals. The survey questionnaire was originally written in English before being translated into Chinese by Chinese researchers. Since they have detailed knowledge of corporate affairs and other relevant procedures, we communicated with upper, medium, and front-level staff members, in line with previous research (Shahzad et al., 2020b). Accordingly, these were considered the most suitable respondents for this study.

This study adopted a 10× rule for sample size. Hair et al. (2016) proposed "10 times the largest number of structural paths directed at a particular latent construct in a structural model." The questionnaire was circulated among 850 respondents via email, WeChat, LinkedIn, and other social media platforms. The data collection process took six months to complete, beginning in September 2021 and ending in March 2022. A total of 279 surveys with satisfactory responses were returned. We obtained 264 surveys after removing those that lacked key information or had missing data, resulting in an actual response rate of 31%. The sample summary is presented in **Table 1**.

For this study, the researchers split the survey into two main sections. The first section is related to the respondents' demographic information, and the other section contains survey items related to our targeted variables, namely, GOS, ECSR, GTI, and OSP. Four items were selected for ECSR (Turker, 2009; Farooq et al., 2014). Eight items were connected to GOS, adopted from Le (2022) and Olson (2008). Further, we used a six-item scale for GTI adopted from Chen et al. (2006) and Shahzad et al. (2020c). Furthermore, a six-item scale was adopted for OSP (Wang, 2019; Le, 2022). The items were rated by means of a seven-point Likert scale (7 = strong agreement; 1 = strong disagreement). We conducted a pilot study before official data collection to confirm the validity and reliability of the accepted constructs in the research environment.

4 RESULTS AND ANALYSIS

4.1 Analytical Approach

Following Hair et al. (2017), we utilized PLS-SEM to analyze the data in this research. The main attraction of this technique is that it allows academics to approximate complex models with multiple constructs without imposing data distribution assumptions. It is a causal prognostic approach to SEM that emphasizes predictions when estimating statistical models, the structure of which is envisioned to explain causal relationships (Hair Jr et al., 2016). This technique caters for small sample sizes while providing the most accurate results possible.

4.2 Common Method Bias (CMB)

Common method bias (CMB) is a primary concern in survey-based studies. CMB is caused by the bias or variances that exist in the measurement methods of the survey rather than being caused by the constructs (Podsakoff et al., 2012). Many expert statisticians and researchers have developed sophisticated statistical measures to control CMB. Preventive strategies include respondent anonymity, avoiding complicated and confusing questions, and providing extensive recommendations in the survey to avoid bias and inaccuracy. Along with these traditional measures to control CMB, we applied a modern approach suggested by Kock (2015). This measure is based on a full collinearity test using the inner variance inflation factor (VIF) of all constructs. We estimated the inner VIF by using each construct as the dependent variable. The standard value for the inner VIF recommended by Kock (2015) is 3.30; if the inner VIF value exceeds this threshold, it signals that there common method bias exists in the methodology. Our results illustrate that all values of inner VIF are less than the threshold of 3.30, proving that CMB does not exist in this research.

4.3 Outer or Measurement Model

PLS-SEM contains two main models: the outer or measurement model, which is used to assess the reliability and validity of

TABLE 4 | Reliability and validity.

Constructs	Item	Loading	α	CR	AVE	VIF
ECSR	ECSR1	0.76	0.89	0.91	0.69	1.894
	ECSR2	0.79				1.519
	ECSR3	0.77				1.672
	ECSR4	0.84				2.370
GOS	GOS1	0.78	0.90	0.92	0.67	2.284
	GOS2	0.75				2.437
	GOS3	0.82				1.876
	GOS4	0.84				2.511
	GOS5	0.83				1.894
	GOS6	0.84				1.519
	GOS7	0.78				1.572
	GOS8	0.79				2.370
GTI	GTI1	0.86	0.84	0.88	0.66	1.894
	GTI2	0.84				1.565
	GTI3	0.83				1.721
	GTI4	0.81				2.370
	GTI5	0.84				2.741
	GTI6	0.82				2.437
OSP	OSP1	0.71	0.88	0.89	0.68	2.421
	OSP2	0.74				2.722
	OSP3	0.79				1.863
	OSP4	0.85				2.151
	OSP5	0.81				1.984
	OSP6	0.82				1.719

ECSR, environmental CSR; GOS, green organizational strategy; GTI, green technology innovation; OSP, organizational sustainable performance.

constructs; and the inner structural model, which is used to test the hypothesized correlations. Following Hair et al. (2017), we evaluated the validity and reliability of the constructs by evaluating the internal consistency, discriminant validity (DV), and convergent validity. DV has been defined by Fornell and Larcker (1981) as "how the constructs of the study are different from each other in the context of the same model." Using the Fornell-Larcker criterion, we compared the root of average variance extracted (AVE) with the inter-construct correlation. The root of the AVE must be greater than the correlation values in the same column to confirm the DV of the constructs. **Table 2** illustrates the values for the Fornell-Larcker criterion; all the values fulfill the criteria (Fornell and Larcker, 1981). Another measure, suggested by Henseler et al. (2015), has been used to validate the DV of constructs, namely, the HTMT ratio. The threshold level of HTMT is 0.85. The HTMT ratio for all constructs was less than 0.85, indicating no DV issues (Henseler et al., 2015). **Table 3** presents the detailed results.

Reliability tests are employed to measure consistency, whereas DV and convergent validity tests are used to confirm the validity of the constructs (Hair et al., 2016). Factor loadings ensure that the questions for a construct measure precisely what that are intended to measure (Sarstedt et al., 2017). The threshold for the factor loading of items is 0.70, and items with loadings below this threshold should be dropped. **Table 4** illustrates the findings for the validity and reliability of the variables. Factor loadings fulfill the criteria of 0.70, as proposed by Hair et al. (2017). Cronbach's alpha (α) and composite reliability (CR) are used to assess the reliability of constructs; as shown in **Table 4**, the α and CR values surpass the threshold level as suggested by Cohen (1988) and Hair et al. (2017). Convergent validity, on the other hand, is evaluated through AVE; the results are shown in **Table 4**, which are larger than the threshold of 0.50, as suggested by Sarstedt et al. (2017).

4.4 Inner or Structural Model

Since the outer measurement model reflects the validity and reliability of the constructs, now the inner structural model is our main concern. The inner or structural model is intended to evaluate the path relationships. The inner model consists of path coefficients, significance tests, the goodness of fit, and the coefficient of determination.

4.4.1 Significance of Path Coefficients

PLS-SEM uses the path coefficient term, which is similar to the beta coefficient of regression analysis. Path coefficients reflect the unit variation in dependent variables caused by independent variables and provide the basis for hypothesis acceptance and rejection. The higher the value of the coefficient, the stronger the impact of that particular variable on the dependent variable. However, the beta coefficient alone is insufficient to determine hypothesis acceptance; it is the t-statistic that is used to assess the significance of the coefficient. The bootstrapping procedure was used to calculate the coefficients, t-statistics, and p-values. **Table 5** illustrates the results of the regression analysis. *H1* anticipated a positive association between GOS and ECSR, and results in **Table 5** support *H1* (β = 0.785, t-statistic = 12.19, p = 0.000). We detected a positive association between GOS and GTI (β =

TABLE 5 | Regression analysis.

Hypothesis	Coef.	*t*-statistic	*p*-value	Decision
H1: GOS—> ECSR	0.785	12.19	0.000	Supported
H2: GOS—> GTI	0.531	7.096	0.000	Supported
H3: GOS—> OSP	0.200	2.828	0.005	Supported
H4: ECSR—> GTI	0.197	2.512	0.012	Supported
H5: ECSR—> OSP	0.224	3.426	0.001	Supported
H6: GTI—> OSP	0.635	11.39	0.000	Supported
		Mediation analysis (total and indirect effects)		
GOS—> OSP	0.200	2.828	0.005	Supported partial mediation
H7: GOS—> GTI—> OSP	0.086	2.920	0.004	
ECSR—> OSP	0.224	3.426	0.001	
H8: ECSR—> GTI—> OSP	0.041	2.210	0.028	

p-*values = 0.000 shows significance level ***.*

TABLE 6 | Coefficient of determination.

	R^2	R^2 adjusted
OSP	0.709	0.706
GTI	0.633	0.628

TABLE 7 | The goodness-of-fit (GOF) index.

	AVE	R^2	GOF
ECSR	0.69		
GOS	0.67		
GTI	0.66	0.633	
OSP	0.68	0.709	
Average	0.675	0.671	
GOF			0.670

0.531, t-statistic = 7.096, p = 0.000); hence, *H2* is robustly accepted. *H3* posited a positive relationship between GOS and OSP; the results support *H3* (β = 0.200, t-statistic = 2.828, p = 0.005). *H4* posited a positive relationship between ECSR and GTI; this hypothesis is accepted empirically (β = 0.197, t-statistic = 2.512, p = 0.012). *H5* is also supported by the results (β = 0.224, t-statistic = 3.426, p = 0.001), which predicted a positive association between ECSR and OSP. In *H6*, we proposed a positive relationship between GTI and OSP, and the results strongly support this (β = 0.635, t-statistic = 11.39, p = 0.000). Further, we checked the mediation of GTI through the two-step approach proposed by Hair et al. (2017). In the first stage, this study looked at the indirect effect of GOS on OSP through GTI. With a β value of 0.200, the indirect impact of GOS was determined to be significant. We also looked at the direct impact of GOS on OSP without eliminating the mediator (GTI) in the second phase and found that GOS has a significant positive effect (β = 0.086). As a result, complementary partial mediation supports *H7*. Similarly, the indirect impact of ECSR on OSP via GTI was substantial (β = 0.224), while the direct effect of ECSR on OSP without GTI was shown to be significant (β = 0.041). As a result, *H8* is supported, showing complimentary partial mediation. These findings reveal partial mediation. Furthermore, both the indirect and direct effects showed a positive indication, showing that GTI exhibits complementary partial mediation. Thus, all the developed hypotheses in the study are accepted. Further, the coefficient of determination was employed to quantify the model's predictive accuracy and measure the overall effect size. **Table 6** provides R^2 values; the value for OSP is 0.709, explaining 70.9% variance in OSP. The R^2 value for GTI is 0.633, explaining 63.3% of variance.

4.4.2 Goodness-of-Fit (GOF) Index

The GOF index is utilized to quantify the model fit to confirm that model adequately explains the data (Hair et al., 2017). The GOF index ranges from 0 to 1, with 0.10 considered a minor value for validating the model, 0.25 a medium value, and 0.36 substantial enough to demonstrate the global validation of the model, while also indicating that the model is rational (Henseler et al., 2016). We used the formula given below to calculate the GOF index. The mean of AVE values and R^2 values were used to calculate GOF, which is 0.670, considered substantial and indicating a good model fit. The model fit is shown in **Table 7**; the SRMR value is also below the threshold value of 0.08, fulfilling the standard criteria (Hair et al., 2017).

$$GOF = \sqrt{\overline{AVE}*\overline{R^2}}$$

5 DISCUSSION AND CONCLUSION

5.1 Discussion of the Key Findings

This study integrates RBV and ST in a study framework that observes the GOS, ECSR, GTI, and OSP relationships. We collected data from Chinese manufacturing industries to test the hypotheses in this study. Despite the literature suggesting a positive association between GOS, ECSR, GTI, and OSP, no study has empirically examined these associations in an inclusive research model. This work makes a substantial contribution to the existing literature by being the first to assess the effects of these targeted variables in an all-encompassing model; further, identifying the critical mediating role of GTI is also a considerable contribution. According to the results of our data, GOS inspires ECSR, GTI, and OSP to implement environmental preservation methods as predicted by RBV theory. Our results suggest that GOS has a significant effect on ECSR, GTI, and OSP, with beta values of 0.785, 0.531, and 0.200, respectively, confirming *H1*–*H3*. These findings are in accordance with Le (2022) and Yousaf (2021). Arfara and Samanta (2020) also argued that GOS is not enough independently to explain the phenomenon under study; the present study shows that ECSR plays a key role in GTI implementation for OSP enhancement. This discovery adds to the existing literature since this mediation mechanism has not been empirically investigated in the past.

Additionally, the effects of ECSR on GTI and OSP were also found to be significant, with beta values of 0.197 and 0.224, respectively, supporting *H4* and *H5*. These outcomes are consistent with Shahzad et al. (2019) and Shahzad et al. (2020a). Khalil and Nimmanunta (2021) also claimed that ECSR could be a significant source for businesses to innovate proactively, which leads to OSP. Furthermore, GTI was shown to have a significant direct impact on OSP, with a beta value of 0.635, supporting *H6*. These findings align with Le (2022) and Shahzad et al. (2021), who found a positive connection between GTI and OSP. Jum'a et al. (2022) also emphasized that sustainable innovation significantly affects organizational TBL. According to these authors, the GTI level influences OSP to differentiate the company from competitors by producing eco-friendly and consumer-friendly innovative goods. Consequently, market efficiency improves, competitiveness improves, and ecological performance improves. In addition, GTI was also shown to play a key complementary partial mediating role among GOS, ECSR, and OSP, with beta values 0.086 and 0.041, supporting *H7* and *H8*. GTI thus plays an influential role in cultivating environmental awareness and achieving OSP. In this research,

sustainable innovation refers to new technologies and techniques that help the environment and businesses in a way that improves long-term competitive advantage and sustainable performance.

5.2 Research Implications

From a theoretical standpoint, this study adds to the limited literature in various ways. First, the suggested model adds to the sparse literature on GOS, ECSR, GTI, and OSP, especially in the Chinese industry context. This study has investigated an uncharted region and tried to fill a literature gap by empirically assessing the crucial role of GOS and ECSR in implementing GTI for enhancing OSP with the help of the RBV and ST. GOS and ECSR allow all stakeholders to stand on the same platform, which may assist firms in achieving their targeted sustainable goals. This study supports the assertion that incorporating ecological and social sustainability into organizational strategies and decision-making procedures drives organizational behavior toward societal norms, values, and environmental and social urgency. Second, this study has demonstrated the significance of the green tactic in the literature on sustainability. Awan et al. (2017) suggested that GOS and ECSR initiatives by firms are essential for improving environmental protection by signifying a strong environmental obligation. These initiatives also support the implementation of GTI. Further, the key mediating role of GTI also highlights that OSP becomes a reachable target by saving energy resources and reducing pollution, carbon emissions, industrial waste, and water pollution backed by GOS and ECSR initiatives. Further, according to our findings, GTI is the most significant motivator, providing answers for ecological deterioration and economic efficiency. As the global acceptance of hybrid and electric automobiles demonstrates, green solutions may change a sector with a significant carbon footprint into a sustainable, lucrative, and cost-effective business. The examples above and our results indicate that when organizations and stakeholders seek to pursue SD, environmental protection plans help them to the raise GTI.

Based on the current research findings, some practical implications and policy recommendations are proposed that may support the importance of incorporating GOS and ECSR activities into organizations' operations to help them become eco-innovative in terms of technological innovation and environmental sustainability. It is now advised that regulatory, government, and senior leaders commit to attaining SD. This commitment has been followed by increased interest in green strategies and ECSR programs. Our findings indicate that organizational commitment to CSR would drive GTI and eco-sustainability. Organizations must prioritize green strategy and ECSR to achieve more ecologically sustainable outcomes. Organizations have invested vast resources in CSR and TBL cognizance worldwide; however, these are ineffective in the Asian area, possibly because corporations are unaware of the desire to address environmental concerns (Farooq et al., 2014). Governments and legislators should take remedial actions to minimize environmental degradation caused by poor industrial practices and waste and invest in promoting sustainable operations through growing GTI in developing nations such as China. Finally, this research has highlighted that techno-driven firms that focus on new technologies and capitalize on process and product innovation are able to attain SD; GOS and ECSR actions are also among the contemporary economy's key components.

6 CONCLUSION

This research study contributes to the growing literature in the SD field by examining the impact of GOS, ECSR, GTI, and OSP on the manufacturing industry by using the SEM with a sample size of 264. We developed eight hypotheses based on previous literature and RBV and ST. The direct association between GOS, ECSR, GTI, and OSP was investigated in this study. Further, the discovery of the mediating role of GTI in these relationships represents a significant contribution. The findings show that GOS, ECSR, and GTI are essential in accomplishing OSP goals, both directly and indirectly, through GTI. Based on the results, the following suggestions to key stakeholders are made. First, organizations should use green and sustainable strategies in their decision-making to reap the benefits of green development. Second, organizations should implement a green plan. Notably, the green approach should be integrated with the ECSR strategy to promote GTI and sustainable growth. Furthermore, the findings of this study can be used as a yardstick for augmenting OSP in the future.

This study has limitations due to a lack of resources and time; however, these constraints may allow further research. We adopted a cross-sectional strategy for this investigation; in the future, a longitudinal or experimental study is recommended to acquire more conclusive results. Further, we gathered data mostly from developing countries. Researchers should replicate this research model and expand this study to different locations in the future to get obtain comprehensive results. A contrast study is also suggested, as it may advance the generalizability of this study.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Sustainability Assessment of Marine Economy in China: Spatial Distributions of Marine Environmental Governance Entities in Shanghai

*Debin Yang[1], Hong Geng[1], Yan-Kai Fu[2] and Ting Zhu[3]**

[1]College of Economics and Management, Jiangsu Maritime Institute, Nanjing, China, [2]Department of Aviation Services and Management, China University of Science and Technology, Hsinchu, Taiwan, [3]School of Finance and Trade, Wenzhou Business College, Wenzhou, China

The amount of investment in marine environmental governance (MEG) is growing fast in China, which brought the prosperity of environmental treatment entities (e.g., water treatment enterprises and port pollution control institutions). Based on spatial big data, this paper adopted kernel density method, standard deviational ellipse, and nearest neighbor index to explore the spatial distribution pattern of MEG entities in Shanghai from 2005 to 2021. Several conclusions emerged from this study: (1) From 2005 to 2021, the new MEG entities in Shanghai have increased by more than 10 times; (2) The analysis showed that the nearest neighbor index of Shanghai's MEG entities was larger than 0.2, with Z values all being lower than −30, indicating that the spatial agglomeration characteristics in Shanghai was significant at an alpha level of 1%. (3) Chongming District, Pudong New District, Fengxian District, and Minhang District were the core agglomeration areas. (4) The standard deviational ellipse analysis suggested that the distribution of Shanghai MEG entities from 2005 to 2021 showed an obvious pattern of spreading from the center to both the north and south. This results in an industrial belt along the Huangpu River. This paper argues that the spatial distribution of MEG entities in Shanghai confirms the central place theory, which highlights the network characteristics that combine centrality with spreading to the surrounding areas.

Keywords: marine environmental governance, sustainable development, spatial distribution, Shanghai, marine economy

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Correspondence:
Ting Zhu
dr.zhu.ting@outlook.com

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INTRODUCTION

The ocean plays an important role in the survival and development of human beings. For instance, 75% of the large cities in the world and 70% of the industrial capital and population are concentrated in coastal zones within a distance of 100 km away from the coastline (McGranahan et al., 2007). In addition, humans are increasingly engaged in activities related to exploring the ocean. However, the weak awareness of the importance of marine ecological environmental protection, the continuously increasing demand for marine resources, and the extensive way of developing marine economy have caused great damage to the marine ecosystem, resulting in a decline in the restoring ability of the marine ecosystem and a serious threat to marine ecological security (Curtin and Prellezo, 2010). These marine issues need to be addressed urgently. However, there are also serious challenges in ocean governance. Problems such as weak governance, lag in action, and limited governance have

emerged in the governance process (Walters, 1997; Boesch, 2019). In recent years, as guided by the *Maritime Power Strategy* and *Rules for the Implementation of the Law on the Prevention and Control of Marine Pollution*, China has vigorously stived to develop a green and sustainable marine economy, while enhancing the governance of the marine ecological environment (Hsu, 2018; Ren et al., 2018; Shao, 2020). Since 2005, coastal provinces in China have increased the total investment in environmental pollution control and energy transition from less than 100 billion yuan to nearly 500 billion yuan (Li et al., 2019; Zhang et al., 2022). The investment in marine environmental control is still growing. Such investment brought prosperity to the marine environment treatment industry in coastal cities, with a significant increase in the number of industrial and commercial registrations of various water environment treatment and port pollution control companies and organizations (Liu et al., 2018; Li et al., 2020; Bai et al., 2021a). The spatial distribution of the industry has always been a hot research topic in the fields of regional economics and economic geography. Industries never show a random or scattered way of spatial distribution, but that they follow a certain and meaningful pattern (Rosés and Wolf, 2018). Previous research about the distribution of the marine environmental governance (MEG) industry mainly focuses on the macro causal relations, distribution and combination of marine industry sectors in a certain region, from economic perspectives (Khan et al., 2020; Teng et al., 2021). A comprehensive understanding of the spatial distribution and evolution of the MEG industry is the key to promoting the development of a green and sustainable marine economy. Thus, it has important contributions to the decision-making regarding the coordinated development of the land and sea to promote high-quality economic development.

Previous research has made in-depth studies and discussions about the spatial distribution of industries in developed countries. For example, Gervais and Jensen, (2019) believed that almost all manufacturing industries in the United States have shown certain degrees of agglomeration in geographical distribution. Within a given space, a more detailed industry classification leads to a higher degree of spatial agglomeration of industries. For the same industry, a larger space leads to a higher degree of agglomeration. González-Val, (2019) used the location Gini coefficient to study the spatial distribution of 6 different types of environmental governance industries in Miami and found that the pollution control industries related to ports tended to show a pattern of spatial agglomeration, whereas other pollution industries such as marine ecological environment tended to be scattered in spatial distribution. Platjouw (2018) applied principal component analysis to evaluate the annual comprehensive strength of marine economic development and analyzed the evolution of the MEG industry and the differences in the regional spatial structure of the marine economy in Norway. Some other scholars are more dependent on environmental economic methods for discussion (Chou, et al., 2020; Bai et al., 2021b; Zakari et al., 2021; Cao et al., 2022; Dagar et al., 2022). These studies were largely based on rich data. However, limited by the availability of large data, Chinese researchers tended to focus on the overall layout of the industry. For instance, Mou et al. (2018) explored the development of distributions of the marine industry as well as the factors affecting the distribution; Wang et al. (2020) focused on the internal attributes and suggested effective strategies to optimize the distributions of emerging marine industries. Such qualitative research emphasizes the deepening and deduction of the existing economic basic theory. Compared with theoretical research, there are more empirical studies based on yearbook data about different regions. For example, Ding et al. (2020) proposed that distributions of the marine industry follow a pattern of three points and two axes; Su and Yang, (2018) used the NRCA model to analyze the distribution of the marine industry in the Bohai Rim region. In addition, important achievements were made in research about measuring the spatial agglomeration of the marine industry and identifying the leading marine industries, taking provinces as a unit. These studies were mainly related to coastal provinces such as Liaoning, Shandong, and Zhejiang. Abundant studies have provided policy-making suggestions for the overarching planning of marine industry from both a national level and a provincial level. With the development of research about the overarching planning of the national marine industry, researchers have begun to focus on mesoscopic and microscopic levels. For instance, Ren (2021) introduced a dynamic mechanism for the optimization of the spatial distribution of the marine high-tech industry; Bailey et al. (2019) evaluated the rationality of the spatial distribution of marine fisheries and came up with the standard index for the optimization of the spatial distribution of marine aquaculture from the perspective of space. In addition, Tian et al. (2020) also assessed the rationality of the spatial distribution of blue pastures proposed in recent years based on environmental protection and ecological theories. These studies all adopted a more timely way of acquiring data. As an example, Mao et al. (2020) was based on monthly coastal carbon emission grid data. In recent years, with the availability of spatial big data, a rich body of studies have used spatial methods to examine the spatial influence and industrial distribution pattern. Among them, the most prominent is the application of POI data. For example, Chen et al. (2021) used the green space POI data to investigate the accessibility of park sports and the green accessibility rate of Shanghai residents. The present study followed this idea of employing empirical data. Data were obtained from an official real-time industrial and commercial data platform in China (gsxt.gov.cn), which records the main business of various enterprises, organizations, and public institutions. Types of properties and business activities. These data largely enable us to locate the spatial locations of the MEG entities of interest. In general, previous studies on the green and sustainable development of the marine economy have employed real-time data from different perspectives, whereas only a few studies have used spatial big data and highly reliable data from official platforms. Therefore, this paper aims to narrow this research gap. We focused on Shanghai, an international port city in China, and applied spatial pattern statistical methods to comprehensively explore the spatial distributive characteristics and developmental trends of MEG entities (including enterprises, organizations, and public utilities). Observation methods were also used to analyze the factors affecting the development of the

marine economy in Shanghai. By analyzing the distributive pattern, this paper aims to understand the development of the marine governance industry in Shanghai and provide suggestions for the decision-making of optimizing the future marine governance layout. The spatial statistical methods used in this paper are introduced in the Methodology section. Results of these statistical analyses are presented in the Results section.

METHODS

Standard Deviational Ellipse

This article takes Shanghai as the research object because Shanghai has implemented a series of urban greening constructions since the 1980s. According to the 2020 Shanghai Municipal Statistical Yearbook, the current green area of Shanghai is 157,800 hm^2. By specifying parks with fitness facilities, there are 352 with an area of 21,400 hm^2. The green coverage rate of the built city is 39.7%, and the per capita GSS area reaches 13 m^2. Two types of data are mainly used in this research. The first type is spatial data, including Shanghai administrative boundary, regional parks, and GSS data, regional road traffic network data, regional residential area data, etc. All spatial data acquisition follows scientific and systematic methods, making full use of official portals such as Shanghai Urban Planning and Natural Resources Bureau, Shanghai Municipal People's Government, and electronic maps such as Gaode map. A unified spatial coordinate system is used to calibrate the data to ensure that all data are compatible. The spatial point data of all green parks in Shanghai and the descriptive text of relevant parks were crawled at the same time, and we screened out the parks with fitness facilities in the description by searching. Finally, 607 GSSs were found in Shanghai. In order to help analysis, the government statistical data also used, which mainly comes from the Shanghai Statistical Yearbook released by the Shanghai Municipal Bureau of Statistics in November 2020.

The standard deviational ellipse method (SDE) is suitable for understanding the development of spatial distribution of ocean governance entities. SDE can describe the spatial distribution characteristics of geographic elements from multiple perspectives such as the center, long axis, short axis, and azimuth. This method has become a popular statistical tool in the ArcGIS Spatial Statistics module and has been used in several studies. For instance, Han et al. (2021) studied changes in the energy industry and proved this method is effective in realizing the visualization of spatial orientation. Therefore, this paper applied the spatial statistical standard deviational ellipse method to quantitatively analyze the developmental characteristics of the spatial distribution of marine governance enterprises. By using this method, we were able to simultaneously describe the overarching and global characteristics of the spatial distributions of marine governance enterprises such as centrality, subject range, and directionality. Through analyzing the changes in the ellipse parameters of the spatial distribution by time, we can further explore the development of the spatial distribution of marine governance enterprises. The main parameters are calculated as follows.

Mean Center:

$$\bar{X}_w = \sum_{i=1}^{n} w_i x_i \Big/ \sum_{i=1}^{n} w_i ; \bar{Y}_w = \sum_{i=1}^{n} w_i y_i / \sum_{i=1}^{n} w_i \tag{1}$$

The standard deviation of x-axis:

$$\sigma_x = \sqrt{\sum_{i=1}^{n} \left(w_i \tilde{x}_i \cos\theta - w_i \tilde{y}_i \sin\theta \right)^2 / \sum_{i=1}^{n} w_i^2} \tag{2}$$

The standard deviation of y-axis:

$$\sigma_y = \sqrt{\sum_{i=1}^{n} \left(w_i \tilde{x}_i \sin\theta - w_i \tilde{y}_i \cos\theta \right)^2 / \sum_{i=1}^{n} w_i^2} \tag{3}$$

In the equation, $\bar{X}$ represents the mean center of the ellipse; σ_x and σ_y is the standard deviation of the x axis and y axis, respectively; (x_i, y_i) represents the spatial area of the efficiency distribution; w_i is the weight, calculated by the industrial output value of the marine governance entity; x and y indicates the relative location of each point from the center of the ellipse; θ is the angle between the true north of the ellipse and the long axis.

Kernel Density Analysis

Kernel density analysis is the most commonly used method to measure the spatial distribution of pointed data. It can calculate the agglomeration status of the entire area according to the input elements, and mainly reflects the intensity of the influence from a kernel on the surrounding area. A larger kernel density estimate reflects a denser distribution of the points and a higher probability of the occurrence of regional events. The formula is presented below:

$$f(c) = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{c - c_i}{h} \right) \tag{4}$$

In the equation, $f(c)$ is the estimated kernel density; $k(*)$ is the kernel function; n is the number of marine governance entities; h is the bandwidth; $c - c_i$ represents the distance from the evaluation point c to c_i.

Nearest Neighbor Index

The nearest neighbor index R is used to estimate the distribution pattern and the degree of agglomeration of the overall and all sub-types of marine governance industries. The distribution area A is taken as the administrative area of Shanghai (6340.5 km^2). The distribution patterns can be divided into three categories: random, uniform, and agglomerated distribution. When R>1, the spatial distribution of the marine water treatment industry (organization) tends to be random. When R = 1, it tends to be uniform, and when R<1, it tends to be agglomerated. A smaller value of R represents a higher degree of agglomeration. The equation is provided below:

$$r_E = 1/2\sqrt{n/A} \tag{5}$$

$$R = r_1 / r_E \tag{6}$$

In the equation, A is the area of the district; n is the number of data.

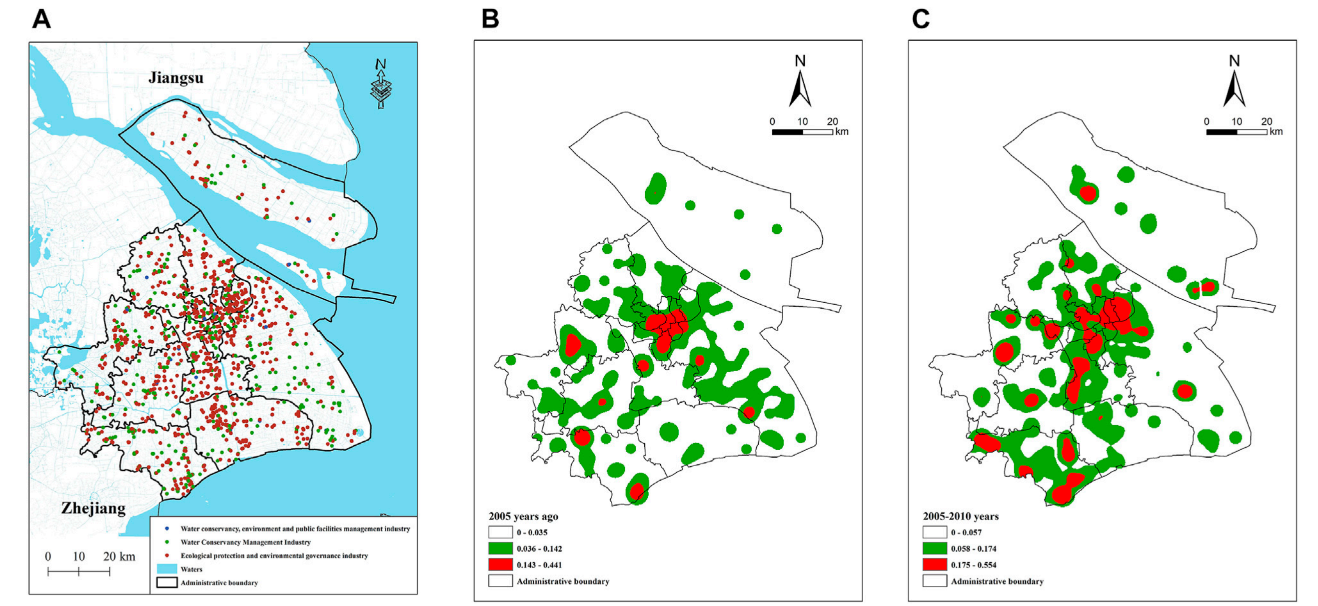

FIGURE 1 | Distribution map of MEG entities and institutions in Shanghai up until 2021 **(A–C)**.

RESULTS

For the spatial distribution characteristics of MEG entities in Shanghai, it is can be seen that there is an obvious pattern of agglomeration in terms of the spatial distribution in the interior area of the city. The degree and location of agglomeration have changed over time (**Figure 1**). In 2005, MEG entities and institutions were mainly concentrated near the old downtown area along the coastal area in the southern part. Specifically, they were distributed around the Hujia highway to Nanxiang North Station in Jiading District. There were some agglomeration in the north part of the Pudong new district and the coastal area in the south. In 2021, the agglomeration expanded, and the agglomerated area gradually shifted to Minhang District, Fengxian District, and Chongming District, with the number of entities in the three regions accounting for 49.96% of the total number of entities in Shanghai. Specifically, these entities were located in the eastern coastal area of Pudong New District, such as the intersection area of Shenjiang Road and Longdong Avenue, as well as in the part of Hongkou District that is close to the Huangpu River. As a near-inland jurisdiction, Songjiang District has the advantages of having policy preference and a large space for development, whereas it lacks obvious location advantages. Therefore, it is less attractive for MEG entities and institutions and has shortcomings in the layout. Consequently, it has not become a new agglomeration center. In contrast, Fengxian District has made obvious breakthroughs in attracting MEG entities. For instance, the Fengxian Campus of East China University of Science and Technology and Fengxian Shenlong Ecological Park have created a radiation area in the center. In Hangtang Highway, Puxing Highway, and Pingzhuang East Road, there have gathered a group of MEG entities and institutions mainly focusing on research and development. Chongming District has also attracted an increasing number of MEG entities in recent years under its outstanding geographical advantages. For example, the area around Dongping National Forest Park and radiating from the north to the south along the highway has shown agglomeration characteristics. From 2005 to 2021, the spatial distribution of MEG entities and institutions generally shifted from a pattern of one-core agglomeration to contiguous development, and then to multi-center agglomeration. The expansion trend is reflected in the radiation and expansion of old districts to new districts.

Agglomeration Characteristics of Major Marine Entities in Shanghai

In terms of the number of entities, entities from ecological protection and environmental governance industries accounted for the vast majority of the total number of MEG entities. In contrast, entities from water conservancy, environment, and public facilities management industries accounted for the smallest proportion. The average nearest neighbor distance analysis showed that (see **Table 1**) the nearest neighbor indices of Shanghai MEG entities were all larger than 0.2. Considering that the number of water conservancy, environment, and public facilities management was very small and almost negligible, all the Z values were smaller than −30, being significant at an alpha level of 1%. It showed that the above industries all presented a significant pattern of agglomeration, that is, the spatial agglomeration characteristics of these marine governance entities were substantial. As the main position of developing the marine economy in Shanghai, the coastal area showed that there were differences in the spatial distribution of marine entities across different industries. Chongming District, Pudong New District, Fengxian District, and Minhang District

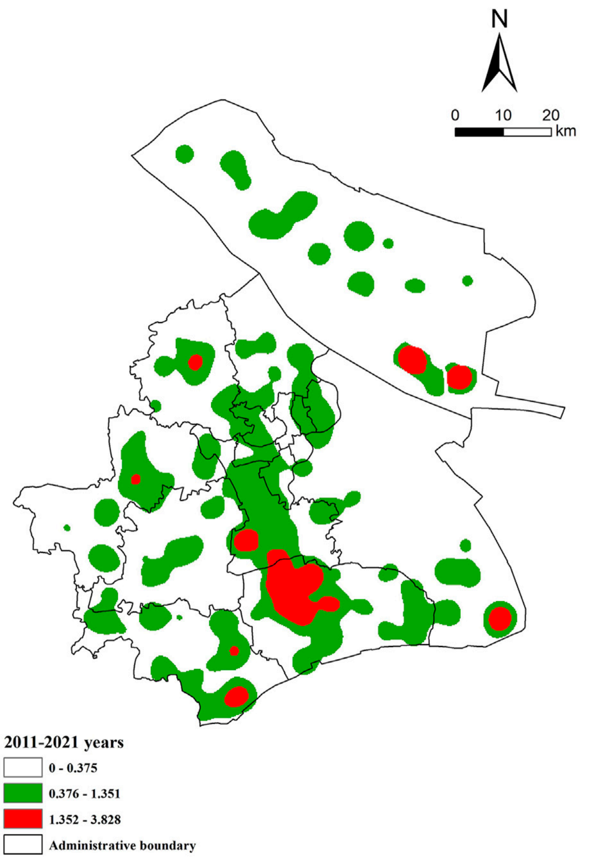

FIGURE 2 | Changes in core density of MEG entities and institutions in Shanghai.

were the core agglomeration areas of marine governance entities in Shanghai, with other areas being secondary areas for different industries. The specific distribution is shown in **Figure 1**.

Spatial Distribution of Marine Entities in Shanghai From 2005 to 2021

In terms of the spatial distribution of entities and institutions, marine entities continued to agglomerate in the central urban area, especially in Hongkou. The suburban marine entities stayed to concentrate in the main urban areas of districts and counties. In larger districts and counties, there appeared the phenomenon of multi-center agglomeration. The characteristics of marine entities and institutions migrating to the coastal areas became more pronounced during this period. Marine entities formed a significant industrial belt on both sides of the Huangpu River. The industrial belt started from the Wusongkou area in Baoshan District along the Yangtze River, passed through the Waigaoqiao area in Pudong, and extended to the outside of Pudong Airport. At the same time, on the left bank of the Yangtze River, Changxing Island, and Chongming Island also began to show the prototype of a relatively loose marine entity belt (see **Figure 1**).

Between 2005 and 2021 (see **Figure 2**), the distribution of 2,212 new MEG entities and institutions in Shanghai was as follows: 11 in Hongkou District, 193 in Pudong New District, 33 in Yangpu District, 9 in Changning District, 256 in Minhang District, and 256 in Xuhui District. 11 in Putuo District, 131 in Jiading District, 92 in Baoshan District, 117 in Songjiang District, 162 in Qingpu District, 531 in Fengxian, 260 in Jinshan District, and 393 in Chongming District.

Based on the abovementioned analysis, it can be found that the spatial agglomeration of MEG entities in Fengxian District has accelerated rapidly, with the number of new entities increasing exponentially than in the previous period. Consequently, it has become the district with the largest number of marine entities in the city. The entities were still mainly concentrated in the area on the east and west sides of the Puxing road. The number of new MEG entities in Chongming District has also increased significantly. Except for the obvious agglomeration in the southeastern part of Chenhai Highway, the rest of the entities were distributed in a relatively balanced manner throughout the region. The spatial polarization of Minhang District accelerated during this period, and the number of new marine entities increased from 14 in 2005 to 270 in 2021, with an increase of nearly 20 times. During this period, the MEG entities in Jinshan District also developed rapidly. The number of new entities increased from 26 in 2005 to 286, an increase of more than 10 times. Marine entities and institutions spread in multiple directions from 2005 to 2021. In addition, the spatial distribution of marine entities and institutions in Shanghai from 2005 to 2021 showed several major characteristics (see **Figure 2**). First, the increase in MEG entities in Fengxian District exceeded 7,000%; Second. The marine entities in Lujiazui, the district government and the Waigaoqiao area of Pudong New Area continued to agglomerate. Third, there were several marine entity agglomeration areas in the larger area, such as Waigaoqiao in Pudong, Lujiazui and district government marine environment governance entities area, Hongqiao Airport in Minhang district, Xinzhuang Meilong Town Agglomeration Area, Nanhui District Government, and Lingang New City Aggregation Area. Fourth, the suburbs continued to accelerate the agglomeration of MEG entities

TABLE 1 | Analysis of the nearest neighbor distance of MEG entities in Shanghai.

Types of industry	Amount	Mean observed distance	Expected mean distance	Nearest neighbor ratio	Z score
Ecological protection and environmental governance industry	2217	250.1566	1131.2947	0.221124	−70.158771
Water conservancy, environment and public facilities management industry	36	5473.4488	6828.4013	0.801571	−2.277651
Water conservancy management industry	787	704.2159	1913.6552	0.367995	−33.918657

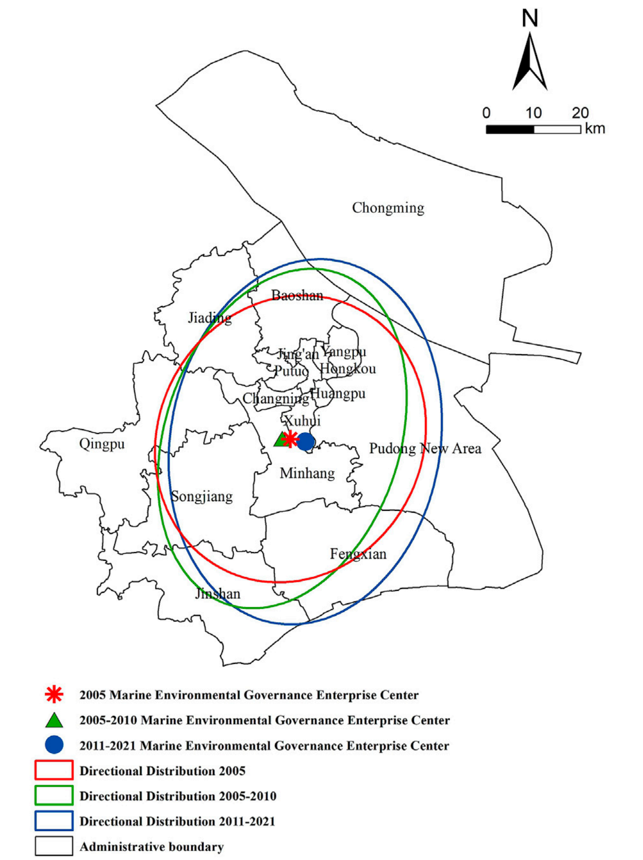

FIGURE 3 | Standard deviational ellipse of resource distribution of MEG entities and institutions in Shanghai from 2005 to 2021.

in central urban areas, such as Qingpu, Songjiang, Nanhui, Jinshan, and Jiading.

The results of standard deviational ellipse analysis showed that the distribution of MEG entities in Shanghai showed significant diffusion characteristics, with the diffusion trend following a certain direction. The centers of the spatial standard deviational ellipses of the MEG entities across the three time-points were all located in Xuhui District and showed a trend of moving from the center to the north and south. The area of the ellipse continued to increase, and the spatial distribution of MEG entities spread outward (see **Figure 3**).

Before 2005, the aggregation effect was concentrated in fewer areas. Thus, the length difference between the major and minor axes of the standard deviational ellipse was not obvious, with the directional angle approaching 90° and the distribution showing no directional characteristics. From 2005 to 2010, the ratio of the long and short axes of the standard deviational ellipse gradually increased and the direction angle gradually decreased. Meanwhile, affected by the terrain and urban economic development, the distribution of MEG entities showed a relatively obvious pattern of spreading from "the southwest to the northeast". The area of the standard deviational ellipse in 2021 was significantly larger than that in 2005, indicating that the diffusion effect of entity distribution was significant. Due to social and economic development and the allocation and utilization of urban public resources, as well as the increase in urban population and land prices brought about by urban expansion, most entities optimized their location selection and resided in the periphery of cities, especially in coastal areas, in order to reduce operating costs and improve operating efficiency. This phenomenon was especially salient in Chongming District in the north of Shanghai and Fengxian District in the south of Shanghai. At the same time, the gradual policy guidance has also explained the increasingly obvious pattern that the MEG entities are spreading to the north and south of the city.

CONCLUSION

To conclude, we had the following findings: (1) Between 2005 and 2021, the number of new MEG entities in Shanghai increased by more than 10 times, of which ecological protection and environmental governance entities accounted for 73% of the total number of entities. These entities were mainly small entities with small sizes. (2) The number of new water conservancy, environment, and public facility management industries began to decline, and the number of other MEG entities rose steadily. (3) Through the analysis of the average nearest neighbor distance, it is found that the nearest neighbor indices of Shanghai MEG entities were all larger than 0.2, with the Z test values all being less than −30 and being significant at an alpha level of 1%. It can be seen that the spatial agglomeration characteristics of marine governance entities in Shanghai were salient and substantial. (4) Chongming District, Pudong New District, Fengxian District, and Minhang District were the core agglomeration areas of marine governance entities in Shanghai. Other areas were secondary agglomeration areas for different sub-industries. (5) Results of the standard deviational ellipse suggested that the distribution of MEG entities in Shanghai from 2005 to 2021 had shown an obvious diffusion characteristic. The centers of the spatial standard deviational ellipses of the MEG entities across three timepoints were all located in Xuhui District, showing a pattern of spreading from the center to both the North and South.

The period from 2005 to 2021 is a period where the foreign trade and gross national product in China experienced rapid development. As a result, the explosive growth of the marine economy has led to the occurrence of a series of environmental governance issues. Based on the results of data analysis, we have reason to believe that the rapid growth of the number of small and medium-sized entities is often the result of sufficient policy guidance and encouragement. Our future research may be able to discuss the role of different policies. In terms of spatial distribution characteristics, the entities followed a distribution that was highly concentrated in the inner circle and that was developed "from point to face". The entities were also spreading orderly to the central urban area of each suburb. Such spatial distribution characteristics are similar to the atypical "central place theory". The German urban geographer Kristaller theorized that on an ideal surface, a series of central places are evenly

distributed. In order to maximize the profit of merchants, each central place has a maximum sales or service distance of goods and services, resulting in the formation of several circles that are tangent to each other. In order to eliminate the shadow area between the three tangent circles that the goods and services cannot reach, the optimal approach is to move the tangent circles until the shadow area is eliminated. Then, a hexagonal network that covers the whole area and maximizes the profit can be obtained by connecting the centers in each area. In line with this theory, during the period from 2005 to 2021, marine governance entities in Shanghai were highly concentrated in the inner circle area, forming a marine industry center. Although these entities did not form a hexagonal network, they still formed a network system radiating from the center to the periphery.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by DY and HG. The first draft of the manuscript was written by Y-KF and TZ, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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REVIEW
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Modeling Socio-Economic Consequences of COVID-19: An Evidence From Bibliometric Analysis

Yasmeen Ansari[1], Mohd Arwab[2], Mohammad Subhan[2], Md Shabbir Alam[3], Nazia Iqbal Hashmi[4], Mohammed Wamique Hisam[5] and M. Nasir Zameer[2]*

[1]Department of Finance, College of Administrative and Financial Sciences, Saudi Electronic University, Jeddah, Saudi Arabia, [2]Department of Commerce, Aligarh Muslim University, Aligarh, India, [3]Department of Economics and Finance, College of Business Administration, University of Bahrain, Sakhir, Bahrain, [4]Department of Finance, College of Business Administration, Prince Sultan University, Riyadh, Saudi Arabia, [5]Department of Management, College of Commerce and Business Administration, Dhofar University, Salalah, Oman

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Mohsin Shahzad,
Dalian University of Technology, China

***Correspondence:**
Mohammad Subhan
msubhan@myamu.ac.in

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The COVID-19 pandemic has pushed the world towards a digital era and affected the environment significantly. The present study uses a bibliometric approach to provide a comprehensive overview based on existing literature related to COVID-19 and E-learning and its environmental consequences, particularly from the year 2020–2022. In addition to the terrible impact of the pandemic on the world, environmental advantages have also been noticed. The findings show that the use of E-learning reduces the consumption of paper and prevents the cutting of trees which makes the environment more sustainable. The optimum use of technology leads to the conservation of the environment. Second, E-learning ensures developing and less developing countries to provide education at lower levels or remote areas of the society. The findings also suggest that governments and educational institutions should upgrade technology and digital tools in order to enhance E-learning education. Additionally, reviewing 1807 published articles extracted from the SCOPUS database, enrich literature related to COVID-19, E-learning, and the environment. This study also represents a graphical visualization of the bibliometric analysis using VOSviewer and R studio software. A coupling map and three-field plot also have been used for directions for future research.

Keywords: socio-economic activities, COVID-19, VOS-viewer, bibliometric, coupling map, R studio

INTRODUCTION

The COVID-19 pandemic does not only manifest multiple complexities for human lives but also severely affects the socio-economic conditions of the people. Each and every sector has been badly hit by this deadly disease, directly or indirectly, throughout the world (Razzaq et al., 2020; Wang & Tian, 2021). In addition to the negative aspects of the pandemic, some positive outcomes have also been seen in relation to the environment. Due to the lockdowns and other travel restrictions, environmental improvement was also noticed. Improved air and water quality, reduced noise pollution, and minimized energy consumption are some of the key well-beings for the environment. Additionally, a revolution has occurred in the education sector in the form of Online/E-learning. It enables teaching-learning activities more convenient. Hence, affordability, flexibility, and accessibility are considered determinants of E-learning. The main aim of this study is to extensively explore the diverse consequences of the pandemic. It also provides an insight into

the environmental knowledge that helps to formulate policies for a sustainable environment. The present study indicates that E-learning is an effective tool to reduce the excessive use of paper which prevents the cutting of tree and helps to maintain the environmental sustainability.

Particularly, the education sector has been highly affected by this pandemic across the globe. The effect of this pandemic is unprecedented and wide which has disturbed the entire community of teachers and students. As a result of this tragedy, many schools, colleges, and universities were temporarily shut down, globally (Daniel, 2020; Rashid & Yadav, 2020). However, several tactics, for instance, lockdown, social distancing, and stay-at-home were implemented by the administration of the different countries to deal with and control the spread of this transmitted disease (Sintema, 2020; Pokhrel & Chhetri, 2021; Singh et al., 2021). At the same time, educational institutions were scrambling to come up with solutions to these fierce circumstances. During such situations, Online or E-Learning proved as a panacea and facilitated teaching-learning activities (Dhawan, 2020). Online classes provide innovative teaching-learning methods, advanced tools, and techniques as well as the ability to reach a large number of students (Appana, 2008). On the other hand, students and teachers become familiar with emerging technologies, for example, how to use various tools and methodologies, pay concern to recorded or live talks with world-known professionals, interact and learn lessons often, and work with creativity pace (Arkorful & Abaidoo, 2015).

Furthermore, the pandemic has completely transformed the traditional pattern of education into digital. Before such changes, people were not much conscious of academic E-resources. It could be said that E-learning made teaching-learning more accessible, flexible and affordable (Dhawan, 2020). Teachers and students can now easily collaborate anytime and anywhere for learning activities, there is no need for physical classrooms. Especially in India, most of the students belong to rural or remote areas and it was difficult for them to get an education due to the lack of resources, online learning provides a chance to obtain substantial education (Alvi & Gupta, 2020). Apart from the several advantages of online learning, challenges and difficulties also exist. It was a great challenge for the entire educational community to transform themselves to deal with such a digital era. Therefore, the government is more concerned about education during and after COVID-19 and has taken several initiatives for dealing with the smooth teaching-learning process across the world (Singh et al., 2021). Consequently, multiple digital-educational platforms, EdTech startups, and online learning portals came into the limelight to continue the educational system's rhythm. E-learning resources made education much more convenient and facile. One can easily access academic and professional literature from anywhere within a few moments using strong internet connectivity. However, a variety of issues and topics associated with E-learning have been explored in recent years in multiple disciplines including science, social sciences, engineering and technology, and management (Djeki et al., 2022). To be familiar with emerging and trending researches, most-contributed universities and countries, and influential articles and authors in the field of education become approachable using E-learning. For a deep and extensive understanding of this wide and diversified topic, a thematic review of related works is required. Several research articles exist related to"COVID-19 and E-Learning", but a few of them have been done with bibliometric analysis. The "COVID-19" and "E-Learning" keywords have been frequently used to search out research papers containing bibliometric analysis. A bibliometric analysis is an analysis tool to investigate the existing literature using some specific keywords and set criteria. The main objective of the present study is to examine the research trends and topics concerned with COVID-19 and E-Learning and to analyze how the educational pattern has transformed within the foregoing 3 years (i.e., 2020–2022). The bibliometric analysis method has been employed on the SCOPUS database from the year 2020–2022 to exhibit the research themes and effective entities.

Apart from the tremendous influence of COVID-19 on human lives, economy and culture, it has also proved a panacea for the environment from different perspectives (Alvarado et al., 2021; Dagar et al., 2021). In addition, online learning is an excellent source to reduce paperwork that results in saving trees, minimizing pollution and emission from traffic, less energy consumption, and water and other natural resources being conserved (Jan et al., 2021; Islam et al., 2021; Khan et al., 2022). These are the unavoidable and indirect benefits of online learning that help to create a sustainable environment (Zhang et al., 2022). Environment conservation is the major concern of the world under which several initiatives are being taken across different countries (Rehman et al., 2021; Zakari et al., 2021). The pandemic has coerced the educational system to change from traditional patterns to online learning. During the pandemic, obtaining proper education was a great challenge across the world due to the lockdowns and shutdown of schools. In this regard, E-learning proved as a catalyst to maintain the rhythm of systematic educational activities. E-learning plays a crucial role in the education sector making people aware of how to utilize the emerging resources for getting an education without exploitation of the pandemic restrictions. Hence, E-learning has been considered as an eco-friendly instrument to use in which multiple resources could be sustained for the long term (Irfan et al., 2021). Prior studies have not had many environmental concerns while this study mainly focuses on environmental sustainability through the implementation of E-learning resources. With the aim to emphasize on the socio-economic outcomes of the pandemic, the present study is distinct from previous ones. The incorporation of the bibliometric approach reveals the research novelty in examining the wide range of consequences of COVID-19. This study enhances the awareness among consumers about environmental conservation through the optimum use of digital resources and reports the wide range of socio-economic consequences globally.

Therefore, based on the aforementioned discussion, this study proposes the following objectives. First, the present study tries to investigate the socio-economic consequences of COVID-19 from different perspectives using bibliometric analysis. Second, this study reports the influences of COVID-19 regarding the environmental concerns. Third, it also extensively marks the

impacts of COVID-19 from the educational as well as socio-economic perspectives. Fourth, it also identifies the most-relevant journals, articles, institutions, and authors in this field of study, as well as the collaboration network of authors and universities. It also examines the COVID-19 and E-Learning research trends and publication productivity from 2020 to 2022. Authors and countries have made a significant contribution with respect to COVID-19 and E-Learning research; therefore, this study investigates the most-cited publications on the subject of COVID-19, E-Learning, and education research and reports on the emerging research topics and trends in the field of education.

REVIEW OF LITERATURE

In addition to the gruesome effects of the COVID-19 pandemic on human lives, it has proved a catalyst for the environmental aspect. In addition, travel restrictions lead to the minimization of air pollution, water pollution, and exploitation of natural resources (Alvarado et al., 2022; Razzaq et al., 2022). Conservation of the environment and natural resources has been a major concern of the world ever. But during/after the COVID-19 pandemic, several positive changes have been seen with respect to the environment and its sustainability (Razzaq et al., 2021). Lockdowns, social distancing, and other restrictions imposed by the government to facilitate the environmental rectification such as improved quality of air and water, CO_2 emissions reduced by transportation, Information and communication technologies, and technological innovation, and also decreased the energy consumption (Chien et al., 2021; Islam et al., 2021; Razzaq et al., 2021). During the pandemic, apart from the environmental advantages, integration of the different means of information and communication technology has taken place to deal with the pandemic hindrances and maintain the magnifier of the education sector (Irfan et al., 2022). Online learning, one of the most significant instruments of information technology, has emerged in the education sector that has made teaching-learning activities more convenient by providing E-learning assistance without violation of the pandemic norms (Chauhan et al., 2021). Certainly, E-learning is also an exquisite means of conservation of the environment by reducing the use of paper which is the main cause of cutting down the trees. Moreover, E-learning contributed a lot to the education sector during the pandemic while it was not much prevalent earlier but now has become a convenient instrument for getting an education.

Several meta-analyses and bibliometric analyses have occurred related to the education sector and COVID-19. For instance, Djeki et al. (2022) conducted a bibliometric study using 12,272 articles related to E-learning from the year 2015–2020 using the Web of Science database in which they examined the collaborations between authors, universities, and countries, and trending research topics and issues. Resulted collaborations are very low and the pandemic has a significant influence on education during the period. Baber et al. (2022) have reviewed 2307 research articles extracted from the Web of Science database related to the digital literacy pre and during the COVID-19 pandemic. Cluster analysis has been done to identify the rotative keywords and their thematic progression and trends over 5 years. In conclusion, a consistent pace of publications comes from the domains of education and library, and the United States moving ahead in this area. Moreover, some trends are emerging such as competence, health literacy, fake news, COVID-19, and education. Chaturvedi et al. (2021) have explored the impact of COVID-19 on the education, mental health, and social life of students belonging to different age bars through a set criterion. The results have shown that the administration should pay deep concern and adopt essential steps for improving the learning experience and cope with the negative impact of the pandemic. A systematic review has been conducted by Donnelly and Patrinos (2021) that reported the learning loss due to COVID-19 for 1 year. On the basis of eight studies, the author reported that one of them claimed learning gains in a specific subgroup and the rest have witnessed heavy learning loss. Some of the studies reveal inequality among demographics of students resulted in a learning loss. According to Abu Talib et al. (2021), technological advancements rapidly took place in the field of higher education during the period of a pandemic. To deal with unprecedented changes in the education field, the educational system has now become more dependent on technology. In the light of emerging trends in technology-based education, it would not be wrong to say that gaining education without using technology would be impossible in the near future. A bibliometric analysis was performed by Karakose and Demirkol (2021) to examine the emerging trends and current status associated with COVID-19 and the education, in which data has been extracted from the "Web of Science Core Collection" and analyzed using VOSviewer and "GraphPad" software. They found that most of the articles were published with a "theoretical model" using "scale/interview forms". Another interesting finding is that articles sent for publication at that time were responded to very quickly and got published before the usual time period of respective journals. Adedoyin and Soykan (2020) reported the opportunities and challenges regarding COVID-19 and online learning in a previous study; E-Learning would be more effective and sustainable if the teaching-learning would become hybrid. Accordingly, the distinctiveness of the current study is to explore the literature of highly sensitive years (2020, 2021, and 2022) of the COVID-19 pandemic which has enormous unprecedented transformations in different facets of normal life and simultaneously educational perspectives. Most of the studies have been conducted using the Web of Science database but this study is being conducted with the Scopus which is the largest combination of abstract and citation database of reputed peer-review literature. It widely covers approximately 36,377 titles, around 11,678 publishers, and around 34,346 peer-reviewed journals on multidisciplinary subjects. No previous studies have revealed the influence of information technology means, that is, online/E-learning on environmental and socio-economic perspectives through the existing literature during/post-pandemic. The present study bridges this gap by bringing a more lucid and vivid study on e-learning and the environment.

An overview of studies related to COVID-19, e-learning, and environment.

An overview of studies related to covid-19, e-learning and environment

References	Period	Data source	Methodology	Outcomes
Djeki et al. (2022)	2015–2020	Web of Science Core Collection	Bibliometric Analysis	COVID-19 has a significant impact on e-learning
Baber et al. (2022)	2017–2021	Web of Science Core Collection	Bibliometric Analysis	COVID-19 has been associated with fake news, higher education, social media, and information literacy
Karakose & Demirkol (2021)	2020–2021	Web of Science Core Collection	Bibliometric Analysis	COVID-19 has affected education negatively
Abu Talib et al. (2021)	2019–2020	Google Scholar	Systematic Literature Review	Lockdown has negatively impacted education and promotes online learning
Chaturvedi et al. (2021)	13 July–17 July 2020	cross-sectional survey (Primary Data)	Non-parametric test and Chi Square test	COVID-19 outbreak has made a significant impact on the mental health, education, and daily routine of students
Donnelly & Patrinos (2021)	2020–2021	ECONLIT, Google Scholar, PubMed, Education Resources Information Center, and Cochrane Library	Systematic Literature Review	Student learning loss among participants while one of these found instances of learning gains in a particular subgroup. Some studies observed increases in inequality where certain demographics of students experienced learning losses more significant than others
Islam et al. (2021)	1972–2016	World Development Indicator (WDI)	dynamic ARDL	The environment has been affected positively by Transportation, quality of air, and the manufacturing sector during COVID-19

DATA COLLECTION AND RESEARCH METHODOLOGY

Data Collection

The Scopus database was used to collect extensive professional and scientific literature to cover global research on E-learning and COVID-19. The data was extracted on 18 March 2022. The key terms have been used in the search: topic = ("E-Learning" and "COVID-19"), in title-abs-key ("e-learning" and "COVID-19″) and [limit-to (doctype,"ar")] and [limit-to (srctype,"j")] from 2020 to 2022, and 4207 studies were found over the years (Conference paper 1882, Articles 1807, Review 169, Letter 140, Editorial 62, Conference Review 47, Book Chapter 36, Data Paper 6, and Short Survey 5) but the researchers have selected only research articles in this study.

The data of the bibliometric study represent the entire research on "COVID-19 and E-learning" in the Scopus database. The usage of e-learning was anticipated to rise in the last 3 years (2020, 2021, and 2022) owing to the lockdown and quarantine processes.

There are various reasons why this database was chosen above others, notably web of science (WoS) and Science Direct: the area of scientometrics has improved greatly as a result of the Scopus database. Scopus is much more than a simple database of academic publications.

Research Methodology

Bibliometrics is a subfield of library science which analyzes bibliographic data statistically (Mas-Tur et al., 2020). Bibliometrics analysis is a method of gaining a comprehensive picture of huge breakthroughs in either a research journal, specific area, or a country (Hood and Wilson, 2001). Moreover, it facilitates the identification of prominent authors working in the area in order to enable future collaborations. The data were evaluated using a graphical analysis using VOS-viewer to better comprehend the results (Van Eck & Waltman, 2010). Statistical analysis and graphical representation are useful because they can assist researchers in a deeper understanding of what has been studied so far in the field of e-learning and COVID-19 related topics. Moreover, it assists in identifying and mapping the megatrends throughout this discipline. VOS-viewer is a software that gathers bibliographic data from several databases such as Scopus, PubMed, Science Direct, and Web of Science, etc. It provides graphical maps that depict and present the results of several procedures, such as co-citation analytics, bibliographic coupling, co-authorship, and keyword co-occurrence (Guo et al., 2021). When two articles are cited by the same third article, this is known as co-citation. The tremendously valuable results of bibliographic coupling have been evaluated by determining those common articles that cite the articles in observation more frequently. Co-authorship refers to the number of publications produced by a group of variables, such as countries, authors, and institutions, as well as their relationships. The most frequent and common keywords used by the articles in the study are referred to as co-occurrence of keywords.

Lotka's Law is considered a bibliometric measurement of authorship concentration that quantifies the frequency with which authors publish research articles. The key premise is that in any particular topic, a limited number of authors are extremely productive, while a large number of authors contribute only a single article. According to Lotka's law, the numerous authors who publish x number of articles is about $1/x^b$ of those who only publish one article. As a result, a larger b value implies greater authorship concentration, while a low value implies the absence of a devoted group of authors in a certain research field. Lotka's Law does have the following general formula:

$$f(y) = \frac{C}{x^b} \tag{1}$$

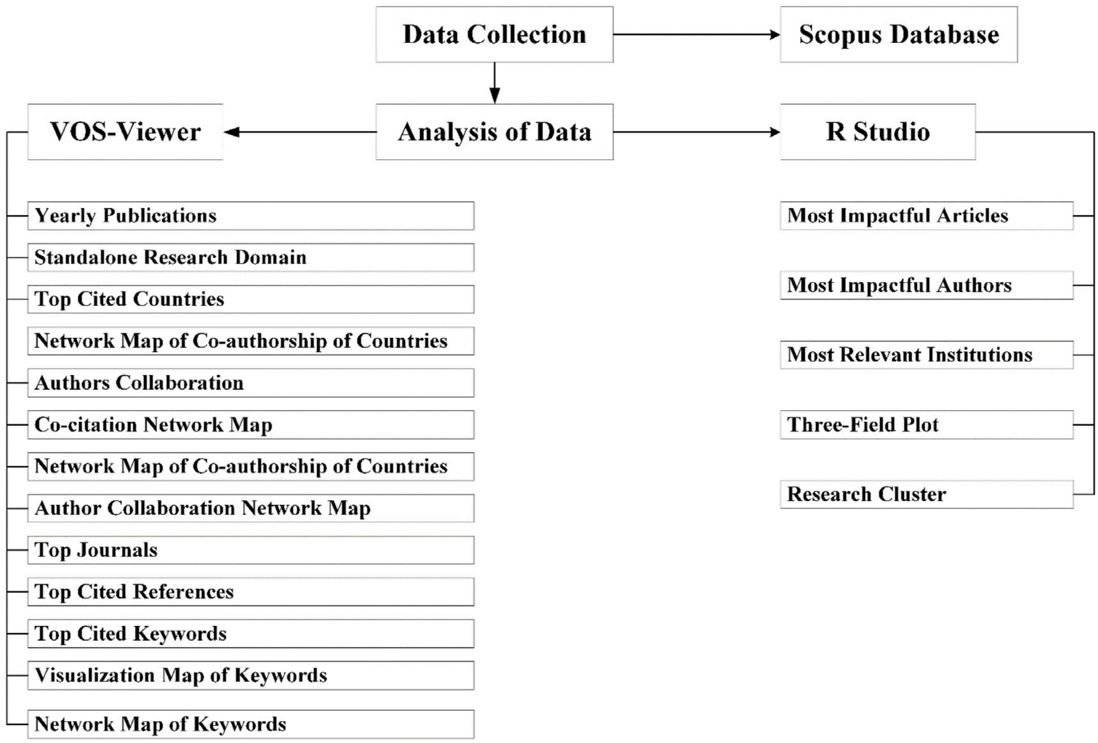

FIGURE 1 | Process of research methodology.

C is a research area-specific constant, while f(y) is the number of occurrences of studies produced by each author of a population.

Using a Walktrap clustering technique provided by Pons and Latapy (2005), we show university and author collaboration. This network analysis approach has a notable advantage in terms of the quality of the calculated partition and the running duration for large networks (Pons & Latapy, 2005). Additionally, we employ a *Three-Fields* plot based on a Sankey diagram to depict the relationships between journals, keywords, and countries. Kessler's (1958) bibliographic coupling approach is utilized to identify the cluster of the underlying research and map present research advances. Two or more publications are said to be bibliographically coupled if they carry at least one common citation (Kessler, 1963). As a result, studies that are bibliographically coupled are likely to share the same underlying research theme. The following standard formula can be used to express a bibliographic coupling network of studies published (Aria & Cuccurullo, 2017).

$$B_{coup} = A \times A \quad (2)$$

B_{coup} consists of the matrix b_{ij}, which reflects the number of common references between articles, and A is a document × cited reference matrix. We have used the open-source R programming application Bibliometric package (Biblioshiny) to analyze bibliographic coupling (Aria & Cuccurullo, 2017). **Figure 1**.

TABLE 1 | Total publications over the years.

Publication years	TP	% of 1807
2020	340	18.81
2021	1184	65.52
2022	283	15.66

Note: TP, total publications; % of 1807, Percentage over the years.

RESULTS AND DISCUSSION

Yearly Publication Trends

The yearly publishing trend is useful for determining the topic's progress, literature accumulation, and maturity. **Table 1** shows that there were 1807 articles published between 2020 and 2022. The highest research articles were published in 2021 (65.5%). It was more than 50% over the years like 2020 (18.8%) and 2022 (15.6%). The trend of publication is an inverted V shape because in 2021 more than 50% published articles. And the year 2022 has also seen a good number of publications until the 18 March of 2022.

Standalone Research Domain

Research productivity in the context of e-learning and COVID-19 in education demonstrates that there are 6977 authors in this field who have published only one publication. One author, on the other hand, has contributed to a maximum of seven published research articles. According to Pao (1986), the value of b in Lotka's law normally ranges from 1.78 to 3.78 for most fields. In

TABLE 2 | Top 10 most impactful authors in this field.

Rank	Author	TP	TC	TC/TP	TLS
1	Stuby L.	6	59	9.8	27
2	Suppan L.	6	59	9.8	27
3	Suppan M.	6	59	9.8	27
4	Harbarth S.	5	53	10.6	25
5	Sharma S.	5	195	39.0	0
6	Gartner B.	4	53	13.3	22
7	Purwanto A.	4	58	14.5	0
8	Raza S.A.	4	52	13.0	6
9	Wang W.	4	57	14.3	2
10	Wu H.	4	60	15.0	2

Note: TP, total publications; TC, total citation; TC/TP, average citations of per paper; TLS, total link strength.

TABLE 3 | Top 10 most cited Countries.

Country	TP	% of 1807	TC	TLS
United States	245	13.558	1336	133
Saudi Arabia	146	8.080	1084	264
United Kingdom	96	5.313	817	80
China	118	6.530	783	111
India	151	8.356	743	130
Pakistan	56	3.099	630	111
Spain	99	5.479	602	109
Malaysia	83	4.593	572	155
Italy	77	4.261	529	78
Indonesia	95	5.257	522	122

Note: TP, total publication; TC, total citation; TLS, total link strength.

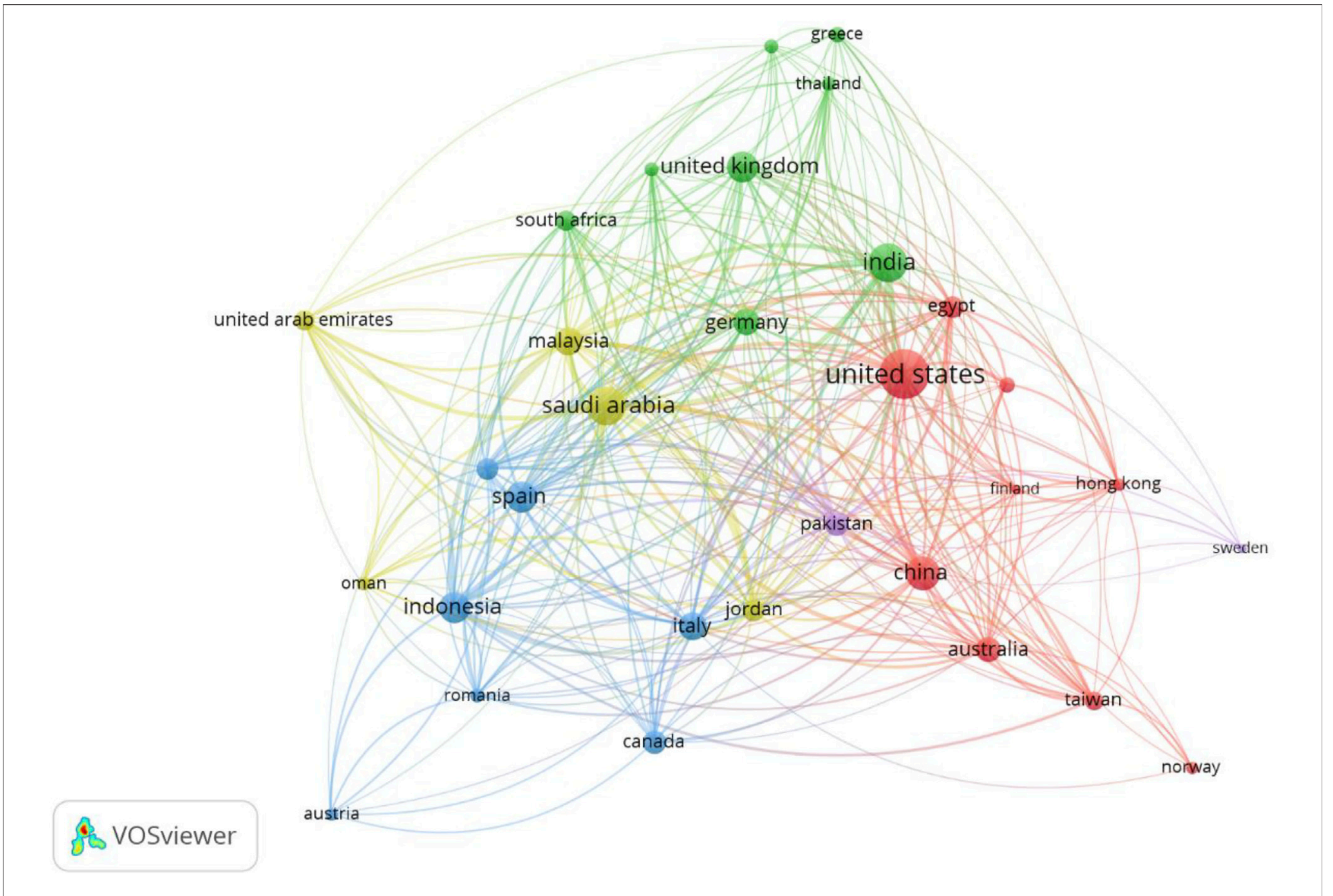

FIGURE 2 | Network map of co-authorship of countries.

this investigation, the calculated b value of 1.904 fits within the range seen by (Pao, 1986). As a result, e-learning and COVID-19 in education constitute a separate research topic, although one with a high degree of authorship concentration.

Analysis of the Top 10 Most Cited Countries

The geographic distribution of articles may be discovered by looking at the number of countries that were published in this field. According to **Table 2**, the United States has published the most prominent productive research articles on the field of e-learning and COVID-19 from 2020 to 2022, and United States has published 245 articles (13.5%), preceded by India, which published 151 articles (8.3%). The top 10 countries published 1166 out of 1807 articles, which contributed to 64.52% of the total on the topic of e-learning and COVID-19 and the rest of the country's 35.48%. **Figure 2** shows that the United States and India have published the most publications on

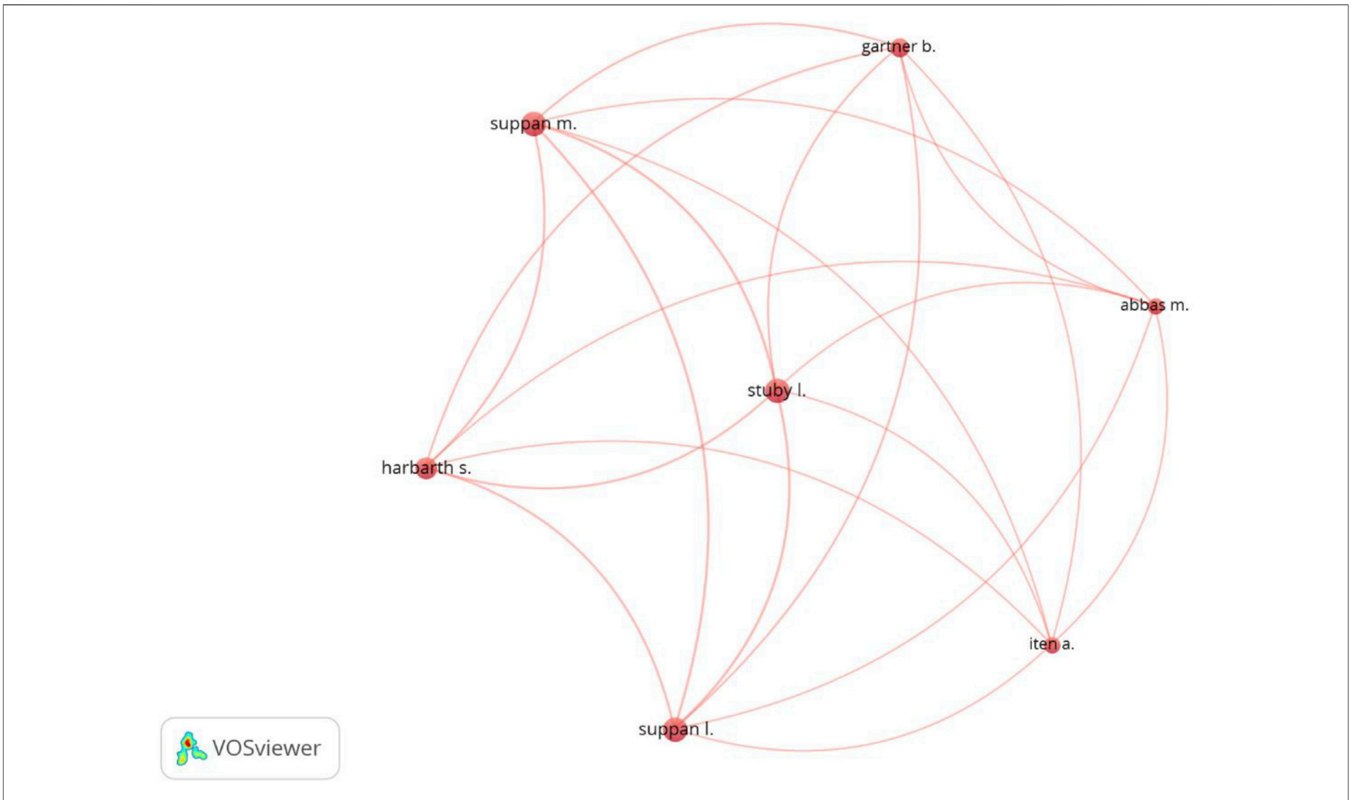

FIGURE 3 | Network map of author collaboration.

this topic. The most cited countries are the United States and Saudi Arabia (1336 and 1084, respectively), but India is not the most cited country as seen in the network map and **Table 3**. Saudi Arabia and Malaysia are the most collaborated countries, with 264 and 155 total link strength (TLS). United States, United Kingdom, China, India, Pakistan, Spain, Italy, and Indonesia are the countries having the most collaborations with Saudi Arabia and Malaysia. Furthermore, these two countries have collaborated with each other. The United Kingdom is the third country in terms of citations, with 817 citations, and has collaborated with the United States and Saudi Arabia. Since 2020, the United States and India have been actively publishing research articles on this field, but some countries have joined lately, such as Ukraine, Nepal, Vietnam, Croatia, Ghana, Philippines, Chile, Colombia, Finland, Morocco, Palestine, and Sweden. It's important to note here that countries that fail to collaborate with other countries are eliminated from the network map by default. The lines linking the map's nodes denote co-authorship between countries, and the length between them denotes their strength and the number of publications among co-authoring countries. This presents a comprehensive assessment of the different countries' collaboration strengths in the area of e-learning and COVID-19.

Analysis of Author Collaboration and Author Co-Citation Network Map

The examination of author collaboration indicates the topic's research potential and provides insight into the topic's advancement (Guo et al., 2021). While analyzing the 1807 publications, the authors discovered that 7128 different authors made significant contributions in this field. The smallest number of publications and citations contributed by an author was set at 3 and 50, respectively. Nineteen authors met the criteria shown in **Figure 3** and collaborated with others. **Table 3** shows the top ten most productive contributors from 2020 to 2022. Stuby L. (6 articles, 6 links, and 27 link strength) lead the list of publications in this field. Suppan L. (6), Suppan M. (6), Harbarth S. 5), and Gartner B. 4) articles are among the other authors with a significant publication record.

Analysis of Top Journals

It is crucial to investigate the number of publications and the frequency of citations in order to identify journals in this field. **Table 4** shows the top 5 most productive journals in terms of total publication and average citation per article. International Journal of Environmental Research and Public Health has 71 articles on this subject from 2020 to 2022. This journal publishes mainly on Environmental Health, Health Economics, Digital Health, Mental Health, and Digital Learning themes and has an H-index of 113 and an impact factor of 3.39. It means that researchers frequently link digital learning to mental health and Digital health during COVID-19. It's interesting to note that the Pakistan Journal of Medical Sciences with an average citation per article (45.88) belongs to medical science and public health, indicating the importance of health during COVID-19 for humanity. Frontiers in Pediatrics has a high H-index (53) and impact factor (3.41), which is followed by the

TABLE 4 | Top 5 productive journals (total publication and average citation per paper).

Top 5 Journals in terms of total publication

Rank	Journals (TP)	Research Field,	TP	TC	TC/TP	H-Index	IF
1	International Journal of Environmental Research and Public Health	Environmental Health, Health Economics, Digital Health, Mental Health, Digital Learning etc.	71	715	1.8	113	3.39
2	Sustainability (Switzerland)	Social Sciences, Natural Sciences	43	261	11.9	103	3.25
3	International Journal of Emerging Technologies in Learning	Online Learning Tools, Blended Learning, Mash-up Technologies, Language/Speech etc.	41	117	6.4	35	NA
4	PLOS ONE	Science, Engineering, Medicine, Social Sciences	29	248	7.4	185	NA
5	Education Sciences	Education & Educational Research	27	225	8.33	39	2.15

Top 5 Journals in terms of average citation per paper

Rank	Journals (ACPP)	Research Field,	TP	TC	TC/TP	H-Index	IF
1	Pakistan Journal of Medical Sciences	Medical Sciences	8	367	45.88	35	NA
2	Journal of Surgical Education	Surgical Education,	5	94	18.80	39	2.89
3	Frontiers in Pediatrics	Science	6	95	15.83	53	3.41
4	Systematic Reviews in Pharmacy	Pharmaceutics, Biopharmaceutics, Biomedical Sciences, Law and Education etc.,	5	71	14.20	21	NA
5	Education and Information Technologies	Education & Educational Research	20	251	12.55	52	2.95

Note: TP, total publications; TC, total citation; TC/TP, average citations of per paper; ACPP, average citation per paper; IF, impact factor; Sources of H-Index and IF, journals website and google scholar metrics.

Journal of Surgical Education (H-index 39 and impact factor 2.89), indicating the importance and relevance of this field. **Figure 4** also shows the top productive journals of COVID-19 and E-learning.

Analysis of Top Cited References

The top 5 highly cited references from 2020 to 2022 were examined, as shown in **Table 5**. The highly cited article was published by the Journal of Educational Technology Systems, and it has been cited 25 times during this period. Journal of Educational Technology Systems has published articles on Information Literacy and online learning for a long time. It has gained a lot of popularity among the scholars of online learning; that is why this article is listed in the highly cited reference during this period. The third most citations were obtained in the publication Human Behavior and Emerging Technologies' article "COVID-19 and Online Teaching in Higher Education: A Case Study of Peking University". The objective of this research was to conduct a case study of online education at Peking University. Six alternative instructional approaches are presented to describe current online teaching experiences for university professors who may perform online education in similar conditions.

ATTRACTIVE RESEARCH FIELD

The frequency of occurrences of a keyword indicates the domain space and vital content of a certain topic/subject. **Figure 5** depicts the keyword co-occurrence networks and highlights digital literacy research encompasses a varied and mixed set of areas. This map was generated using the criteria-type of analysis described as follows: co-occurrence, all keyword and counting method, and full counting. The threshold number of occurrences for a keyword in the article was set at 100 to ensure that we focus exclusively on the most prominent keywords. 32 keywords were extracted from 8263 total keywords, and the frequency and strength of the link of the top 20 keywords are demonstrated in **Table 6**. With a frequency of 1368, E-Learning is the most studied topic in this area, followed by COVID-19 (1037), Human (694), and Pandemic (582), as illustrated in **Figure 6** using density visualization. It's important to note that the most commonly occurring keyword is E-Learning and COVID-19. Although COVID-19 has recently received significant attention by people due to the pandemic issues in many areas (e.g., education, economics, and social issues), the field of pandemics considers COVID-19 as a focal keyword. Additionally, the distance between e-learning and COVID-19 is relatively near among the top five keywords, showing the keywords' strong relationship. The map classified the keywords into six distinct clusters.

MOST IMPACTFUL ARTICLES

Bibliometric techniques for TC identify seminal or recent breakthrough studies. **Table 7** shows the most cited articles in

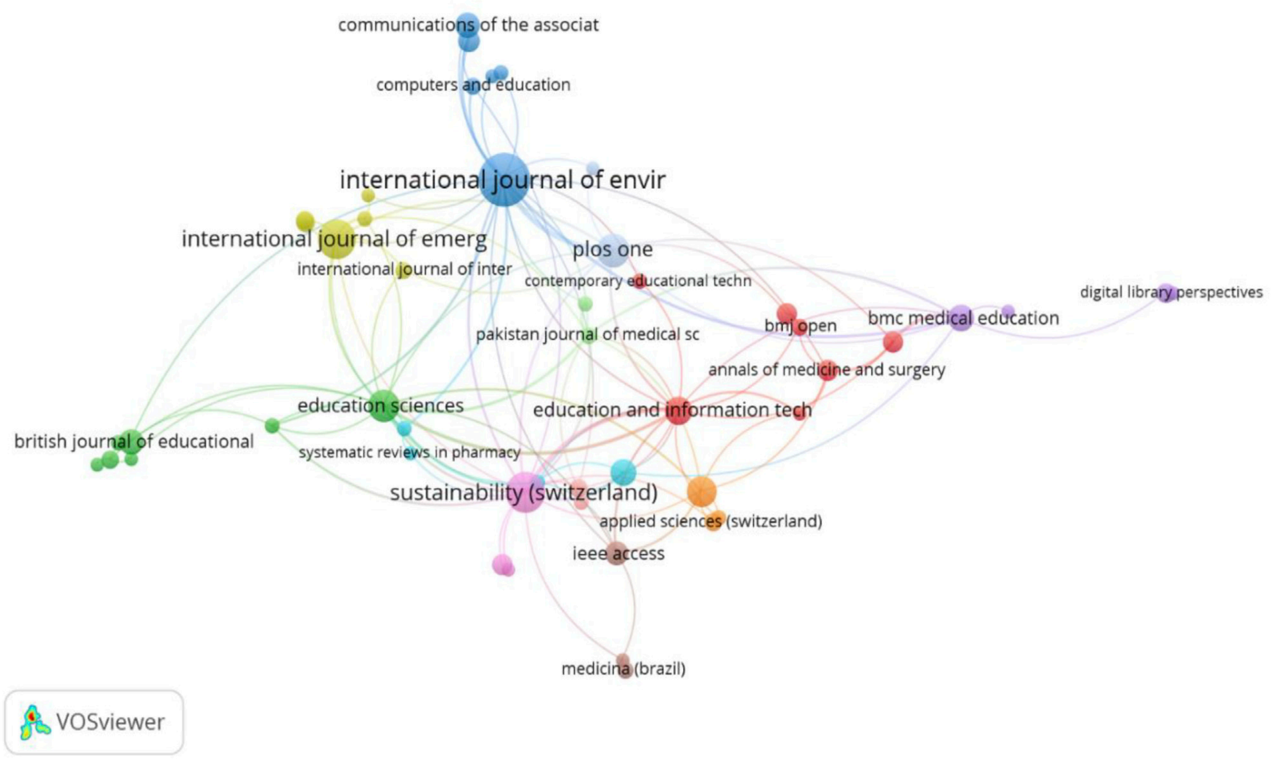

FIGURE 4 | Top 10 journals (Total Publication).

TABLE 5 | Top 5 cited references in E-learning and COVID-19.

Rank	Title	Author	Source	Year	TC
1	Online Learning: A Panacea in The Time of COVID-19 Crisis	Dhawan, S	Journal of Educational Technology Systems	2020	25
2	Evaluating Structural Equation Models with Unobservable Variables and Measurement Error	Fornell, C., Larcker, D.F.	Journal of Marketing Research	1981	18
3	Covid-19 and Online Teaching in Higher Education: A Case Study of Peking University	Bao, W	Human Behavior and Emerging Technologies	2020	16
4	Using Thematic Analysis in Psychology	Braun, V., Clarke, V	Qualitative Research in Psychology	2006	14
5	Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology	Davis, F.D.	MIS Quarterly	1989	13

Note: TC: total citation.

terms of TC. We can identify significant publications that got the most citations within and beyond the sample of 1807 studies. According to estimates, Blake et al. (2020) is the most influential article on the e-learning and COVID-19 in the education sector, with the TC 205 and TC per year 68.3. Other influential studies with TC of one include (Kapasia et al., 2020), (Mukhtar et al., 2020), and (Almaiah et al., 2020).

MOST RELEVANT INSTITUTIONS

Figure 7 represents the most-relevant academic institutions that published e-learning and COVID-19 research in this field. The first position is King Abdulaziz University from Saudi Arabia, which contributes to 43 articles, the second is Monash University from Australia, which contributes for 41 articles, and the third position is All India Institute of Medical Sciences from India, which contributes 39 articles.

The other top relevant institutions comprise universities from Saudi Arabia (IMAM Abdulrahman Bin Faisal University, King Saud University, King Khalid University, Umm Al-Qura University, and Qassim University), Jordan (Jordan University of Science and Technology), United State (the University of California and Harvard Medical School), Indonesia (Universitas Indonesia) and Malaysia (University of Malaya). Under the top 10 universities are seven universities from Saudi Arabia.

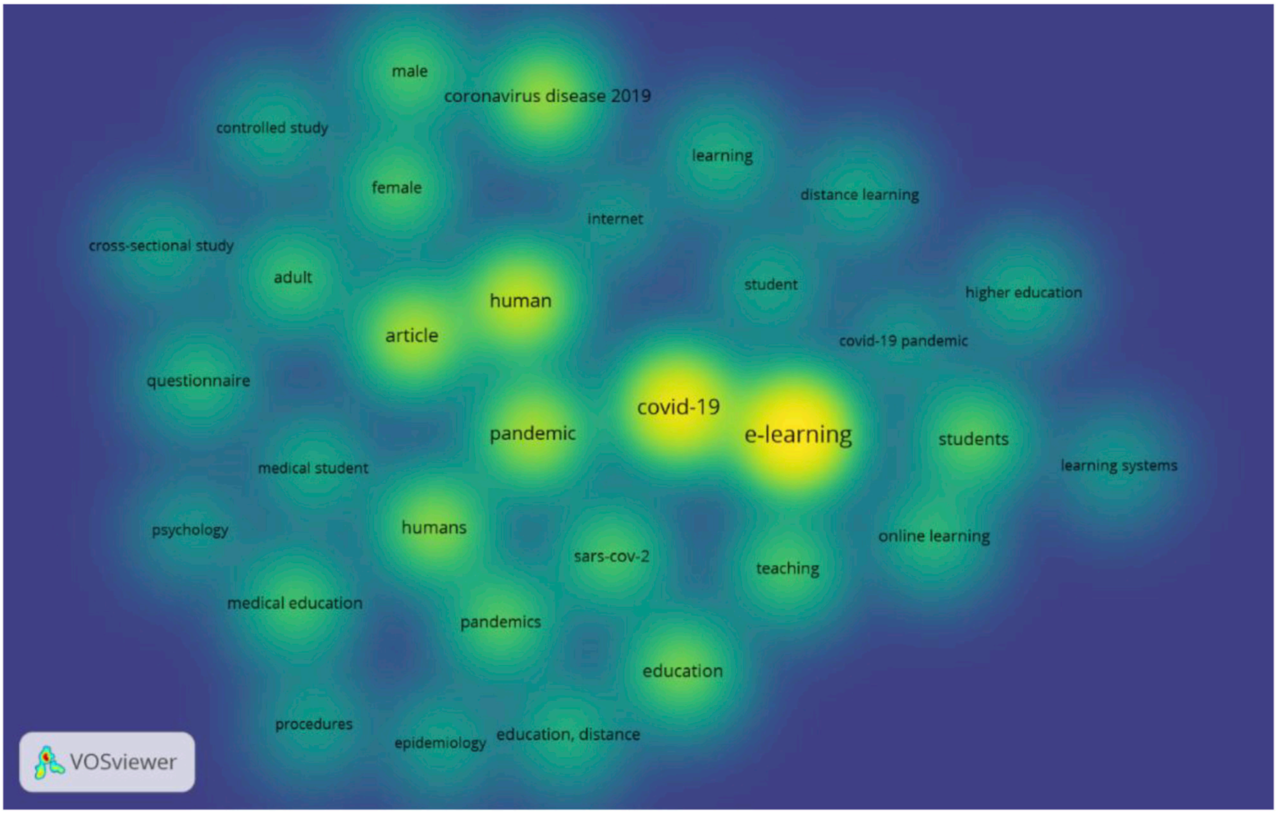

FIGURE 5 | Visualization map of keywords co-occurrence in the field of e-learning and COVID-19.

TABLE 6 | Top 20 cited keywords.

Rank	Keyword	Occurrences	TLS
1	E-Learning	1368	7982
2	Covid-19	1037	7099
3	Human	694	7300
4	Pandemic	582	6010
5	Article	580	6245
6	Coronavirus Disease 2019	512	5672
7	Humans	461	5468
8	Education	407	4279
9	Students	342	1938
10	Pandemics	325	3959
11	Sars-Cov-2	305	3568
12	Female	304	3906
13	Teaching	300	2651
14	Male	299	3870
15	Medical Education	286	3118
16	Adult	262	3400
17	Online Learning	226	1105
18	Questionnaire	212	2575
19	Education, Distance	194	2644
20	Learning	191	1828

Note: TLS, total link strength.

THREE FIELDS PLOT

Relationships among journals, research areas, and countries can share important information. As a result, in **Figure 8**, the authors provide a new Three-Fields Plot that depicts the relationships between the most-relevant publications sources (left), author keywords (middle), and countries (right) in e-learning and COVID-19 in education research. The authors observed that most research on online learning and e-learning is published in the International Journal of Advanced Computer Science and Application, with the majority of them authored by the United States and India. Generally, the United States focused on COVID-19 research, India, Saudi Arabia, and Indonesia focused on e-learning research, and all other fields were covered by almost all these countries.

RESEARCH CLUSTERS AND FUTURE RESEARCH DIRECTIONS

There are various underlying research themes in every research field. Using bibliographic coupling analysis in e-learning and

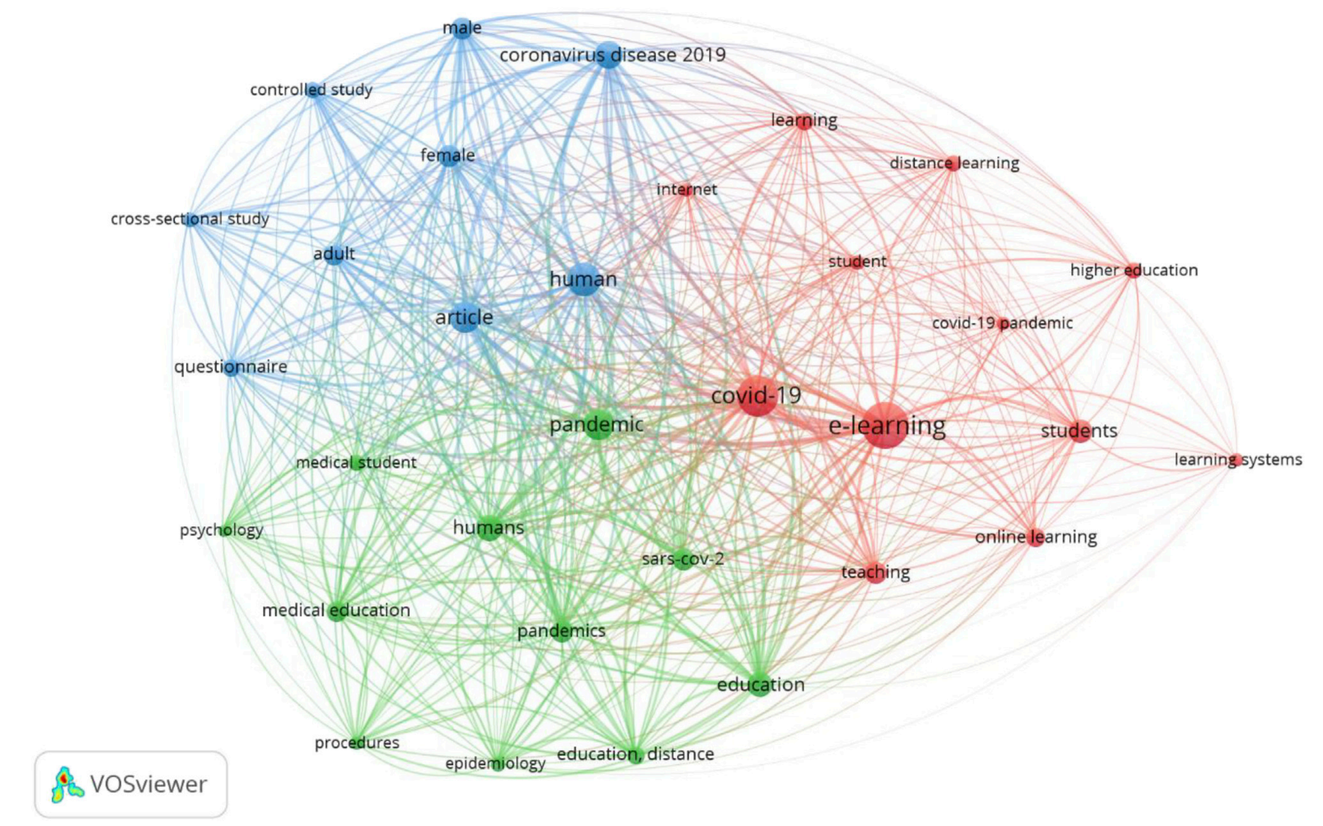

FIGURE 6 | Network map of keywords occurrence in the field of e-learning and COVID-19.

TABLE 7 | Most impactful articles.

Rank	Paper	DOI	TC	TC/Y	NTC
1	BLAKE H, 2020, INT J ENVIRON RES PUBLIC HEALTH	10.3390/ijerph17092997	205	68.3	12.3
2	KAPASIA N, 2020, CHILD YOUTH SERV REV	10.1016/j.childyouth.2020.105194	179	59.7	10.8
3	MUKHTAR K, 2020, PAK J MED SCI	10.12669/pjms.36. COVID19-S4.2785	179	59.7	10.8
4	ALMAIAH MA, 2020, EDUC INF TECHNOL	10.1007/s10639-020-10219-years	176	58.7	10.6
5	IIVARI N, 2020, INT J INF MANAGE	10.1016/j.ijinfomgt.2020.102183	169	56.3	10.2
6	FAVALE T, 2020, COMPUT NETWORKS	10.1016/j.comnet.2020.107290	154	51.3	9.3
7	SUNDARASEN S, 2020, INT J ENVIRON RES PUBLIC HEALTH	10.3390/ijerph17176206	140	46.7	8.4
8	MAILIZAR, 2020, EURASIA J MATH SCI TECHNOL EDUC	10.29333/EJMSTE/8240	138	46.0	8.3
9	HASAN N, 2020, CHILD YOUTH SERV REV	10.1016/j.childyouth.2020.105355	133	44.3	8.0
10	ABBASI S, 2020, PAK J MED SCI	10.12669/pjms.36. COVID19-S4.2766	126	42.0	7.6

Note: TC, total citation; NTC, normalized total citation; TC/Y, total citation per year.

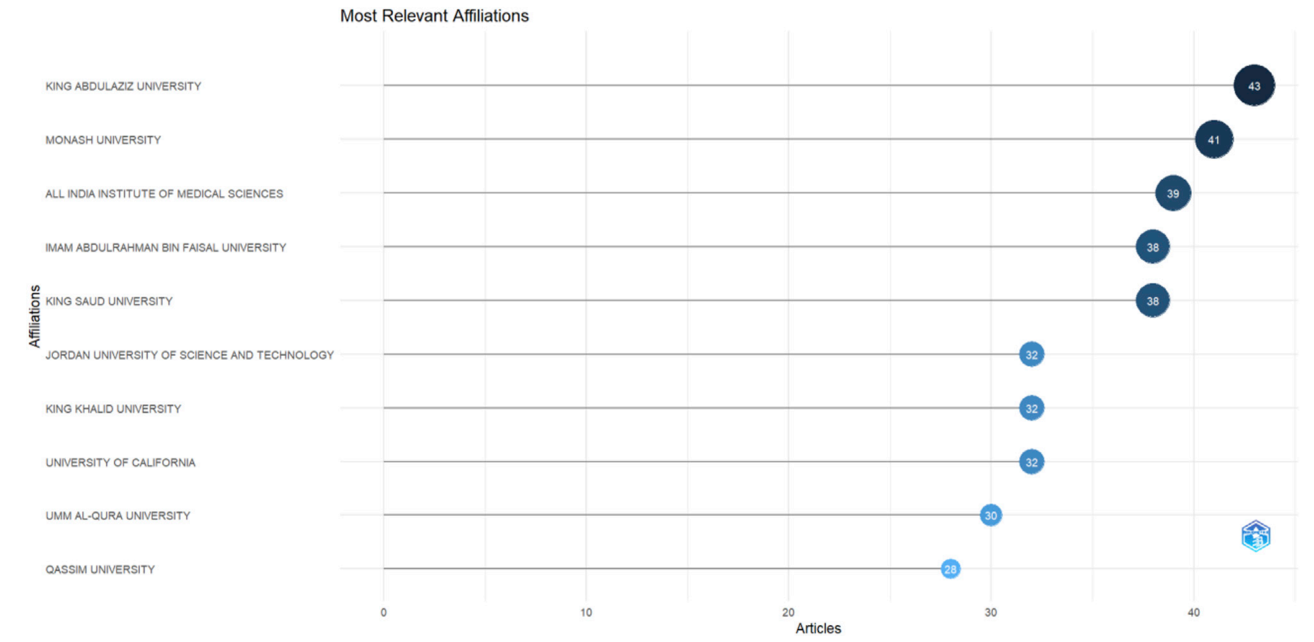

FIGURE 7 | Relevant institutions.

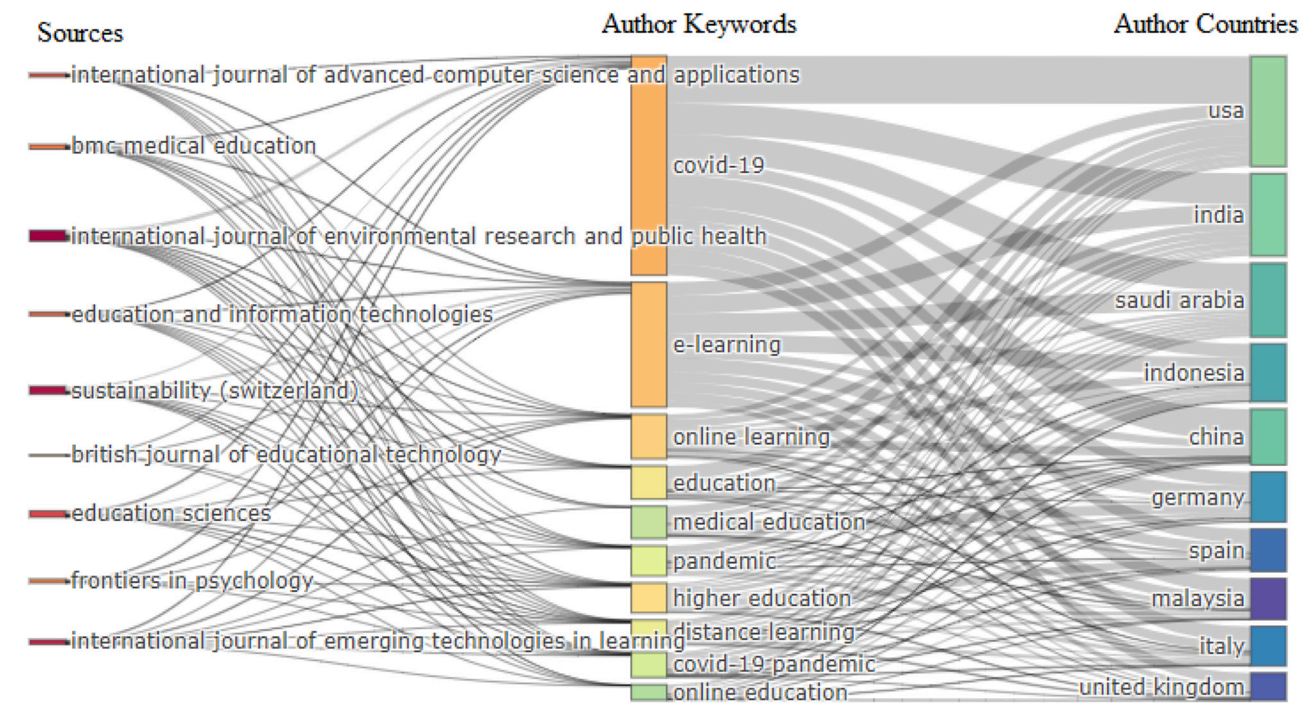

FIGURE 8 | Three-fields plot.

COVID-19 in education research, the authors identified two underlying clusters: 1) COVID-19, E-learning and Online Learning, and 2) Personal Protective Equipment, Randomized Controlled Trial and COVID-19 (see **Figure 9**). Both clusters are interconnected and built on each other. Inside every cluster, the authors critically assessed the contents of bibliographically related articles that provide similar underlying study topics and extracted significant directions for future research. To conduct the content

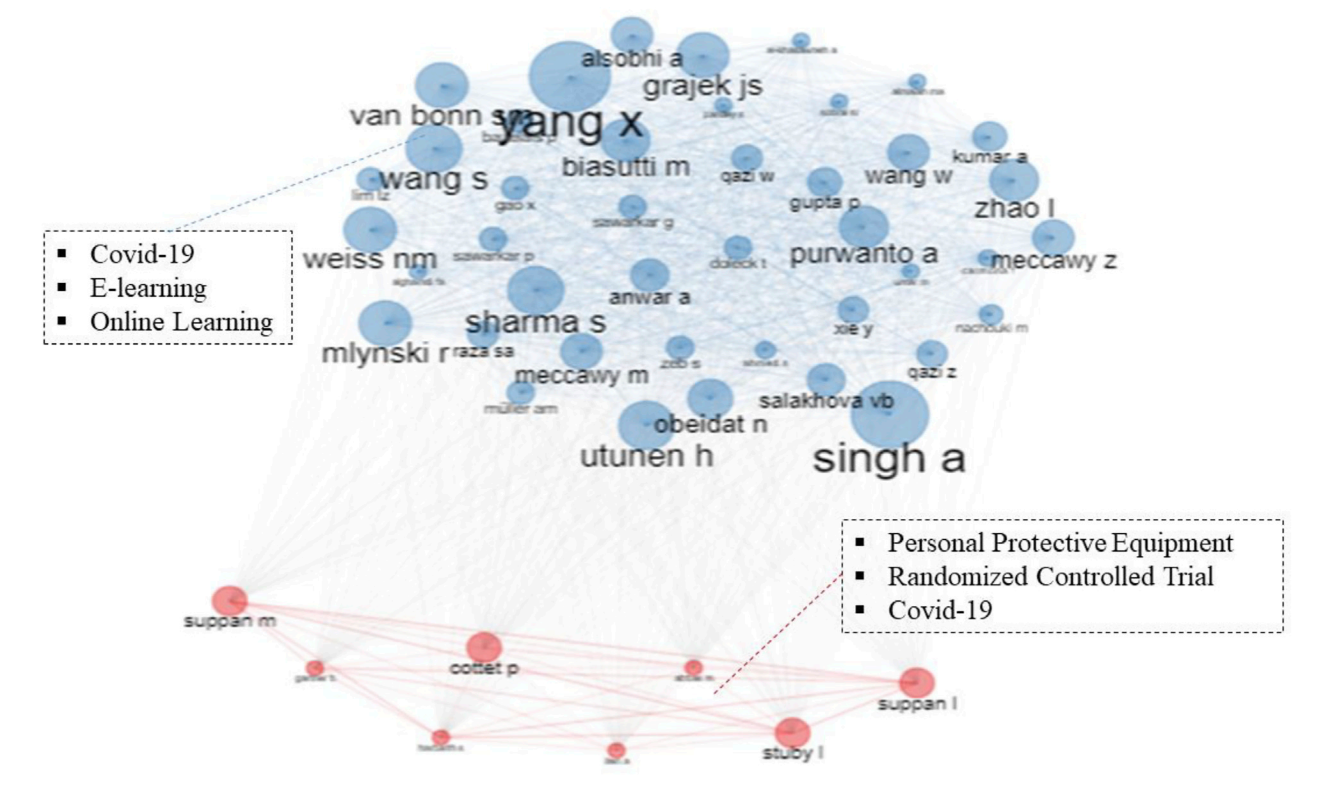

FIGURE 9 | Coupling map.

TABLE 8 | Top 10 used keyword occurrences in different years.

Rank	Keyword occurrences in 2020		Keyword occurrences in 2021		Keyword occurrences in 2022	
	Keyword	O	Keyword	O	Keyword	O
1	E-Learning	258	E-Learning	927	E-Learning	181
2	Human	179	Covid-19	735	Covid-19	128
3	Covid-19	173	Human	450	Students	69
4	Article	153	Article	376	Human	65
5	Pandemic	153	Pandemic	375	Pandemic	54
6	Coronavirus Disease 2019	151	Coronavirus Disease 2019	320	Article	51
7	Education	109	Humans	303	Humans	51
8	Humans	107	Education	254	Sars-Cov-2	47
9	Pandemics	93	Sars-Cov-2	230	Education	44
10	Medical Education	82	Students	217	Online Learning	43

Note: O: occurrences.

analysis, the authors utilized an excel sheet with columns for the title of articles, publication's year, author(s), journals, frequent keywords, methodology, key finding(s), and abstract (Salipante et al., 1982).

HOT RESEARCH TOPICS IN DIFFERENT YEARS (2020, 2021, AND 2022)

Table 8 shows the top 10 keyword occurrences in 2020, 2021, and 2022. The minimum number of occurrences was set to 10 for a keyword in the article for 2020, 2021, and 2022 so that the authors focus on the prominent keywords only. The authors would extract 97 out of 2407 keywords, 248 out of 6146 keywords and 44 out of 1951 keywords, respectively, and occurrences of the top 10 keywords are shown in **Table 8**. E-learning is the hottest topic in this field, with the highest occurrences (258, 927, and 111) in 2020, 2021, and 2022, respectively. The e-learning keywords are most famous, with 927 occurrences in 2021 because the pandemic was at its peak, and researchers were most devoted to studying this field.

CONCLUSION AND RECOMMENDATIONS

This study states how the Scopus database was used to explore online learning trends in education during the pandemic using a bibliometric approach. In terms of methodology, the suggested technique may visualize the temporal relationships of the most cited articles within separate streams and offers a comprehensive picture of the evolution of subjects in the Scopus database. Furthermore, citation network analysis enables researchers to study e-learning-related publications and offer a comprehensive summary of the issues raised in the papers.

In perspective of mapping research publications, this piece of research provides an insight into E-learning world. A scientific study was done with 1807 e-learning and COVID-19 documents from 2020 to 2022 that were found through the Scopus database. For most of the researchers and leading institutions, this study identifies emerging trends and contributes significantly in this field as well as prominent sources over period. This study aligns with a number of earlier studies in this field, including Hung (2012), Chiang et al. (2010), Cheng et al. (2014), Fatima and Abu (2019), Tibaná-Herrera et al. (2018), Mashroofa et al. (2020) and Bai et al. (2020). Nevertheless, this research depends on a variety of software to analyze diverse models and networks of E-learning and COVID-19. According to the analysis data, growth trends in research publications in various forms of e-learning and COVID-19 have drastically increased in recent years, particularly in 2 years (1184 in 2021 and 283 in 2022). 2021 was a peak time of COVID-19, so researchers found alternatives of traditional method to e-learning during COVID-19. The following are the significant findings of the bibliometric analysis: the prominent authors in this field are as follows: Stuby L., Suppan L., Suppan M., Harbarth S., Sharma S., Gartner B. and Purwanto A.; The King Abdulaziz University from Saudi Arabia is the most-frequently cited institution in this field of study; with respect to citations and publications, the United States leads the world; and during COVID-19, education drastically transformed into the e-learning mode and has developed into a recent research trend for many researchers.

This research investigated at a highly access topic, that is one of the hot topics right now "e-learning and COVID-19 in education" employed a bibliometric analysis of 1807 articles published in the Scopus database from the years 2020–2022. The authors determined that the sample of the study should be larger; additional studies and a longer time frame are required, particularly when analyzing citations, and research on this topic would be more explored in the future domain.

All the above findings of the study state that the developed countries quickly focused on e-learning method during COVID-19 but developing and less developing countries could not easily shift from traditional to e-learning processes. The reason behind it, that developed countries have been compatible with e-learning process because technology and digital tools were available easily but developing countries and less developed countries did not have proper resources for implementing the e-learning process during COVID-19 and other critical conditions.

This study indicates that the e-learning process mitigates environmental degradation through less paper use. The traditional education method is renowned for overusing "busy work," which is a major cause of paper waste. Even the energy and materials used to recycle paper are reduced when students teach online (Irfan et al., 2021). Before COVID-19 transports services had an adverse effect on environmental quality (Sun et al., 2021), but E-learning eliminates the negative environmental effects of manufacturing and transportation services during COVID-19. The traditional educational methods required (textbooks, desks, electricity, and buildings) are drastically decreased through the e-learning method, which also reduced waste and protects natural resources. Finally, this study majorly contributes to society at all levels of education during COVID-19. There are mainly three key contributions of this study to society. First, this study suggests that developing and less developing countries can upgrade technology and digital tools (Internet, Digital devices and broadband connections etc.,) for e-learning education reached to the lower section of the society. Second, environmental degradation is a major issue across the world, e-learning improve the quality of the environment, so governments should initiate an awareness program about the advantages of e-learning education. Third, developing and less developing countries are unable to provide education to everyone in the lower section of the society, the reason behind this is that low income of the people, less infrastructure, and fewer transportation facilities, e-learning methods reduce the cost of education and deforestation. So all these countries should implement e-learning methods to improve the literacy rate.

There are certain limitations of this study. First, the authors gathered data from Scopus only, which does not include all academic article such as Web of Science and other journal databases. Second, the most recent articles (those published till 18 March 2022) that have been accepted but not indexed in Scopus were omitted. However, such limitations are unlikely to have an impact on the findings of this study.

AUTHOR CONTRIBUTIONS

YA wrote the introduction, MA designed the research and wrote Introduction and Literature Review, MS collected data, processed data in VOSviewer and R Studio, analyzed data, wrote sections: Research Methodology, Results, and Discussion, Conclusion, MA arrange the funding, NH wrote Introduction and Literature Review, MH collected data and NZ supervised the research.

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Modeling the Impact of Cotton Production on Economic Development in Benin: A Technological Innovation Perspective

Dafia Chabi Simin Najib[1], *Chen Fei*[1]*, *Azer Dilanchiev*[2] *and Samson Romaric*[3]

[1]Department of Textile Economics and Management, Zhejiang Sci Tech University, Hangzhou, China, [2]Department of Economics, Faculty of Business and Technologies, International Black Sea University (IBSU), Tbilisi, Georgia, [3]Innovative Research in Economics and Governance-IREG Cotonou (Benin), Porto-Novo, China

Edited by:
Asif Razzaq,
Dalian University of Technology, China

Reviewed by:
Shahid Ali,
Nanjing University of Information Science and Technology, China
Yunfeng Shang,
Zhejiang Yuexiu University of Foreign Languages, China

***Correspondence:**
Chen Fei
chenfei1208@sina.com

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This research provides an in-depth understanding of cotton production in Benin. The analysis explored the effects of cotton production on economic growth using a vector error correction model (VECM). Prior to the VECM, a descriptive analysis was conducted on a time series database collated over 56 years (1965–2021) from national and international organizations including World Bank, the United States Department of Agriculture, and the National Accounts. Depending on the availability of the information over this period, the data were trimmed down to enable a better overview of the trend for variable of interest. Thus, the review of the trend for agricultural land (hectares) for cotton observed from 1965 to 2021 revealed that the trend evolves over the years in three different patterns, while the yields demonstrate four patterns over the same period. For the VECM analysis that permits to understand the long- and short-term relation, the time bound covers 30 years from 1990 to 2019 given the availability of data for all the variables used for the model. The findings highlighted that a strong and positive connection is found between cotton export and economic growth and a long-term relation between the human capital and the economic growth in Benin. A rapid human capital development will increase quality of the employment generation, and the country's economy will adjust upward. Furthermore, a short-run coefficient unveils feedback necessary in a relative level of investment to bring back the economic growth to equilibrium. From these findings discussed in this study, the government of Benin is commended to diversify the production of cotton through a town target policy.

Keywords: Benin republic, cotton production, economic growth, vector error correction, technological innovation

1 INTRODUCTION

Environmental degradation and energy poverty are major issues in the current world scenario (Sun et al., 2022). Agriculture plays a very important role in some major economies (United States, Canada, and Russia) and in the reduction of famine worldwide. Also, it demonstrates a tremendous impact on the industrialization process through the supply of raw materials (Cotton, Rubber, Sugarcane, Cereals, and many others) to many transformation industries. Agroforestry and agriculture demonstrate a significant part in the economies of West African countries. They account for about 40% (with cotton being the most important contributor) of the gross domestic product (GDP) and provide a wide range of ecosystem benefits to local residents (Djihouessi et al., 2022).

Cotton production plays key role in many economies across the world. With an estimated $600 billion annual economic impact worldwide, cotton is the leading natural fiber produced and commercialized in the world (Ahmad, 2014). The industrialization of cotton sector involves about 150 countries and provides income to about 100 million families (Tarazi et al., 2019; Meyer, 2020). Cotton output in 2019 was estimated to be worth USD 46 billion, with global trade worth USD 15 billion. In 2018/19, global cotton mill use reached 26.7 million tons, the same amount as in 2007/08.

In Sub-Saharan Africa (SSA), cotton, also known as white gold, gained attention from government and through scientific research, and it is considered as an essential commodity crop that is expected to grow by 14% by 2025 and about 15% of the world's cotton lint exchanges, according to SSA (OCDE/FAO, 2016). Cotton is essential to the economies of several African countries, providing livelihoods to lots of small farmers around the world. Cotton is experiencing a revival in other countries, such as Ethiopia, and as well as voluntary certification programs like the global organic textile standard to encourage and ensure the sector's sustainability (Partzsch and Kemper, 2019; Partzsch et al., 2019).

Cotton development in SSA faces a significant challenge in terms of environmental sustainability. In recent time, studies have been undertaken in the sector to revamp the value of African countries' cotton production. For instance, study led by the World Bank in 2008 found out the economic advantages of cotton exports to developing countries and the disadvantages faced by producing countries due to lack of key technologies (Estur and Gergely, 2010). Next, the cotton sector plays a major role in the growth of economies and the improvement of living standards as well as purchasing power of the rural population. Also, (Morris, 1989) indicated that countries that grow and process cotton fiber emerged as a major provider of foreign exchange in nine emerging countries, including Benin.

However, in the past 5 years, Benin's cotton industry has been in a major crisis resulting in a dramatic drop in the crop production. Looking at the process, cotton production in the country is heavily dependent on imported inputs, which increases the cost in production and is most time challenging for peasants and producers. Given the importance of the sector, many studies focused on ways to improve and stimulate the sector. Thus, according to (Togbé et al., 2012), the pest control technique in the production chain improved the cotton yields and its quality. As a main source of foreign exchange in Benin, the production of cotton, over time, evolved in a saw path before gaining since 2016, a remarkable and steady increase with the highest record tolled at 597,985 tons at the end of the 2020 agronomical season. Indeed, after 4 years (2012–2016) of crisis due to the extreme interference of politics, which has dropped its performances, the cotton sector recovered with the Inter-professional Association of Cotton (AIC) bouncing back within the system as the system core managerial body and structural umbrella. The progressive disengagement of the state from the provision and distribution of inputs accelerated and reinforced the liberalization of the cotton commodity chain under this umbrella. Thus, private national operators increasingly took over import and distribution operations, and their numbers grew over time. As a result, AIC has become the executing agency for key chain operations such as cotton research, seed production, producer training and supervision, cotton grain quality control, fiber grading, and road maintenance. Some of these tasks are delegated to government-run technical services and service companies. Along the line, the functioning of the AIC[1] and some of quantified results are rewarding. For example, Benin's five-year average production is 435 kg/ha, which is significantly higher than that of the other franc zone's countries' five-year average output of 393 kg/ha.

Researchers estimated that the cotton industry employs 30% of Benin's workforce. In the past, previous studies focused mainly on the impact of agricultural activities on the economy of developing countries in general. An in-depth study to analyze the contribution of cotton production to the economic growth of Benin will be vital for our research. However, as these recent performances remain visible, it is worth revisiting the nexus between cotton agricultural production and the economic growth in Benin. In addressing this aim, the present research develops two hypotheses related to the interaction between cotton production and economic growth, as follows: (H1) the impact of increasing production of cotton on economic growth is positive; (H2) the gains from improving human capital affect in long run both cotton production and economic growth. The findings from testing these hypotheses through a vector error correction model (VECM) will feed into the existing literature. Thus, while the next section discusses the relevant literature, the third section will detail the methodology and data. The final section will present and discuss the results and wrap up the study with socioeconomic policy implications.

2 LITERATURE REVIEW

Agriculture exhibits a crucial contribution to the economic development of a nation (Gollin, 2010; Brückner, 2012; Cao and Birchenall, 2013; Fayçal and Ali, 2016). A case study of Benin as a WAEMU member state (Amoussouga Gero and Egbendewe, 2020) showed that enhancing agricultural productivity could boost the overall economic growth through a mechanism that reduces the trade deficit and subsequently increases household income and government revenues. According to (Awokuse and Xie, 2015), a strong agricultural contribution is a driving factor of economic growth in a country. Also, (Los and Gardebroek's (2015) study implies that the agricultural sector performs different roles in different stages of economic development. Along with investment and the private sector, the share of agriculture demonstrates a significant added value to the country's GDP (Mijiyawa, 2013). Similar to this, (Amao et al., 2021) recommended that reforms designed to improve the accessibility to loans and the productivity of cash

[1]In recent years, Benin's yield trend grew following investments in cotton supply chain modernization by government and private business and timely provision of seeds and fertilizers

crops, including cotton, will boost the country's export and economic growth. Güzel and Akin (2021) found that increased agricultural production during the industrialization process in middle-income countries can stimulate a growing economy. However, the research findings did not conclude a significant connection between trade openness and a growing economy. Furthermore, other agricultural products such as tea, cereals, and tobacco significantly impact the GDP of the Indian economy. In contrast, some agricultural products, such as coffee and sugarcane, demonstrate the reverse effect (Urmi Pattanayak and Minati Mallick, 2019). In support of agriculture's role in economic growth, (Agboola et al., 2020) explained unidirectional causality from various sub-sectors of agriculture such as forestry, agricultural production, fisheries, and life stock to economic growth.

Besides this thesis, other scholars concluded that agriculture and economic growth are related to the sector's profitability. Boosting agricultural profitability could be an essential pathway toward poverty reduction and socioeconomic development. Thus, according to (Matsuyama, 1992), such products can only be achieved in an unregulated environment where states demonstrate a comparable production benefit in agriculture. However, the rural income could not increasingly improve alongside the productivity increase over the years because of the poor quality of commercial transactions in the agricultural sector (Bautista, 1986). The theoretical and empirical research findings of (Mellor, 1983) provide useful indications of how increased agricultural production sustains economic development and poverty reduction. Thus, the agricultural sector is considered a labor-intensive sector but with very low wages (Khor and Feike, 2017).

It is worth noting that the relationship between agriculture and economic growth has lately been re-examined. Using analytical and dynamic models, (Yang and Zhu, 2013) employed the double-sector dynamic United Kingdom model and demonstrated that in the absence of improved agricultural output, an agricultural economy could not compensate for the restrictions of natural assets. Similar to this, (Irz and Roe, 2000); (Ogunlesi, 2018) concluded on a minimum growth rate at which agricultural performance is required to overcome the growing population and the subsequent Malthusian trap.

On the other hand, various studies from developing countries (Dorosh and Thurlow, 2014) show evidence of aggregate improvements in economic performance and a decline in poverty that can be accomplished with agricultural productivity expenditures. For instance, (McArthur and Sachs 2014) Uganda's CGE mod showed how substantial economic growth might be achieved by focusing development aid on policy finance to improve agricultural production efficiency. Furthermore, with an auto-regressive distributed lag model, studies indicated that the sustainability of agricultural production would significantly affect agricultural growth, even though it will negatively impact the long run economic growth (Fayçal and Ali, 2016).

Cotton is seen as an integral part of the livelihoods of many countries in the world and as an important cash crop in West African countries, including Benin. Since 1960, world cotton production increasingly evolved, resulting in a slight annual improvement of 1.7%. Across the world, during the year 2018–2019, China was the world's largest producer with nearly six million tons, followed by India with 5,879,000 tons and the United States with 4,004,000 tons. In 2016, USAID indicated that cotton contributed 3–10% of the GDP in Benin, Burkina Faso, Mali, and Chad, among other key producers of cotton, where the crop is heavily produced and seen as a main source of income and as a crucial contributing factor to poverty reduction (Sabesh and Prakash, 2018).

In particular, according to the USDA (2019), Benin was the largest cotton producer in the West African region in the 2019–2020 cotton season (1,450 thousand bales). As a result of this, it is expected to be the same this coming year. Within the West African franc zone, it is followed by Mali (1,425), Burkina Faso (1,200), Côte d'Ivoire (830), Cameroon (565), Togo (265), Chad (200), Senegal (35), and Niger (9). Looking at the volume of cotton trade (import and export operations), SSA is ranked as the third top with 12% of the overall cotton export. In addition, (Baffes, 2007) and (Gray and Moseley, 2008) argued that cotton total merchandise exports ranging from 25% to 45% contributed to West African countries' GDPs and remains many households' sources of income.

In Benin, according to World Bank. (2016), agriculture contributed for 4.33% to the country's GDP from 1994 to 2014. For a decade, Benin's economy is agriculture reliant, with cotton as its main cash crop (Gergely, 2009). The cotton sector directly or indirectly generated more than 40% of rural employment and provided for nearly 50% of the population. According to the National Institute of Statistics and Economic Analysis, it contributed 13% to the GDP. In the same vein, according to the platform of civil society actors in Benin (PASCiB, 2013), cotton was the major contributor to Benin's rural producers' incomes. In as much as this is attributable to the cotton sector, this study, in pursuing its keen interest, will drive into understanding how cotton production could affect the economic growth in Benin in the long run.

3 DATA AND METHODOLOGY

3.1 Data and Key Variables

This study utilizes macroeconomics data collated from 1965 to date. The dependent variable is "The Gross Domestic Product (GDP) per capita" drawn from the world development index database (World Bank. 2019). Other relevant variables include cotton production, the area under cotton production, and the cotton productivity assembled from production, supply, and distribution database of the United States Department of Agriculture. The gross fixed capital formation (GFCF), also called "investment," as well as human capital to measure respectively investment in property developments, the total employment, or labor force in the cotton production chain are also used as independent variables.

As can be observed, regression models are frequently used to examine production and economic difficulties, and most research publications (Hollinger and Staatz, 2015; Nyamekye et al., 2021; Ngong et al., 2022) focus on the relationship between agriculture and other factors in developing countries.

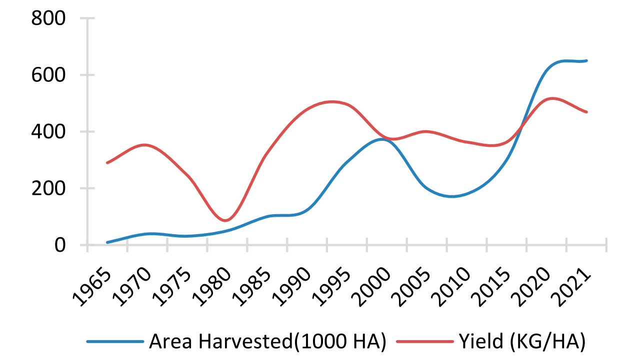

FIGURE 1 | Cotton yield and agricultural land in Benin. Source: Authors with data from USDA, https://apps.usda.gov/psdonline.

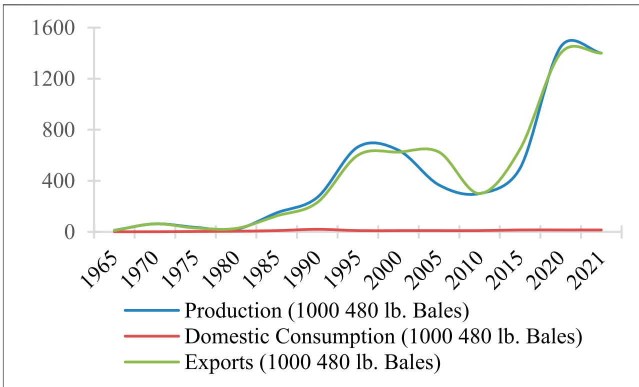

FIGURE 2 | Cotton production in Benin. Source: Authors with data from USDA, https://apps.usda.gov/psdonline.

It is good to add that other research employs a non-linear auto-regressive distributed lag framework to address non-linearity arising from abnormal data distribution (Sun et al., 2022).

However, little relevant research exists that specifically investigates that element of agriculture in cotton farmers in West African countries (Benin, Mali, and Burkina Faso). We used the VEC model to investigate the implications or influence of cotton output on economic growth in the Benin Republic.

3.2 Analytical Procedure

This study will use a VECM which can explore not only a long-term causal relationship between the two major variables but also gives the advantage to underscore the short-term impact. In the process, before running a VECM model, one may perform a unit root test to ensure the stability of each series in the model. This study will perform the augmented Dickey-Fuller (ADF) test. However, for the sake of robustness, the Phillips-Perron (PP) test will subsequently run to control the volatility of the series over the long period under review.

3.3 Empirical Model Specification

In reference to (Ren et al., 2020; Ai et al., 2021), the impact of cotton production on economic growth will be assessed through the following model.

$$GDP = f\,(EXPCT,\ HC,\ LAB) \tag{1}$$

The econometric expression of **Eq. 1** is the following:

$$GDP_t = \beta_0 + \beta_0 EXPCT_t + \beta_2 HC_t \text{-} \beta_3 LAB_t + \mu_t \tag{2}$$

where β0, β1, β2, and β3 > 0, EXPCT is the quantity of cotton exported, HC denotes the human capital, and LAB is the labor employed in the labor market; they are all likely to be positively related to economic growth. Also, μ signifies the error term and represents the year period.

Taking log on **Eq. 2** turns to **Eq. 3**:

$$In\,(GDP)_t = \beta_0 + \beta_1 In\,(EXPCT)_t \beta_2 In\,(HC)_t + \beta_3 In\,(LAB)_t + \mu_t \tag{3}$$

3.3.1 Unit Root Test

As a macroeconomic long-term series, estimating the root unit and ensuring they are not integrated is essential. This test is necessary to evaluate variable stability and, thus, to avoid biased findings. With the ADF and the PP test, the following hypotheses are tested:

H0: β1 = β2 = β3 = 0 → the null hypothesis of this model is that co-integration is not available.

H1: β1≠β2≠β3≠0 → the alternative hypothesis asserts that co-integration exists.

If the F-statistics computed value is higher than the top critical limits, then the null hypothesis of no long-lasting link is rejected. Otherwise, it is accepted if the calculated F-statistics value is below the critical limit values. The PP test ensures reliability of the results.

3.3.2 Co-Integration Analysis

The co-integration test is performed to confirm whether the VECM will run with stationary time series. This leads to a discriminatory criterion that determines the best order of lag and evaluates the necessary amount of co-integration by co-integration testing. Also, the Engle Granger two-stage method and the Johansen maximal probability method were most frequently used (Shao et al., 2021).

3.3.3 Estimation

In addition to the descriptive analysis, the final equation that will be used to explore the casual long and short-term relations is given as follows:

$$D\,[ln\,(GDP)]_t = \beta_0 + \beta_1 D\,[ln\,(EXPCT)]_t + \beta_2 \mathrm{D}\,[ln\,(HC)]_t + \beta_3 D\,[ln\,(LAB)]_t + \mu_t \tag{4}$$

4 RESULTS AND DISCUSSION

4.1 Trend of Cotton Production: Yield and Exports

The descriptive analysis shows that the trend for agricultural land (hectares) for cotton evolves over the years in three different

TABLE 1 | Decomposition of the factor contributing to the gross domestic product.

	In local millions of local currencies				% Of total GDP			
	2015	2016	2017	2018	2015	2016	2017	2018
Primary sector	1,776.9	1,936.3	2,082.7	2,235.4	26%	28%	28%	28%
Agriculture	1,347.7	1,496.5	1,626.3	1767.2	20%	22%	22%	23%
Breeding, hunting	243.7	251.7	270.9	284.4	4%	4%	4%	4%
Fishery, forestry	185.6	188.1	185.6	183.7	3%	3%	3%	2%
Secondary sector	1,103.2	1,113.0	1,118.2	1,172.4	16%	16%	15%	15%
Mining and quarrying	26.1	26.7	26.8	29.5	0%	0%	0%	0%
Agro-food industries	434.9	454.3	463.3	490.2	6%	7%	6%	6%
Other manufacturing industries	240.8	264.9	251.8	252.0	4%	4%	3%	3%
Electricity, gas, and water	89.4	53.2	55.4	57.2	1%	1%	1%	1%
Construction	312.0	314.0	321.0	343.4	5%	5%	4%	4%
Tertiary sector	3,315.3	3,376.7	3,561.1	3,764.1	49%	49%	48%	48%
Commerce	867.8	949.2	969.2	1,015.2	13%	14%	13%	13%
Restaurants and hotels	238.8	209.6	217.0	227.8	4%	3%	3%	3%
Transport	580.0	617.6	660.2	699.7	9%	9%	9%	9%
Post and telecommunications	134.2	127.4	135.1	141.9	2%	2%	2%	2%
Banks and financial institutions	106.3	117.8	121.0	123.4	2%	2%	2%	2%
Public administration	461.1	430.4	460.4	488.1	7%	6%	6%	6%
Education	334.2	295.5	319.1	341.4	5%	4%	4%	4%
Health and social work	75.3	63.4	68.4	73.2	1%	1%	1%	1%
Other services	517.7	565.7	610.8	653.6	8%	8%	8%	8%
Total values added	6,195.4	6,426.0	6,762.1	7,171.8	92%	92%	92%	91%
Taxes net of Subsidies	537.4	531.7	590.2	672.8	8%	8%	8%	9%
Total GDP	6,732.8	6,957.7	7,352.3	7,844.7	100%	100%	100%	100%

Source: The authors with data from the National Accounts, 2018.

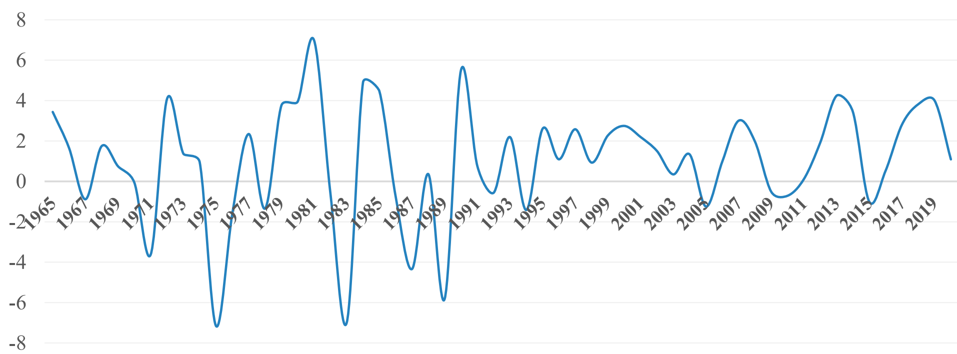

FIGURE 3 | Trend of the annual percentage growth rate of gross domestic product per capita. Source: World Development indicator, https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG?locations=BJ.

patterns, while the yield demonstrates four patterns over the same period. Looking at the yield, after a challenging decade, the trend shows, around 2010, a noticeable relaunch of the sector with the arrival of AIC and the settlement of new leadership, which offers, until 2020, a positive outlook for Benin's cotton future (**Figures 1**, **2**).

Also, this period marks the period where the government and private business engaged in modernizing the entire cotton supply chain and providing more timely seed and fertilizer inputs. Thus, Benin's five-year average yield is 435 kg/ha, which is much higher than the franc zone's five-year average production of 393 kg/ha. Moreover, looking at the production and exports, the graph suggests similar progress with a larger part being exported. Indeed, since 2010, reforms primarily included the privatization of input supply, the introduction of private ginners, and the formation of inter-professional bodies to take over sector management. This resulted in an increase in cotton production and export of up to 1,450 thousand bales.

In sum, this recent trend reinforces the assertion that cotton is the main cash crop for exports, even though the yield does not demonstrate a stable trend over time. Therefore, to bridge the gap of missing years, the government of Benin[2] commenced, since 2016, to diversify the agriculture sector and consider new crops such as cashew nuts, rice, and pineapple. This enables investment

[2]Programme d'Action du Gouvernement- PAG

TABLE 2 | Summary statistics for variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
lnGDP	30	6.899252	0.117952	6.72577	7.138715
lnINVEST	30	2.86276	0.18041	2.535405	3.254474
lnEMPLOYM	30	14.94914	0.26922	14.48577	15.38955
lnExports	30	13.21192	0.42965	12.34583	14.14481

Source: Authors.

of agro-value chains, safety standards, and promoting research and development through the National Program for Agricultural Research known as INRAB.[3]

4.2 Emergence of Economic Growth

Economic growth is the continuing increase of GDP per capita which is determined by dividing the gross domestic product by the mid-year population, according to the World Development Indicators. It is the sum of the gross value created in the economy by all residential manufacturers, plus product taxes, minus subsidies not included but estimated without taking into consideration depreciation of produced items or natural resource depletion and deterioration. Next, in line with this definition, the Benin National account reveals that structural characteristics of the Benin economy are predominantly agricultural. Regarding the structure of Benin economics, agriculture is the main contributor of the GDP, followed by trade, transport, and key services. For instance, the analysis of percentage of contribution reveals an increasing trend for agriculture (**Table 1**).

However, the main concern is how does it link to the overall average variation of economic growth. The GDP per capita yearly growth rate based on constant local currency varied considerably across the years, and stable growth has not occurred. Thus, from −0.06 in 1970, the GDP per capita growth (annual %) evolved at an average of 0.30 between 1970 and 1990, while the GDP per capita changed at an average rate of 1.10 since then to 2010 before an average annual rate of 2.09% during the last decade (2011–2022) (**Figure 3**).

Real GDP growth has been highly volatile throughout most of the country's post-independence history, related to its dependence on commodity exports (cotton) and transit trade with Nigeria. However, between 2015 and 2019, Benin recorded a solid economic outcome, which is depicted by a steady but robust GDP per capita growth regardless the Covid-19 pandemic and the border closure of Benin's main economic partner. Politics put in place showed the country's relative resilience, and though the economic activity, mainly export-import slowed down and yielded a slight drop-down of GDP annual growth at 1.01%, as shown in **Figure 3**.

4.3 Analysis of the Empirical Results

In the subsequent analysis, the time bound covers 30 years from 1990 to 2019 given the availability of data for all the variables used for the VECM analysis. The summary of the data for the variables utilized in this investigation showed that the average value for ln GDP is 6.99, which means that the estimated average of the economic growth over the period under review is 991.53 USD (constant 2010 US$) (**Table 2**).

Similar to this, the estimated value for investment, human capital, and export are, respectively, and in the same order equal to 17.51% GDP: 3,106,912.42 of the total population and 546,844.63 480 lb. Bales.

The bi-variate relationship between each of the independent variables and economic growth over the period under review indicates that there exists a strong positive relationship between cotton exportation, the quality of people (farmers directly for cultivation and harvest of the cotton crop and indirectly those somehow on the industrial labor force) involves in the cotton value chain, the type of equipment or investment done to support the value chain, and the economic growth of the country.

4.3.1 Unit Root Tests

The unit ratio could lead to a misleading conclusion in the underlying variable or lead to a fake regression (Vau and Bourlès, 2021). To avoid this, check first and foremost whether the sequence contains a unit root. If a unit root is discovered, it means the sequence is non-stationary, necessitating the use of first differences. In this study, the ADF and PP tests are used simultaneously to examine the dropout rate separately from the time trend (**Table 3**).

Apart from EMPLOYM, the remaining original series failed the ADF test, regardless of whether either intercept terms or the time trend was taken into account, indicating a non-stationary time series, which was confirmed by the PP test. As a result, we cannot reject the null hypotheses for all series. EMPLOYM is a stationary time series that does not need to be lagged.

4.3.1.1 Identification of Optimal Lag Order

The criterion test for selecting the optimal lag length required to differentiate our series is presented in the table below.

It includes the Akaike criterion for information (AIC), the SBIC, the Hannan-Quinn information criterion, and the log-likewood criterion. The SBIC is the final prediction error (FPE) (LIK). This document based its judgment on SBIC, although the function of discrimination differs from criterion to criterion (**Table 4**). Also, the probability ratio test shows that there are four in the best possible lag order, although, in addition to Akaike, Hannan-Quinn, and Schwartz (SBIC) data criterion, one in the final prediction error seems the most appropriate.

4.3.1.2 Johansen Co-Integration Test

Before running the co-integration test, the unit ratio will be re-run on the lagged original variables based on the selected ordered lag. The following table that synthesizes the results suggests that all series are now stationary series. The ADF and PP tests show that the calculated value of the statistics for each of the three variables is greater than the upper critical bound values (see annex) and is associated with statistically significant (1 and 5%) p-values (**Table 5**). Therefore, the neutral hypothesis of no long-term relationship is denied, and the Johansen test can be performed easily.

[3]Implementation Completion Report ICR00004927, July 2020

TABLE 3 | The model variables were subjected to augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests.

		Augmented dickey fuller test		Phillips-Perron (PP) test	
		Statistic	*p*-value	Statistic	*p*-value
lnGDP	Constant	−1.564	0.9954	1.249	0.9963
	Constant & trend	−1.564	0.8062	1.699	0.7513
lnExport	Constant	−1.628	0.4686	−1.799	0.3812
	Constant & trend	−1.71	0.7466	1.92	0.6442
lnEMPLOYM	Constant	−3.123	0.0249	−2.023	0.2767
	Constant & trend	−3.762	0.0186	3.211	0.0822
lnINVEST	Constant	1.348	0.6068	1.126	0.7047
	Constant & trend	−2.124	0.5324	−2.059	0.5689

Source: Authors.

TABLE 4 | Optimum order selection of lag.

Lag	LL	LR	df	*p*	FPE	AIC	HQIC	SBIC
0	39.778				0.000012	−2.82907	−2.7873	−2.68E+00
1	112.424	145.29	9	0.0000	8.9e-08*	−7.72495*	−7.55774*	−7.14429*
2	116.005	7.161	9	0.6200	1.40E-07	−7.30806	−7.01545	−6.29191
3	123.838	15.666	9	0.0740	1.70E-07	−7.21829	−6.80027	−5.76664
4	137.372	27.069*	9	0.0010	1.40E-07	−7.56711	−7.02368	−5.67996

Source: Authors.

TABLE 5 | Root testing of lagged variables by ADF and PP units.

		Dickey fuller augmented Test		Phillips-perron (PP) Test	
		Statistic	*p*-value	Statistic	*p*-value
D (lnGDP)	Constant	−3.949	0.0017	−3.78	0.0031
	Constant & Trend	−4.107	0.0062	−3.968	0.0098
D (lnExport)	Constant	−5.394	0.0000	−5.395	0.0000
	Constant & Trend	5.305	0.0001	−5.31	0.0001
D (lnINVEST)	Constant	−6.349	0.0000	−6.519	0.0000
	Constant & Trend	−6.232	0.0000	−6.391	0.0000

Source: Authors.

After the unit root properties have been satisfied, the relationship of long-term co-integration of variables is studied. A wide range of tests exist to analyze the co-integration (Engle and Granger, 1987; Juselius and Johansen, 1990; Pedroni, 2000; Pradhan et al., 2014). (Engle and Granger, 1987) presented a two-step test to detect co-integration, but this test is incapable of handling circumstances in which many co-integrating relationships are feasible. This issue is addressed with (Juselius and Johansen, 1990), who introduced two distinct likelihood ratio tests that allow linearly independent co-integrating vectors to be determined. In this study, we apply this latter technique (**Table 6**). It will help underpin the co-integrating rank of a VECM. The study looked for co-integration links between variables using the Johansen test with the optimal first-order lag.

Only when ranked, 1 does the trace statistic fall below the crucial value under 95% confidence, indicating that the null hypothesis is accepted at a 5% threshold, whereas all others reject the null hypothesis with co-integration connection, as seen in the (**Table 6**). As a result, the Johansen Co-Integration test reveals that the three variables demonstrate only one co-integration relationship.

TABLE 6 | Results of Johansen co-integration tests.

Rank	Parms	LL	Eigenvalue	Trace statistic	5% critical value
0	20	258.2201		56.5089	47.21
1	27	272.3293	0.63498	28.2906*	29.68
2	32	282.4213	0.51366	8.1067	15.41
3	35	286.458	0.25049	0.0333	3.76
4	36	286.4746	0.00119		

Source: Authors.

4.3.2 Model for Vector Error Correction

Co-integration is a valuable method for the modeling of time series data long-term relationships, as explained by many studies (McGowan and Ibrahim, 2012; Andrei and Andrei, 2015; Loves

TABLE 7 | Results of the vector error correction models.

	D_lnGDP	D_lnExports	D_lnINVEST	D_lnEMPLOYM
	(1)	(2)	(3)	(4)
L._ce1	−0.555***	−5.072*	−2.434**	0.0622***
	(0.188)	(2.943)	(1.216)	(0.021)
LD. lnGDP	0.324	3.348	0.497	−0.0464*
	(0.244)	(3.824)	(1.58)	(0.0273)
LD. lnExports	−0.00251	−0.219	0.0905	0.0027
	(0.0164)	(0.256)	(0.106)	(0.00183)
LD. lnINVEST	0.0322	−0.28	−0.327	9.13E-05
	(0.0311)	(0.488)	(0.201)	(0.00348)
LD. lnEMPLOYM	−0.416	26.29	2.327	0.653***
	(1.108)	(17.34)	(7.164)	(0.124)
Constant	0.0946**	−0.137	0.263	0.00305
	(0.0372)	(0.582)	(0.241)	(0.00415)
Adjusted R2	0.65613	0.207274	0.301573	0.997954
F-stat	41.97769	5.75233	9.499347	10732.06

Source: Authors.

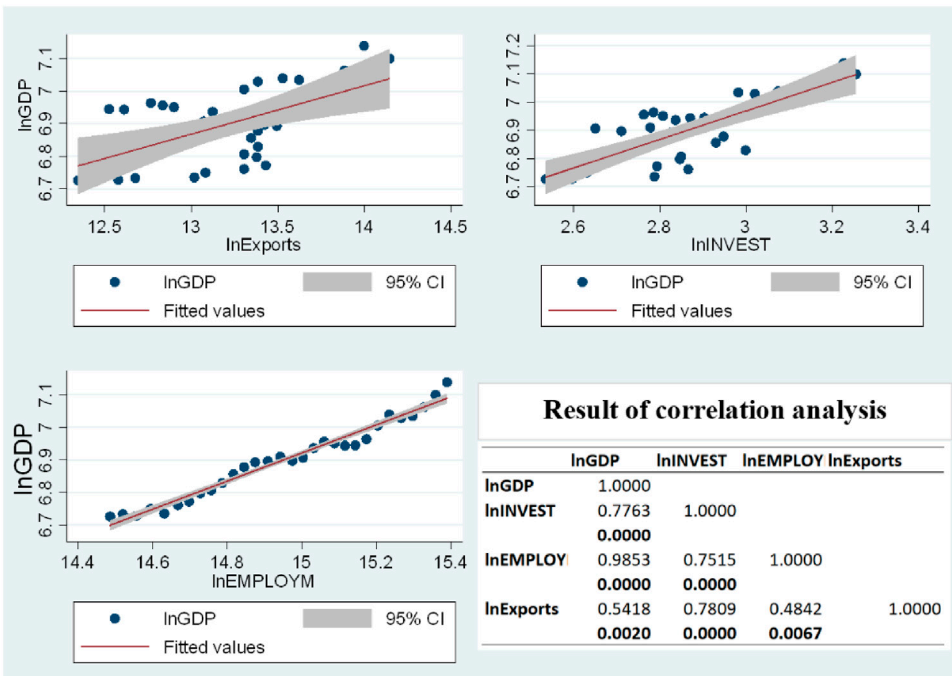

FIGURE 4 | Bivariate relationship between variables and economic growth. Source: Authors.

et al., 2021). It indicates that time series are connected with an error correction model. The relationship between the first-order difference hysteresis of each variable is then better understood, allowing for a better understanding of long run equilibrium dynamics. Also, it highlights a short-term method for dynamic adjustment which illustrates how variables adapt when out of balance.

It helps to measure the factors that push the connection to a long-term balance more easily with the adjustment coefficients. In reference to empirical model developed, the estimated long-term and short-term relationship through the VECM estimation provides the findings synthesized in the (**Table 7**) In the equations, the L1. _ce1 term is the lagged error correction term that presents the long-term variation, while the models constructed under model (1)–(4) represent the short-term variations. The fitness of the VCEM regressions provided by the adjusted R squared reveals that model (4) demonstrates the highest good fit with a value 0.99 greater than 75%. To a certain extent, it is followed by models (1), while models (2) and (3) appear with a low fit. Model (4) exhibits a positive and large (at

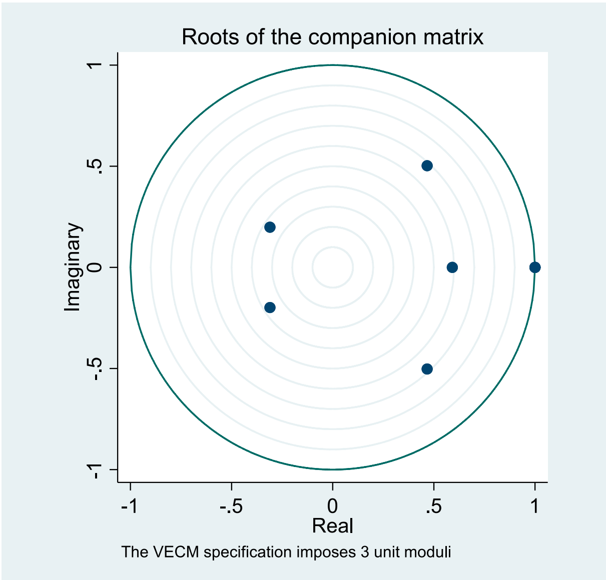

FIGURE 5 | System stability discrimination diagram of the vector error correction model. Source: Authors.

the 1% level) error correction coefficient, and (**Table 7**) shows that if human capital increases rapidly, the country's economy will adapt higher as well, and growth will finally return to the long-term equilibrium state. In addition, only the short-run coefficients for first lagged reveal a negative correlation in the same equation with a value significantly different from zero. In the other models, the negative and significant but at a different level of the error correction coefficient indicates the negative feedback necessary in relative level of exports and investment to bring back the economic growth equilibrium. The short-run relations are insignificant.

4.3.2.1 Vector Error Correction Model Stability Test

To investigate the impulse response results, the VEC model was subjected to a stability test (**Figures 4**, **5**). The following are the results of a typical root test (**Table 5**). The diagram represents its own values of the matrix accompanying the real part at x-axis and the imaginary part at y-axis. All the adjacent unit values are included in the unit circle, with the exception of the VECM three-unit roots. Thus, the model is stable, meaning that an examination of the pulse response can be performed by a study.

4.3.2.2 Error Residual Normality Test

After performing a VECM, checking the null hypothesis that the disturbance in each equation is normally distributed is important. In so doing, this study run three different tests (**Table 8**). In light with the statistics for which the probabilities are displayed in **Table 8** it is clear that the residuals do not suggest abnormality, and therefore, we cannot reject the null hypothesis.

5 CONCLUSION, POLICY, AND FUTURE PROSPECTS FOR STUDY

With a VECM, this study empirically examined the nexus between cotton production and the economic growth in Benin. Before the model, a descriptive study was conducted utilizing macroeconomic data collected by national and international agencies such as the World Bank, the US Department of Agriculture, and the National Accounts, generally from 1965 to 2021. This study utilized the GDP per capita as a proxy for economic growth. At the same time, other major explanatory variables included cotton productivity, investment in terms of GFCF, and employment and export levels in the country. The analysis revealed a strong positive connection between cotton export and economic growth. In addition, the results suggest a long-term relationship between human capital and economic growth in Benin. Indeed, a rapid human capital development will increase the quality of employment, and the country's economy will adjust upward.

Furthermore, a short-run coefficient unveils feedback necessary in the relative level of investment to bring back the economic growth to equilibrium. In the same vein, in some studies in Nigeria, the least-squares results revealed that cash crops and food crops demonstrated a positive and significant impact on economic growth in Nigeria. In contrast, livestock demonstrated a positive and insignificant impact on Nigeria's

TABLE 8 | Normality test from the vector error correction model.

	D_lnGDP	D_lnExports	D_lnINVEST	D_lnEMPLOYM	ALL
Jarque-Bera test					
chi2	1.097	1.104	0.745	0.308	3.253
Prob > chi2	0.5779	0.57579	0.68905	0.8574	0.91747
Skewness test					
Skewness	−0.24838	−0.3857	−0.29813	0.25151	
chi2	0.288	0.694	0.415	0.295	1.692
Prob > chi2	0.59157	0.40472	0.51955	0.58691	0.79215
Kurtosis test					
Kurtosis	2.1674	2.4073	2.4681	2.8965	
chi2	0.809	0.41	0.33	0.013	1.561
Prob > chi2	0.36847	0.52208	0.56561	0.91095	0.81575

Source: Authors.

economic growth (Igoni and Anthony Nwadioha, 2021). Also, a recent study conducted in another cotton-dependent country (Burkina Faso) showed that the value-added of agriculture for households constitute a vector of development and will contribute to 57.33% of final household consumption expenditures, while other sectors such as industry and services contribute only 2.03% and 4.42% (Traore et al., 2021).

These findings nurture a couple of suggestions enlightening henceforth decision making for economic growth in Benin.

The first policy suggestion urges the government of Benin to address the agricultural sector of cotton. The deteriorating performance of this crop (in terms of productivity) will affect the largest value chain, especially the export, which demonstrates a strong long run implication on growth. In addition, as a low-middle country, the government of Benin, to fast track its steps towards a developed country, needs to diversify the production of cotton through a town or district target policy. Indeed, this policy may consist of identifying towns in Benin that could enable large-scale cotton production using advanced technology and cotton seeds. Similar to this, the enhancement of human capital involved in the cotton production chain is key in scaling up production and reducing the time of human resources in the process. Therefore, it is also recommended that the government make coordinated attempts to ensure that farmers, especially small-scale farmers, receive easy access to the financial aids and grants provided. The funds should be disbursed appropriately and adequately without any hitch. Also, we recommend policy by improving environmental quality and fiscal management, as explained in a recent study (Sun and Razzaq, 2022).

To conclude, albeit this study did not perform a detailed comparative and cross-section analysis across the countries in the region, it is worth that the government pays attention to countries' comparison analysis to learn from others and leverage the strengths, challenges, and achievements of other countries in the relations between cotton production and economic growth. Nevertheless, although production increased in recent years in Benin, the cotton sector is still confronted with certain shortcomings that need to be addressed externally. Then, it will be good for future research to focus on climate change in national and regional level policies as a serious threat to socioeconomic development and agricultural productivity in West Africa.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DN: conceived the idea, performed the data collection, statistical analysis contributes to the writing of the manuscript. CF: Proofread the manuscript and gave guidance throughout the process of this study. AD: Formal analysis, Writing-review and editing. SR: Proofread, statistical analysis contributes to the writing of the manuscript.

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The Progressive Correlation Between Carbon Emission, Economic Growth, Energy Use, and Oil Consumption by the Most Prominent Contributors to Travel and Tourism GDPs

Aarif Mohammad Khan[1†], Asma Basit[2], Uzma Khan[1†] and Muhammad Kamran Khan[2†]*

[1]Department of Finance, College of Business Administration, Prince Sattam Bin Abdulaziz University, Alkharj, Saudi Arabia, [2]Management Studies Department, Bahria Business School, Bahria University, Islamabad, Pakistan

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***Correspondence:**
Muhammad Kamran Khan
mkkhan.buic@bahria.edu.pk

†ORCID ID:
Aarif Mohammad Khan
orcid.org/0000-0002-7190-6518
Uzma Khan
orcid.org/0000-0002-7248-090X
Muhammad Kamran Khan
orcid.org/0000-0002-7687-0382

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Travel and tourism have glimpsed a significant and promising implication for economic development. Despite the commendatory implication of tourism, it levies a stringent environmental cost such as environmental degeneration. Hence, this study will incorporate the 18 countries out of the top 20 travel and tourism contributors to economic growth to assess the progressive correlation between tourist arrival, economic growth, energy consumption, and oil consumption on carbon emission by applying panel ARDL spanning from 1995 to 2019. The outcome of the panel ARDL reveals that both periods have witnessed that the endogenous variables have a substantial and positive impact on environmental degradation except for tourism as it indicates –0.22 and –0.48% in the long and short run, having a rate of adjustment as –0.52 toward the equilibrium. The simultaneous quantile regression reveals that in the 50 and 75 percentiles, the effect of tourism has a negative impact, which contradicts the PMG findings. These determinations suggest that the policymakers look for more manageable and environmentally sound tourism and economic growth procedures to safeguard the sustainable environment in the studied countries.

Keywords: economic growth, tourism, energy consumption, oil consumption, environmental degradation

INTRODUCTION

The early stage of economic progress is the prime cause of environmental quality deterioration. Almost both advanced and emerging economies find it hard to cope with environmental deterioration (Arslan et al., 2022). The environmentalist economist has reinterpreted the Kuznets theory with an upgradation by showing the concern toward the environment and termed the environmental Kuznets curve (EKC), intending to examine the affinity between economic growth and environmental degradation. It states that the initial stages of economic extension lead to CO_2 emissions, but these emissions start to decline after a certain threshold level. Grossman and Krueger (1991) conducted the first EKC hypothesis testing. Later on, various researchers have examined it with different econometric techniques applied to different datasets and obtained mixed and inconclusive results (Taghizadeh-Hesary et al. (2022), Hassan et al. (2022), Dinda and Coondoo (2006), Ozturk and Acaravci (2010), Al-Mulali et al. (2015a), Apergis and Ozturk (2015), (Khan et al., 2022a), Shahbaz et al. (2015), and Al-Mulali et al. (2015b).

The present study probed the nexus between environmental degradation measured in carbon dioxide emissions and economic growth. In 1965, the CO_2 emission was 11,207.7 million tonnes, which reached 34,169 million tonnes in 2019. Thus, there is an increase of 204.87% from 1965 to 2019 (BP stats 2020). As a result, international awareness has increased about climate change and global warming. In this reference, an agreement was introduced 1997 to control carbon dioxide emissions that cause greenhouse gas (GHG) emissions in advanced economies named the Kyoto Protocol agreement (Pao and Tsai, 2011; Apergis and Danuletiu, 2014), but these advanced economies led uncertainty toward it as it cost them less economic gain (Shahbaz et al., 2013a). However, again, in 2015, another treaty was signed by 196 countries, known as the Paris climate change agreement, with an ambition to bring all the nations under one roof of an agreement to resist climate change and the adoption of efficient technologies to lower the global temperature by 2°C (UN climate change 2020). Hence, emerging countries are facing the mission of enhancing the efficiency of their energy consumption to achieve sustainable economic growth.

In the contemporary epoch of globalization, tourism is a budding spot for GDP growth in advanced and emerging economies. The tourism sector has shown a resounding impact on economic growth and has become a fast-growing economic activity worldwide. It has arisen as a crucial driver in the process of economic expansion for both advanced and less advanced countries (Li and Lin, 2015; Cetin et al., 2018; Park et al., 2018; Cannonier and Burke, 2019; Chai et al., 2019; Kirikkaleli et al., 2021). In addition to these advantages, it has some unfavorable impacts on the ecosphere as economic activities escalate due to tourism leading to carbon emissions. As Paramati et al., 2017 portrayed, tourism had shown an incredible shift in previous decades despite the sociopolitical instability and economic crisis. Therefore, it is an influential economic sector as it donated 10.4% to global GDP and delivers 1 in 4 of all new jobs created across the world (WTTC, 2021). According to Lew (2011), international travel and tourism comprise a significant part of the global economy and are the most extensive service sector in international trade. As a result, it bumps economic development (Hossain 2011; Yu et al., 2012; Wang et al., 2016; Ouyang and Lin 2017; Zhang et al., 2018). Apart from these benefits, it also contributes about 8% of the world's CO_2 emissions (www.sustainabletravel.org), which is consecutively accountable for contributing to global carbon emissions. Tourism activities not only raise CO_2 emission but also add to environmental degradation by developing the hotels and tourist facilities, consequently creeping the green belt (Gossling, 2002; Day and Cai, 2012).

Additionally, attracting travelers to their destinations will encourage economic growth, resulting in more energy consumption, leading to a higher CO_2 emission (Dogru and Bulut 2018; Zhang and Zhang 2018; Akalpler and Hove 2019; Nie et al., 2019). Other researchers (Becken et al., 2001; Scott et al., 2010; Tsui et al., 2018) strongly advocated that the widening of tourism has unfavorable repercussions on the healthy environment due to the immoderate use of energy related to transportation, goods, food and beverage, lodging facility, boosting the architecture, wood-burning, timber cruiser, and other tourist development. According to sustainable travel, international transportation is tourism's leading source of carbon emission. It accounts for 49%; on the whole, aircraft and cars spawn the most CO_2 per passenger mile, followed by tour buses, ships, and trains. From 2005 to 2016, carbon emissions increased by more than 60 percent for transport-related tourism emissions (www.sustainabletravel.org). Thus, tourism transport is an energy- and carbon-based entity, yielding tourism an influential donor to climate change. Designating the future foresight of an ongoing 4% boost exceeding 2025, the successive observation and inspection of carbon emissions correlated with tourism are becoming more challenging (Lenzen et al., 2018). Hence, it is proved that tourism aspires to economic growth and energy consumption, adversely bashing the standard of the environment in countries that rely on tourism.

Katircioglu (2014) documented that the advancement in tourism enhances energy use and generates substantial ecological pollution in carbon emissions. Moreover, the same findings were revealed by Tsai et al. (2014), Tang et al. (2015), and Durbarry and Seetanah (2015). Still, the affinity between tourism advancement and carbon emission is not apparent.

It is sound evidence that its energy demand also grows as the nation grows. In contrast, if the energy demand becomes still, economic growth in GDP growth will fall. Thus, this has been the case seen since the dawn of the industrial revolution. However, this industrial revolution hit the environment as the world saw a significant increase in urban population, which, accompanied by an increase in living standards, led to having access to more modern appliances and more energy consumption on the grid to see more energy consumption, resulting in more carbon emission and depletion of flora and fauna. The use of chemicals and fuel in factories resulted in increased environmental pollutants and increased consumption of fossil fuels. Different researchers have thoroughly investigated relationships between GDP growth, energy consumption, tourism, financial development, trade openness, and environmental pollutants by utilizing econometric methodologies in different economies and regions. This study plugs a significant knowledge gap by comprehensively calculating the carbon emissions caused by the tourism sector's economic growth and energy and oil consumption. This study for the first time incorporated the mentioned variables by incorporating the panel ARDL model to examine the long run and short impact, while the robustness is checked with simultaneous quantile regression and panel quantile regression.

Literature Review

Many scholars well documented that human activity harms the environment and leads to climate change which has many drawbacks. It can endanger wildlife and harm human health and, as a result, might pressure the medical sector (Root et al., 2005; AlRashidi et al., 2012; Reiter, 2013; Ebi and Hess, 2017). Sustainability and economic development have been comprehensively discussed by scholars (Samie et al., 2020; Nepal et al., 2021; Zhang et al., 2022; Yang et al., 2021; Zakari

et al., 2022a). Tourism contributes significantly to the global gross domestic product as studies showed the blessings of tourism on economic growth; it is an economic activity that can increase employment, bring revenue to the country, and eliminate poverty. However, countries should be aware that tourism can be a double-edged sword. Being a popular tourist destination requires improved infrastructure, which might use land meant for agriculture. Whether they are an international or domestic tourist, they will need to use transportation and accommodation, which are energy-based and contribute to environmental pollution. Also, tourism might harm cultures (Bosak, 2010). Hence, countries should adopt developmental activities in line with sustainability, such as sustainable tourism and limiting carbon and environmental pollution. Governments should consider these variables when promoting the tourism sector without harming the environment to achieve sustainability (McCool and Bosak, 2016).

Kuo and Chen (2009), Zhang et al. (2021c), and Khan et al. (2022b) conducted a study to evaluate the economic activities based on tourism that results in a full range of environmental impacts by utilizing life cycle assessment (LCA) by exploring the environmental loads per tourist per trip on Penghu Island in Taiwan, revealing different features of tourism-linked activities such as the transportation, accommodation, and recreation. Furthermore, they revealed that each tourist per trip uses 607 L of water and 1606 MJ of energy, emitting 109,034 g of CO_2, 2,660 g of CO, 597 g of HC, and 70 g of NOx. They also discharge 416 L of wastewater, 83.1 g of BOD, and 1.95 g of solid waste. In terms of energy use, transportation, especially the airplane sector, consumes the most considerable energy (67%). They revealed that the amount of solid waste discharged per tourist is 1.95 kg per day, while that per local people is 1.18 kg. In a crux, per Penghu tourist results in more environmental loads than local people.

A plethora of research work was available to investigate the pros and cons of tourism on carbon emission. For instance, Khan et al. (2022c), Zakari et al. (2022b), Tang et al. (2017), Tang et al. (2014), and Lee and Brahmasrene (2013), in their studies, reported that the tourism sector harms an ecosphere as it increases the carbon emissions levels, particularly the tourism transportation activities which constitute a notable amount of the total carbon emissions. Solarin (2014) explored the connection between tourism development and CO_2 emission in Malaysia and revealed a long-run connection among the variables and found positive one-way causation between tourism development and the level of CO_2 emission. Correspondingly, Durbarry and Seetanah (2015) realized that the immigration of Mauritius tourists strongly influences CO_2 emission over a long-short period.

Furthermore, Dogan et al. (2017) diagnosed the long-run affiliation between tourism, CO_2 emission, energy utilization, and GDP for OECD countries from 1995 to 2010. Their study saw a collaboration between tourism and CO_2 emission, energy utilization, and economic growth. Likewise, Zaman et al. (2016) observed unidirectional causation among tourism to CO_2 emission and energy utilization to CO_2 emission in East Asia and the Pacific, The European Union, and the high-income OECD and non-OECD economies. Sharif et al. (2017) examined the association between CO_2 emission and tourism growth in Pakistan and established a unidirectional causality that drives tourist arrival to CO_2 emission.

León et al. (2014), Chen et al. (2020), and Chen et al. (2021) explored the association between carbon emissions and tourism for advanced and emerging economies by employing the STIRPAT technique on panel data on the countries for 1998–2006. They established that the tourism sector causes a significant rise in carbon emission levels for all nations, but the magnitude of carbon emissions is more significant in advanced countries than in emerging countries. Furthermore, their study identified a need for a sustainable approach that lower carbon emission levels in tourism sectors. Akadiri et al. (2017), Dai et al. (2022), and Gao et al. (2020) researched the influence of tourism on environmental pollution using the environmental Kuznets curve for seven small island states: Bahrain, Cuba, Cyprus, Dominican Republic, Haiti, Iceland, and Malta. They discovered that a rise in international tourists leads to increased energy usage and real GDP per capita, contributing negatively to the environment and increasing carbon dioxide emissions.

Multiple researchers tried to examine the impact of the arrival and departure of tourists and its associated effect on pollution specifically caused by tourist movement (Gossling, 2002; Byrnes and Warnken, 2006; Howitt et al., 2010). Gossling (2002) reported that the tourism makes the transportation sector alone contribute nearly 94% of greenhouse gas emissions. Similarly, Byrnes and Warnken (2006) uncovered that the tourist boat operated in Australia was responsible for 0.1% of the total greenhouse gas emitted by tourism water transportation. Moreover, Peeters et al. (2007) acknowledged that enhancing tourism transportation by air was primarily liable for air pollution. Perch-Nielsen et al. (2010) noticed that the rise in greenhouse gas emissions in Switzerland is due to air transportation, which witnessed a high percentage of tourists. Howitt et al. (2010) conducted a study in New Zealand to analyze the knock-on associated with CO_2 emission and back and forth trips by cruise, and they discovered that ships emit more greenhouse gas than international travel by a flight. Lin (2010) and Gao et al. (2021) analyzed the carbon emission in five of Taiwan's national parks and witnessed the high greenhouse gas emitted in the form of carbon emissions by the individual tourist vehicles. Likewise, Wei et al. (2012), Ma and Zhu (2022), and Ma et al. (2022) recorded that China's tourism transport significantly contributed to carbon emissions, and it has been very high for the last 3 decades.

Lensen et al. (2018), Quan et al. (2022), and Wang and Luo (2022) tried to quantify the carbon emission associated with the tourism sector for 160 economies spanning 2009 to 2013. They discovered that the global carbon footprint by tourism has risen from 3.9 to 4.5 $GtCO_2e$, recorded four times more than formerly estimated, and estimated an increase to about 8% of global greenhouse gas emissions. Hence, tourism associated with high carbon intensity and continuing growth will constitute a growing part of GHG emissions. Among tourism-related activities, transport, shopping, and food are notable patrons for carbon

emission, where the majority of this carbon footprint is exerted by and in high-income nations. Therefore, this rapid increase in tourism demand is effectively outstripping the decarbonization of tourism-related technology. In line with this, Katircioglu et al. (2020) executed an investigation to estimate the consequence of tourism and environmental degradation spanning 1977 to 2015 for Cyprus and found a striking but inelastic effect on carbon emissions. Thus, tourism growth in Northern Cyprus will result in consequent surges in carbon dioxide emission levels. Therefore, they insinuate that tourism progression may root for environmental deprivation in Cyprus.

Very few studies employed the wavelet methodology to probe the causation of tourism, energy utilization, and carbon emissions. In this regard, Raza et al. (2017) used a wavelet approach to explore the causation betwixt tourism and carbon emission. They figured that tourists' arrivals positively impact carbon outflow in the short-, medium-, and long-run periods. Likewise, they also suggested one-way causation between tourism development and carbon emissions in the US economy. Moreover, Mishra et al. (2019), Wu and Zhu (2021), and Yao et al. (2022) presented a study that explores and provides new insights into the strong alliance between tourist arrivals, transportation services, economic growth, and carbon effluence on the economy of the United States. They employed a unique Morlet wavelet technique to realize partial and multiple wavelet coherence techniques for the monthly dataset from 2001 to 2017. They revealed a remarkable wavelet coherence and substantial lead and lag connections from the frequency perspective. A firm comovement existed among the variables studied, which is not equal across the time scales. Likewise, Tiwari et al. (2019), Zhang et al. (2021a, 2021b) performed an analysis of emerging economies to examine how the geopolitical risks (GPRs) and economic policy uncertainties (EPUs) influence the appearances of tourists in India by utilizing the wavelet analysis and retrieved two exciting results. Initially, the adherence to GPR is more robust than that of EPU. Last, the GPR has long-run implications, whereas the EPU holds short-run consequences for the arrival of tourists. Overall, they found that the impact of GPR is more decisive and notable rather than EPU.

The literature review has illustrated the studies on the connection between tourism, energy use, and oil consumption as a proxy for transportation, economic growth, and carbon emissions. Moreover, our study employs the panel autoregressive distributed lag method to analyze the short- and long-run strategies for linking endogenous and exogenous variables in the studied economies of 18 countries. The study's sustainable tourism policy design viewpoint contributes to the literature by addressing recent issues.

Data and Methodology

Our study incorporated 18 countries out of the top 20 travel and tourism contributors to economic growth to assess the dynamic relationship between tourist arrival, economic growth, energy consumption, and oil consumption on carbon emission from 1995 to 2019. Moreover, the reason is that these countries will provide a unique learning opportunity for the tourist economies that endure the environmental impacts of tourism in their regions. The tourist arrival data are missing for France and Saudi Arabia, so we dropped it and proceeded with the remaining 18 countries subdivided into three broad categories based on their geographical location. The first category comprises Canada, the United States of America, Mexico, and Brazil. The second category comprises Germany, Italy, Spain, Turkey, the United Kingdom, and Russia. Finally, the third group encompasses Australia, China, India, Indonesia, Japan, Philippines, South Korea, and Thailand. GDP was considered a proxy to economic growth at constant 2010 US$ and international tourist arrival as a proxy to tourism both collected from world bank indicator 2020. The energy and oil consumption and carbon emissions were collected from BP stats 2020. This analysis derives and initiates the following basic equation.

$$\boldsymbol{COE_{2it} = \beta_0 + \beta_1 ECG_{it} + \beta_2 TRM_{it} + \beta_3 ENGC_{it} + \beta_4 OLC_{it} + \varepsilon_{it}}. \quad (1)$$

In the aforementioned equation, t indicates the time period from 1995 to 2019, and i indicates the eighteen (18) above-mentioned countries. In the aforementioned equation, COE demonstrates the carbon dioxide emission, ECG indicates the economic growth, TRM demonstrates tourism, ENGC shows energy consumption, and OLC indicates oil consumption.

This research studied the influences of economic growth, tourism, energy consumption, and oil consumption on carbon dioxide emission in 18 selected countries by utilizing the panel ARDL model while the robustness of the results was examined with simultaneous and panel quantile regressions, respectively.

Panel ARDL Approach

Based on the panel data set with time periods $t = 1, 2, 3, \ldots\ldots\ldots.., T$ and groups of countries $i = 1, 2, 3, \ldots\ldots\ldots.., N$, the following panel ARDL (P, Q, Q . . ., Q1) model is estimated.

$$COE_{2it} = \sum_{j=1}^{P} \lambda_{ij} COE_{2it-j} + \sum_{j=0}^{Q} \delta'_{ij} X_{it-j} + \mu_i + \varepsilon_{it}. \quad (2)$$

In the above-mentioned panel ARDL (P, Q, Q . . .,Q1) model, X_{it} $(k\,X\,1)$ indicates the vectors of the regressor groups $i; \mu_i$ demonstrates the fixed effect, the coefficients of the lagged regressand, i.e., COE_2, λ_{ij} demonstrate the scalars in the equation, and finally δ_{ij} indicates the $(k\,X\,1)$ coefficients vector. If cointegration happens among the regressors and the regressand, then the error correction term is conducted for all groups of countries. The main characteristics of the cointegrations among the regressand and the regressors are the reactions to the deviation due to the long-term equilibrium. This characteristic of the regressand and the regressors indicates the error correction model that specifies the short-term dynamics of the regressand and the regressors, respectively, in the system and is impacted by the deviation from the equilibrium. Based on the above-mentioned panel ARDL (P, Q, Q . . . , Q_1) equation, the following error correction equation is specified.

$$\Delta COE_{2it} = \varnothing_i \left(COE_{2it-1} - \theta'_i X_{it-1}\right) + \sum_{j=1}^{P-1} \lambda_{ij}^{*} \Delta COE_{2it-1} + \sum_{j=0}^{Q-1} \delta'^{*}_{ij} \Delta X_{it-j} + \mu_i + \varepsilon_{it}. \quad (3)$$

In the aforementioned equation, $\varnothing_i = -(1 - \sum_{j=1}^{P} \lambda_{ij})$, $\theta_i = \sum_{j=0}^{Q} \frac{\delta_{ij}}{(1-\sum_k \lambda_{ik})}$, $\lambda_{ij}^{*} = -\sum_{m=j+1}^{P} \lambda_{im} \quad j = 1, 2, 3, \ldots, P-1$, and $\delta_{ij}^{*} = -\sum_{m=j+1}^{Q} \delta_{im} \quad j = 1, 2, 3, \ldots, Q-1$. $\varnothing_i$ in the previously mentioned equation indicates the speed of adjustment to its equilibrium which is known as the error correction speed. No long-run relationship exists in the regressors and the regressand if the examined error correction speed of adjustment is equal to zero (i.e., $\varnothing_i = 0$). The error correction term is expected to be significant and negative based on the hypothesis that the used variables in the equation indicate a return to a long-run equilibrium, where the term θ'_i in the aforementioned equation indicates the long-run association among the regressors and the regressand. The following equation is based on **Eq. 3** for all utilized variables.

$$\begin{aligned}\Delta COE_{2it} = \beta_0 + \varnothing_{1,i} \big[& COE_{2it-1} \\ & - \theta'_{2,i} (ECG_{it}, TRM_{it}, ENGC_{it}, OILC_{it})' \big] \\ & + \sum_{j=1}^{P-1} \lambda_{ij}^{*} \Delta COE_{it-1} + \sum_{j=0}^{Q-1} \delta'^{*}_{ij} \Delta ECG_{it-j} \\ & + \sum_{j=0}^{Q-1} \delta'^{*}_{ij} \Delta TRM_{it-j} + \sum_{j=0}^{Q-1} \delta'^{*}_{ij} \Delta ENCG_{it-j} \\ & + \sum_{j=0}^{Q-1} \delta'^{*}_{ij} \Delta OILC_{it-j} + \mu_i + \varepsilon_{it}. \end{aligned} \quad (4)$$

Panel data mean group (MG) estimator was developed by Pesaran and Smith (1995) in which all the used intercept, slopes of the confidence of the variables, and finally, the error variation are different across the groups of countries. Another study (Pesaran, Shin, and Smith 1997, 1999) developed the pooled mean group estimator for panel data that associate both the average and the pool characteristics, respectively. The PMG method permits the intercepts and the coefficients of the short-run variables, and finally, the error variations are dissimilar across the groups of countries while the long-run coefficients of the regressors are similar in different groups of countries.

Furthermore, we used the panel quantile regression to examine the relationship between energy consumption and carbon intensity with export diversification, financial development, economic growth, urbanization, trade openness, and institutional quality variables. The following panel quantile regression equations are based on **Equation 1**.

$$Q_{COEi.t} \left(\tau_k / \beta_i, X_{i,t}\right) = \beta_0 + \beta_1 ECG_{i.t} + \beta_2 TRM_{i.t} + \beta_3 ENGC_{i.t} + \beta_4 OILC_{i.t} + \epsilon_{i.t}. \quad (5)$$

In the aforementioned panel quantile regression equations, i and t show the 29 states and time duration from 1995 to 2019, respectively; β_i indicates the unobserved individual impact, τ indicates the number of quantiles of the conditional distribution, while ECG, TRM, ENGC, and OILC are variables that are utilized to study the influence of these elements on the carbon dioxide emission. Additionally, the τth quantile of the conditional distribution was used to estimate the coefficients by the following equation:

$$\widehat{\beta(\tau)} = argmin \sum_{i=1}^{n} \rho_\tau \left(y_i = x_i^\tau \beta\right. \quad (6)$$

In Equation 17, $\rho_\tau(u) = u(\tau - I(u<0)), I(u<0) = \begin{cases} 1, u<0 \\ 0, u>0 \end{cases}$, indicates the checking function, and I (.) is an indicator function.

RESULTS AND DISCUSSION

This study used Levin–Lin–Chu and Harris–Tzavalis unit root tests to investigate the stationary of the used series before applying panel ARDL in **Table 1**. The examined results of both unit root tests, i.e., Levin–Lin–Chu and Harris–Tzavalis, demonstrate that carbon dioxide emission, economic growth, tourism, energy consumption, and oil consumption are not stationary at level, but these series become stationary at the first difference that confirms that panel ARDL model can be applied with the mentioned variables.

Descriptive statistics is used to examine the mean, standard deviation, and minimum and maximum values of the variables in **Table 2**. The findings demonstrate that carbon dioxide emission has a mean value of 6.4, while the minimum and maximum values are 4.06 and 9.19, respectively. Furthermore, the findings of descriptive statistics indicate that economic growth has a mean value of 28 with a standard deviation value of 1.03. The mean values of tourism, energy consumption, and oil consumption are 16.80, 19.04, and 147.92, respectively. The minimum and maximum values of energy consumption are 0.90 and 141.69, respectively. The findings of descriptive statistics reveal that the maximum and minimum values of oil consumption are 13.19 and 926.77, respectively.

Table 3 is used to examine the correlation in the study variables. The correlation matrix is used to examine the association among the study variables. The examined findings of the correlation demonstrate that carbon dioxide emission has a positive relationship with economic growth, tourism, energy consumption, and oil consumption, respectively. The positive relationship in the study variables confirms that economic growth, tourism, energy consumption, and oil consumption positively impact the environmental degradation in the study countries.

Table 4 demonstrates the results of the panel cointegration tests, i.e., Kao, Pedroni, and Westerlund tests, respectively. The examined results of the Kao, Pedroni, and Westerlund tests indicate that cointegration exists in the study variables that confirm that long-run and short-run pooled mean groups (PMGs) can be applied with the used variables. In the next

TABLE 1 | Panel unit root tests.

Variable	Levin–Lin–Chu		Harris–Tzavalis	
	At level	1st difference	At level	1st difference
Carbon dioxide emission	1.4357 (0.9245)	−5.5761 (0.0000)	3.7490 (0.9999)	−13.8817 (0.0000)
Economic growth	3.8219 (0.9999)	−4.7864 (0.0000)	5.1894 (0.9682)	−12.8454 (0.0000)
Tourism	5.3297 (0.3727)	−4.7049 (0.0000)	1.2792 (0.8996)	−30.9017 (0.0000)
Energy consumption	2.1348 (0.9836)	−5.8491 (0.0000)	4.4401 (0.4838)	−16.3026 (0.0000)
Oil consumption	1.8134 (0.9651)	−7.2795 (0.0000)	4.3239 (0.5489)	−22.5752 (0.0000)

TABLE 2 | Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
Carbon dioxide emission	450	6.4010	1.0641	4.0604	9.1928
Economic growth	450	28.0149	1.0310	25.4168	30.5379
Tourism	450	16.8069	1.2353	14.3808	19.0260
Energy consumption	450	19.0473	27.2041	0.9024	141.6992
Oil consumption	450	147.9218	191.9542	13.1957	926.7793

TABLE 3 | Correlation.

Variable	1	2	3	4	5
Carbon dioxide emission	1.0000				
Economic growth	0.8241	1.0000			
Tourism	0.4524	0.5190	1.0000		
Energy consumption	0.8616	0.6985	0.4749	1.0000	
Oil consumption	0.7922	0.7440	0.4350	0.9146	1.0000

TABLE 4 | Panel cointegration.

Kao test		
	Statistic	*p*-value
Modified Dickey–Fuller t	2.117	0.0171
Dickey–Fuller t	2.1803	0.0146
Augmented Dickey–Fuller t	2.5535	0.0053
Unadjusted modified Dickey–Fuller t	2.1918	0.0142
Unadjusted Dickey–Fuller t	2.2767	0.0114
Pedroni test		
Modified Phillips–Perron t	2.9035	0.0018
Phillips–Perron t	−0.4051	0.3427
Augmented Dickey–Fuller t	0.2686	0.3941
Westerlund test		
Variance ratio	−1.3189	0.0936

TABLE 5 | PMG long-run results.

Variable	Coef	Std. Err	z	P>|z|
Economic growth	0.2608	0.1465	1.7800	0.0750
Tourism	−0.2162	0.0676	−3.2000	0.0010
Energy consumption	0.0585	0.0216	2.7000	0.0070
Oil consumption	0.4293	0.0015	2.9500	0.0030

TABLE 6 | PMG short-run results.

Variable	Coef	Std. Err	z	P>|z|
ECT	−0.5278	0.0134	−39.4599	0.0000
Economic growth	2.9383	0.1440	20.4049	0.0000
Tourism	−0.4790	0.0263	−18.2289	0.0000
Energy consumption	0.1252	0.0240	5.2154	0.0000
Oil consumption	0.3944	0.0014	291.8455	0.0000
_cons	0.0689	0.0328	2.1036	0.0439

step, long-run PMG and short-run PMG are applied to examine the impact of economic growth, tourism, energy consumption, and oil prices on environmental degradation in the study countries.

Table 5 reveals the results of the long-run pooled mean group (PMG) estimation. The examined findings of the PMG demonstrate that economic growth positively and significantly influence environmental degradation in the study countries in the long run. The findings indicate that a 1% increase in economic growth causes degradation of the environment in the study countries by about 0.26 percent. The findings of economic growth and environmental degradation are similar to those of Teng et al. (2021). Teng et al. (2021) demonstrated that economic development causes environmental degradation in OECD countries. OECD countries' economies are growing rapidly, which is harmful to the environment, and most OECD countries are facing a problem of environmental degradation.

Tourism and environmental degradation findings demonstrate negative and significant influence. The findings reveal that educated tourists follow rules and regulations related to the environment in the host countries. The findings

TABLE 7 | Robustness check with quantile regression.

	Simultaneous quantile regression				QRPD
	Q25	Q50	Q75	Q95	
Energy consumption	60.19***	83.44***	91.92***	93.07***	84.19***
	(6.63)	(26.50)	(52.00)	(81.88)	(138.68)
Oil consumption	−0.227	−2.436***	−3.308***	−2.904***	−2.937***
	(−0.22)	(−7.31)	(−20.27)	(−8.07)	(−13.56)
Economic growth	−34.73***	−13.42	−0.235	−10.65	47.66**
	(−3.56)	(−1.72)	(−0.04)	(−0.63)	(2.84)
Tourism	10.36	−14.05*	−6.941*	3.279	−60.76***
	(1.72)	(−1.98)	(−2.02)	(1.39)	(−5.02)
_cons	744.9***	601.9***	170.8	288.8	
	(4.27)	(3.58)	(1.19)	(0.65)	
N	450				450

t *statistics in parentheses.* *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

demonstrate that a 1% increase in tourism helps to reduce the environmental degradation in the study countries by about 0.21 percent. It is observed from the results that developing economies of the world need to encourage developed economies' citizens to explore nature, which will help the host countries' economies to develop. The findings contradict those of Anser et al. (2021), Haseeb and Azam (2021), and Usman et al. (2021). The authors revealed that tourism inflow causes environmental degradation in the host countries. Furthermore, they demonstrated that tourism inflow boosts the economic growth that causes environmental degradation.

On the other hand, the findings of the long-run PMG demonstrate that energy consumption causes environmental degradation in the study countries; the results indicate that energy consumption positively and significantly impacts environmental degradation. Moreover, the findings reveal that a 1% increase in the use of energy consumption causes an increase in environmental degradation by about 0.058 percent. The finding on energy consumption and environmental degradation is similar to that of Khan et al. (2020) and Khan et al. (2021). They demonstrated that environmental degradation is mainly caused by the use of traditional energy resources for energy use.

Oil is considered an important factor for economic growth around the world. The findings reveal that oil consumption has a positive and statistically significant impact on environmental degradation around the world. The examined results indicate that a 1% increase in the use of oil causes boosting the environmental degradation in the study countries by about 0.42 percent. The examined findings on oil consumption and environmental degradation are in line with Khan et al. (2019). In a recent study, Khan et al. (2019) demonstrated that oil consumption in Pakistan causes environmental degradation.

Findings of the short-run PMG model demonstrate that economic development in the study countries positively and significantly influences environmental degradation; the examined results indicate that environmental degradation boosts about 2.93 percent with a 1% increase in economic growth in **Table 6**. The examined findings are the same as the recent research by Shokoohi et al. (2022) and Usman et al. (2022); they demonstrated that economic growth adversely influences environmental degradation. On the other hand, tourism has a negative and significant impact on the carbon dioxide emission in the study countries. Furthermore, this studies the impact of energy consumption and oil consumption on environmental degradation. The findings demonstrate that a 1% increase in energy consumption and oil consumption boosts environmental degradation in the short run by about 0.12 and 0.39%. The findings are similar to those by Adebayo et al. (2022), Magazzino et al. (2022), and Wang (2022); they demonstrated that the use of traditional energy sources for energy consumption and oil consumption causes environmental degradation. The error correction term (ECT) demonstrates the speed of adjustment to the equilibrium that is 0.52.

Furthermore, this study used quantile regression to check the robustness in **Table 7**. The findings of the simultaneous quantile regression and panel quantile regression demonstrate that energy consumption positively and significantly impacts environmental degradation, while the findings of the oil consumption contradict the pooled mean group estimator (PMG) results. The estimated findings of the oil consumption demonstrate a negative and statistical impression of the environmental degradation in the study countries. Furthermore, the estimated findings of the economic growth demonstrate a negative and significant impact on environmental degradation as per the simultaneous quantile regression (Q25), while Q50 to Q95 demonstrate no impact on environmental degradation. On the other hand, the findings of the panel quantile regression indicate a positive and statistically significant impact on the degradation of the environment in the study countries. The examined findings of the tourism inflow demonstrate a negative and significant impact on environmental degradation with Q50 and Q75, respectively, while the findings of the panel quantile regression indicate a negative impact on environmental degradation in the study countries.

CONCLUSION

The study demonstrates the progressive correlation between carbon emission, economic growth, energy use, and oil consumption by the most prominent contributors to travel and tourism GDPs. The Levin–Lin–Chu and Harris–Tzavalis panel unit root indicates that these variables became stationary at the first difference. The correlation matrix shows the positive association among these endogenous variables to environmental degradation. Kao, Pedroni, and Westerlund laid the foundation for the pooled mean group (PMG) as they reveal both periods' presence. The long-run PMG indicate a significant impact of these endogenous variables on the exogenous variable except the tourism, indicating that the tourist is well aware of their responsibilities toward the environment, reflecting their concerns about the rules and regulations related to the environmental laws of the host countries. The adjustment rate to the equilibrium is −0.52, and more or less similar outcomes are revealed for the short-run PMG.

Furthermore, we have gone through the robustness test using the simultaneous quantile regression to validate our results. Panel quantile regression findings demonstrate that economic growth negatively impacts environmental degradation as per the simultaneous quantile regression (Q25). In contrast, Q50 to Q95 demonstrate no impact on environmental depravity. On the other hand, the findings of the panel quantile regression indicate a positive and statistically significant impact on the degradation of the environment in the study countries. The examined findings of the tourism inflow demonstrate an adverse and influential consequence on the environmental degradation with Q50 and Q75, respectively. In contrast, the findings of the panel quantile regression indicate an unfavorable impact on the studied countries' ecology.

In pursuance of achieving stable and endurable tourism in the studied countries, the first and foremost important step that the countries' governments should take is to focus on expanding economic activities that promote sustainable tourism so that the natural resources in the studied countries can support and follow zero or carbon-neutralizing laws framed by UNWTO 2018.

Likewise, 1) they can enforce clear-cut ecological guidelines; for instance, tourist sites with more damaging results on the environment should assign adequate facelifts to preserve the environmental quality. 2) Transportation is the primary promoter of carbon emissions (Sharma and Ghoshal, 2015; Koçak et al., 2020). For that reason, the government's first and foremost step is to educate the masses to use public transport and other alternative fuels, such as advanced hybrid technologies. 3) The government should stimulate viable and green energy production in the economy, specifically in tourist attractions employing grants and duty-free means. Implementing these tactics can considerably upgrade the ecosphere by curbing carbon emissions.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://databank.worldbank.org/source/world-development-indicators.

AUTHOR CONTRIBUTIONS

AK: introduction; UK: literature review; MK: results estimation and interpretation; AB: proofreading and review.

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Assessing Factors Influencing Technology Adoption for Online Purchasing Amid COVID-19 in Qatar: Moderating Role of Word of Mouth

Hussam Al Halbusi[1], Khalid Al-Sulaiti[2], Jaffar Abbas[3] and Ibrahim Al-Sulaiti[4]*

[1]Management Department, Ahmed Bin Mohammed Military College (ABMMC), Doha, Qatar, [2]Al Rayyan International University College in partnership with University of Derby UK, Doha, Qatar, [3]Antai College of Economics and Management, School of Media and Communication, Shanghai Jiao Tong University, Shanghai, China, [4]Newcastle Business School, Northumbria University, Northumbria University, Newcastle upon Tyne, United Kingdom

The COVID-19 pandemic developed new challenges for global consumers. In response to this disaster, digital technology users have faced the necessity to adopt and use specific technology apps for online shopping. This article examines how contingencies disrupt existing theoretical models and their implications for the post-COVID-19 era for online purchases. Customers prefer apps to use on the websites for search and purchase amid the COVID-19 crisis. The websites offer competitive advantages to apps for branding and CRM prospects. This motive keeps customers happy and satisfied with the website offers. This study focuses on consumer electronics and observes the comparative influence of fundamental elements (i.e., hedonic motivation, habits, perceived risk, technological trust, and technological awareness) on purchasing customer satisfaction. The study further examines the impact of customer satisfaction with online purchases with website continuance intention (WCI). Notably, this study explores the moderating effect of word-of-mouth (WOM) on the relationship between customer satisfaction with online purchases and website continuance intention. This study designed a web-based survey and recruited frequent visitors including international and citizens of Qatar for data collection. The study employed a purposive sampling technique and used three standardized psychological tools to obtain the data set needed to measure customer satisfaction with online purchases. The survey used a web link, distributed 600 questionnaires via email and social media, and received only 468 responses. After screening, only 455 were valid responses. The study showed a response rate of 75.83%. The study results showed that hedonic motivation, habits, perceived risk, and technological awareness were positively related to customer satisfaction with online purchasing. Besides, customer satisfaction with subsequent online purchases is also positively associated with website continuance intention (WCI). The results revealed that this relationship remained stronger when word-of-mouth (WOM) was higher. Hence, this shows that online shopping is seen as a vital and interesting activity in the Qatari context. The findings provide useful insights for future studies to explore the effects of COVID-19 on online purchase intentions.

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***Correspondence:**
Jaffar Abbas
dr.abbas.jaffar@outlook.com

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1 INTRODUCTION

The E-commerce market is growing at the fastest rate in the world. Consumer electronics is the most popular category, accounting for 48% of total e-commerce sales in this profitable industry (Wang et al., 2019; Trivedi & Sama, 2020). The active participation of millennial consumers, who make up the largest consumer demographic online, is driving the online retail movement (Edeling, & Himme, 2018; Zhao et al., 2021). As millennials lose interest in traditional advertising, consumer electronics category marketers turn to social media influencers to develop an engaging relationship with them (Cooley & Parks-Yancy, 2019; Bazi et al., 2020; Al Halbusi et al., 2021).

The COVID-19 pandemic developed new challenges for global consumers (Abbas et al., 2019a; Aqeel et al., 2021b; Li et al., 2021; Aqeel et al., 2022; NeJhaddadgar et al., 2022). In response to this disaster, digital technology users have faced the necessity to adopt and use specific technology apps for online shopping (Aqeel et al., 2021a; Abbas et al., 2021; Paulson et al., 2021; Farzadfar et al., 2022; Ge et al., 2022). Customers choose apps to use on the websites for search and purchase amid the COVID-19 crisis (Mubeen et al., 2021; Sarfraz et al., 2021; Aman et al., 2022; Liu et al., 2022; NeJhaddadgar et al., 2022). Disease outbreaks and epidemics have changed online shopping behaviors throughout human recorded history, transformed societies, affected personal relationships, and transformed world paradigms (Moradi et al., 2021; Wang et al., 2021; Zhou et al., 2021; Fu & Abbas, 2022; Rahmat et al., 2022). The coronavirus (COVID-19) virus has severely influenced humans' way of life (Abbas, 2020; Aman et al., 2021; Mubeen et al., 2021; Soroush et al., 2021; Mamirkulova et al., 2022). Governments have imposed several lockdown restrictions that directly affect how people buy stuff online, and businesses function (Pouresmaeil et al., 2019; Khazaie et al., 2021; Lebni et al., 2021; Shoib et al., 2021; Yoosefi Lebni et al., 2021). The response to the pandemic (COVID-19) has led to overnight shifts in people's daily lives, the day-to-day operations of companies, and online buying behaviors' that would otherwise never happen (Abbas et al., 2019a; Abbas et al., 2019b; Moradi et al., 2020; Su et al., 2021a; Su et al., 2021b). Consumers have been inclined to change their preferences and behavioral patterns (Abbas et al., 2019a; Shuja et al., 2020a; Shuja et al., 2020b; Yoosefi Lebni et al., 2020; Azadi et al., 2021; Azizi et al., 2021; Maqsood et al., 2021). It includes shifting to online purchase needs and substitute pickups and delivery options (Uzir et al., 2021a; Uzir et al., 2021b; Ghazali et al., 2022).

Few studies, nevertheless, have attempted to comprehend the impact of influencer marketing on numerous aspects of customer behavior (Lou, & Yuan, 2019; Argyris et al., 2020). Choosing between topic expert influencers and also proven to be a challenge for marketers (Campbell, & Farrell, 2020; Theocharis & Papaioannou, 2020). Few academic research has sought to compare the efficacy of the two methods; thus, this is a crucial addition to the field (Schouten et al., 2020; Trivedi & Sama, 2020). In addition, the impact of influencer marketing on the consumer-brand connection has received less attention. In todays market, such research is critical when marketers attempt to build an emotional link with their customers. Because the impact of different types of endorsers varies depending on the product they promote, finding the right influencer is more complex (De Veirman et al., 2017; Schweitzer et al., 2019). Thus, e-commerce has become a crucial aspect of today's business environment since technological advancements have increased and the proliferation of the Internet (Kabango & Asa, 2015; Leung et al., 2019). Because of its ease of use, comfort, and cost-efficiency, e-commerce has become an essential buying tool for customers worldwide. Different facets, such as the social nature of e-commerce, appear to influence online purchase intentions (Chawla & Kumar, 2021; Hassan et al., 2022).

Nonetheless, e-commerce has changed the way consumers purchase products and services. With the growing importance of online sales and the rise in the number of online shoppers, marketers and academics have focused their interest on better understanding online purchases behaviorally, and there is a significant opening that requires deliberation (Kumar, & Ayodeji, 2020; Tokar et al., 2021). E-commerce is more economical and convenient than offline shopping (Chawla, & Kumar, 2021). Therefore, several issues need to be highly concerned. A combination of fundamental elements (i.e., hedonic motivation, habits, perceived risk, technological trust, and technological awareness) could significantly advance knowledge as these components are critical for several reasons. For instance, hedonic motivation means a person's pleasure and pain receptors on their willingness to move toward a goal or away from a threat (Khatimah et al., 2019). In addition, habit is another element that people do often and regularly, sometimes without knowing that he/she is doing it. The perceived risk could be assessed as a potentiality in pursuing one's desired consequence or resulting in digital technology utilization (Featherman and Pavlou, 2003). Perceived risk is consumer utilization of novel digital technologies having an unfortunate upshot. Besides, consumer inclination to accept risk on the propensity of favorable presumption on behavior in a digital platform could be regarded as a technology of trust (Ennew & Sekhon, 2007; Uzir et al., 2021a). Technology trust as a variable is recently applied in adopting digital medication studies. Technology trust is essential in predicting and examining online behavioral intention in medical sciences. Concerning the technology, awareness reflects the individual's values and beliefs on adjacency and alignment with the new technology. One can see others using the new technological system in an organization (Venkatesh et al., 2003). Thus, this study intends to contribute to the knowledge by examining the mentioned factors toward customer satisfaction with online purchasing and subsequently testing the consumers' satisfaction with online purchasing on website continuance intention (WCI).

Notably, the strength of this study is that we advanced the theory by analyzing the moderating role of Recommendation Words of Mouth (WOM) on the relationship between customer satisfaction with online purchasing and website continuance intention (WCI). WOM is particularly important in marketing and e-commerce since intangible products are difficult to judge before consumption (Reza Jalilvand & Samiei, 2012). They provide more information about the product to help make a more informed decision (Hammood et al., 2020; Talwar et al., 2021). According to Park and Nicolau (2015), they are seen to be crucial empirical information cues. More delight and satisfaction came from higher review ratings than moderate or lower ones.

At present, academia has applied various theoretical frameworks to explore consumer attitudes toward online purchases through website continuance intention (WCI), including the Theory of Planned Behaviour (TPB), the Technology Acceptance Model (TAM), and the Unified Theory of Acceptance. However, different studies have examined the value-attitude-behavior (VAB) model in research on green purchase intention through online shopping (Alalwan et al., 2018), green shopping decisions (Alkailani & Abu-Shanab 2021), and online purchases (Al-Khalaf & Choe 2020). In the literature, to our knowledge, past studies have ignored VAB models linking online purchase intentions. In addition, technology adoption, awareness, and technology trust are critical to customer satisfaction for online purchases through Website Persistent Intent (WCI). In this regard, word-of-mouth (WoM) recommendation plays a crucial role in the technological adoption of online shopping, suggesting that consumer behavior research has not received any attention in the existing literature. Therefore, this study aims to address this identified gap by using the VAB model to identify factors that promote online purchases with website continuance intention (WCI).

The literature shows that few studies have explored employee attitudes and values in various domains (Chen et al., 2004; Cheng & Lee 2011; Chen & Chang 2013; Chawla & Kumar 2021). Still, to the best of the researchers, their application in online purchasing decision research is lacking. These sites provide a competitive advantage for brands and CRM prospecting applications. This motivation makes customers feel satisfied and satisfied with the service provided by the website. This study focuses on consumer electronics and observes the comparative impact of fundamental elements (hedonic motivation, habits, perceived risk, technological trust, and technological awareness) on purchasing customer satisfaction. The study further examines the impact of customer satisfaction with online purchases and website persistence intent (WCI). Notably, this study explored the moderating effect of word of mouth (WOM) on the relationship between customer satisfaction with online purchases and continued website usage intentions. Several studies have examined various factors influencing online purchasing and consumer cognitive attitudes. It shows significant predictors of online purchases in fast food consumption (Chevalier & Mayzlin 2006). Furthermore, testing in different contexts (especially online purchases) is needed to demonstrate the predictability of emotional attitudes to online purchases. Again, in the context of online purchase intentions, past research has failed to incorporate values and perspectives into a single model, leading to a gap in searching for better explanations.

The pandemic (COVID-19) influenced consumer buying behavior worldwide. The pandemic has changed purchase patterns and popular online purchases in response to the COVID-19 protective measures. According to the statistics given by Forbes (2020), in 2019, almost 81% of American consumers never bought groceries by using online platforms. In contrast, the COVID-19 pandemic outbreak has changed the situation and reversed buying patterns. Almost 79% of consumers in the United States purchased groceries and other stuff during 2020 amid COVID-19. US consumers' have purchased groceries through online shopping, and it increased from 1.20 US dollars in August 2019 to 7.20 US dollars by June 2020 (Forbes, 2020). McKinsey (2020) reports that 15% of European consumers have already adopted new online grocery services and 12% have even switched to new grocery stores after home delivery or click-and-collect services. These new customer segments appear to be continuing to use online grocery services even after the first peak of the pandemic (Uzir et al., 2021a; Uzir et al., 2021b; Tyrvainen et al., 2022). The pandemic has changed online shopping worldwide, including Qatar and other Gulf countries.

In this context, while investigation provides various insights to fill the gaps in consumers' purchasing behavior, further research with limited and targeted perspectives is required. Such a study can concentrate on the most recent trends, changes, and transformations in the globalized market regarding consumer behavior and the elements that influence it. Further research is required, particularly in the Middle East region, where online shopping has become increasingly popular. In particular, this research focuses on the Qatari context. With an estimated value of $ 1.2 billion, the e-commerce market in Qatar represents an ideal context for this research, especially since Qatar was ranked the seventh largest e-commerce market in the MENA region in 2015 (Alkailani & Abu-Shanab, 2021). The Qatari market is a favorable setting for e-commerce adoption for varied purposes. The first is the vast amount of discretionary income available to its citizens. Second, Qatar's population is oriented toward younger urban residents who can afford online shopping. Lastly, Qatar provides high-speed internet with fixed connectivity (Al-Sulaiti et al., 2006; Al-Khalaf, & Choe, 2020; Khatoon et al., 2020). All of this points to Qatar as a suitable location for e-commerce development. In essence, this study examines the direct effect of the hedonic motivation, habit, perceived risk, technology trust, and technology awareness toward customer satisfaction with online purchasing and, subsequently, the effect of customer satisfaction with online purchasing on the website continuance intention (WCI). Significantly, this study analyzed the moderating role of recommendation words of mouth (WOM).

2 THEORY AND HYPOTHESES

2.1 The Relation of Hedonic Motivation With Customer Satisfaction of Online Purchasing

Hedonic motivation refers to a consumer's view of how enjoyable it is to use a modern technology system (Venkatesh et al., 2012).

Adoption was primarily motivated by internal values and utilitarian considerations when most user IS were created to be essentially task-oriented (Thong et al., 2006). In particular, Venkatesh et al. (2012, p. 161) defined it as "the fun or pleasure derived from using technology. It has been shown to play an important role in determining technology acceptance, and it is quite similar to 'perceived enjoyment' (Thong et al., 2006). In IS studies, it was revealed to be influential in predicting the intention to implement technology (Venkatesh et al., 2012). As IS designers realized that customers would use information systems to complete tasks and entertainment, they have modified design ideas accordingly (Al Sulaiti et al., 2005; Morosan & Defranco, 2016). Accordingly, it was adapted and added as a construct into the established technology adoption model (Venkatesh et al., 2012). Thus, value in the shopping process raises the pleasure and emotional involvement provided by the bargaining process (Uzir et al., 2021a; Hassan et al., 2022; Naveed et al., 2022). According to Venkatesh et al. (2012), the pleasure and satisfaction generated by the bargaining process is a kind of hedonic shopping value. However, these shoppers love to shop because they enjoy the shopping process (Atulkar, & Kesari, 2017; Al Halbusi et al., 2020; Tyrväinen et al., 2020). Venkatesh et al. (2012) identified the self-gratifying benefits of shopping, which make the shopper feel better during the process of shopping by reducing stress or tensions.

Researchers showed that some shoppers enjoy socializing (Hassan et al., 2021; Thaichon, 2017; Hoyer et al., 2020) with others while shopping and that shopping gives them a chance to bond with other shoppers (Hoyer et al., 2020). Hedonic shopping value is the perception that a customer perceives during shopping, generates greater values by eliminating the disturbance, and helps customers focus on their shopping activities (Jones et al., 2006; An & Han, 2020). Some consumers may enjoy the latest trends in fashion, styling, or innovations, which motivates consumers to browse retail stores (Silva & Bonetti, 2021). In addition, consumer involvement, freedom, fantasy fulfillment, and escapism enhance the hedonic aspect of shopping (Scarpi et al., 2014; Hoyer et al., 2020). Therefore, retailers today invest a massive amount of money in designing hypermarkets to fulfill the needs of the global brand. With a relaxing and valuable retail environment, all of these attempts are to gain customer satisfaction from purchasing. Therefore, we theorized the following hypothesis:

Hypothesis 1. Hedonic motivation is positively correlated with customer satisfaction with online purchases.

2.2 The Relation of Habit With Customer Satisfaction of Online Purchasing

A study by Venkatesh et al. (2012) stated the idea that consumers' automatic behaviors outside of the task context influence their behavior. They comprised habit, which reflects the extent to which consumers are likely to perform automatic behaviors due to learning (Venkatesh et al., 2012), which are put in motion after some amount of repetition (Orbell et al., 2001). The habit was conceptualized separately from behavior in several models (Khalifa & Liu, 2007). However, it was established as a predictor of behavioral intentions (Featherman and Pavlou, 2003; Hassan et al., 2021; Hassan et al., 2022) and continuing usage of IS (Khalifa and Liu, 2007). Lankton et al. (2010) mentioned that consumers involved in commercial tasks spanning from need analysis to product consumption/evaluation go through a series of repeating actions, which, in the context of e-commerce, could lead to habit formation (Venkatesh et al., 2012; Hsu et al., 2015).

The meta-analysis study by Jeyaraj (2022) reported that the choice environment remains relatively consistent in situations where the behavior is frequently practiced (daily to several times a week). The frequency of past behavior has a more substantial direct effect on future behavior than the cognitive-based intention to perform the behavior (Viswesvaran and Ones, 1995). In those cases, the individual's prevalence of previous behavior might be a good predictor of habit formation, commonly referred to as habit formation (Ajzen, 2002; Hsu et al., 2015). Therefore, habit is a factor that will favorably influence customer satisfaction with online purchases. According to Khalifa and Liu (2007) and Kim & Kim (2019), if customers are equally satisfied with an online store, clients with high levels of habit are more likely to repurchase from the same online business. Therefore, the study formulated the following hypothesized statement:

Hypothesis 2. Habit is positively related to customer satisfaction with online purchasing.

2.3 The Relation of Perceived Risk With Customer Satisfaction of Online Purchasing

The concept of perceived risk is that customers interacting with virtual retailers, which have larger unpredictability than traditional businesses, is a significant challenge for internet commerce (Shiau et al., 2017; Wu et al., 2020). Online commerce has less verification and control for a simultaneous exchange of products and money (Cheng & Lee, 2011; Marakanon & Panjakajornsak, 2017). When there is a high amount of perceived risk, consumers might use risk-reduction methods, including warranties, trustworthy suggestions, a solid reputation, and supporting information (Chen & Chang, 2013; Sharma et al., 2021). Consumers would be hesitant to use online purchasing if there was no system-based technique to limit transactional risk from the e-vendors' undesired behavior. As a result, perceived risk is a significant stumbling block for online shoppers making purchasing decisions. The term "perceived risk" refers to a consumer's belief in the possibility of unfavorable consequences from an online transaction (Kim et al., 2008; Wu et al., 2020). The term "perceived risk" has been used extensively in marketing literature. According to an early definition, there are several sorts of risk: financial, performance (product), physical, psychological, social, time, and opportunity cost (Wu et al., 2020). Traditional shopping is dominated by two categories of risk: financial and product risk (Bhatnagar et al., 2000; Wu et al., 2020).

Because these are critical issues in internet-based communications, the information-based risk is a specific worry in online buying regarding uncertainties related to vendors, such

as suggestions, security, and privacy (Chiu et al., 2014). In online businesses, this study presents perceived risk as a single construct with the four qualities of financial, product, suggestion, and security, when privacy is considered part of security. Thus, the role of perceived risk in the poor perception of shopping at e-stores has been highlighted in previous studies (Shaw & Sergueeva, 2019). To better understand the uptake of services like online banking and portfolio management, a study model combining the technology acceptance model (TAM) and perceived risk has been developed (Hwang & Choe, 2020). Perceived risk is described in that study by several factors, including financial, performance, psychological, social, and so on. Perceived danger had an adverse impact on numerous elements due to its uncertainty (Horst et al., 2007; Wu et al., 2020). Accordingly, this study proposed the following hypothesis:

Hypothesis 3. Perceived risk is negatively related to customer satisfaction with online purchasing.

2.4 The Relation of Technology Trust With Customer Satisfaction of Online Purchasing

Trust is described as an individual's willingness to accept vulnerability based on optimistic expectations about the motives or behavior of others in an environment marked by interdependence and risk (Ennew & Sekhon, 2007; Uzir et al., 2021b). Technology adoption research often uses trust as a variable. It was found to be a significant predictor of behavioral intent (Venkatesh et al., 2016). There are also studies on mobile banking (Alalwan et al., 2018), e-learning (Tarhini et al., 2017), and online information services (Oh & Yoon, 2014). Security and trust issues when using the system will dominate the application of trust value in user decision-making. The significant unpredictability, intangibility, heterogeneity, and vagueness related to Internet use and technology may explain the interest in the concept. (Gefen et al., 2003; Barua et al., 2018; Ul Hassan et al., 2020).

The presence of trust is a prerequisite for any transaction to be completed successfully. Thus, technology trust gives predominant leverage to allow them to coproduce the services (Collier & Sherrell, 2010; Pappas, 2016; Alsaad et al., 2017; Alnoor et al., 2022). Nevertheless, there are some solid theoretical bases. For example, researchers report that technical reliability improves trustworthiness (Skard, & Nysveen, 2016; Barua et al., 2018), or trust is customers' perception of credibility and reliability for customer perception (Ashraf et al., 2014; Leung & Ma, 2020). In addition, Kim et al. (2013) suggest that when the users perceive that a system is reliable, that assists in fostering trust in the system. Therefore, the study postulates the following hypothesis:

Hypothesis 4. Technology trust is positively related to customer satisfaction with online purchasing.

2.5 The Relation of Technology Awareness With Customer Satisfaction of Online Purchasing

Technology awareness represents an individual's attitudes and views about the new technology's applicability and alignment. The extent to which others in an organization use a new technical system (Venkatesh et al., 2003). Compared to other constructs, technological awareness has received less attention in the research. More precisely, awareness in connection with technology refers to awareness and comprehension of a specific technological product or service (Mofleh et al., 2008). Per the description, technological awareness is the knowledge of how to utilize and features of a particular technology or technological component (Lingmont & Alexiou, 2020). Awareness of any e-services in the context of this definition can be highly beneficial in improving their use (Huang et al., 2019). Several studies have stated that technological awareness is crucial for many perspectives. For example, Top et al. (2011) and Belanche et al. (2014) have stated that having a good understanding of technology can help people use e-services more effectively. Lee and Wu (2011) and Naveed et al. (2022) have stated that a target audience will only embrace a technical innovation if they are sufficiently aware of it. It was also said that when individuals are informed of the most recent feedback, they have more trust in implementing it. Therefore, Individuals need to understand and comprehend the latest technological advancements to enhance their usability (Bamberg, & Möser, 2007; Huang et al., 2019). Thus, based on these explanations, the current study hypothesized this statement:

Hypothesis 5. Technology awareness is positively related to customer satisfaction with online purchasing.

2.6 The Relation of Customer Satisfaction of Online Purchasing With Website Continuance Purchasing

Customer satisfaction allows businesses to improve sales income and obtain a competitive advantage over competitors (Lewin, 2009; Charoensukmongkol, & Sasatanun, 2017), as well as gain customer satisfaction, which leads to long-term benefits (Wirtz, 2003; Yi, & Nataraajan, 2018). Thus, customer satisfaction stems from the awareness that businesses must interface with dynamic environments in ways compatible with customer behavior to remain competitive (Smith et al., 1996). Customer satisfaction may have a role in the work's success and continuance (Sadowski, 2017; Amin et al., 2020). Hsu et al. (2015) and Khatoon et al. (2020) mentioned the effects of perceived playfulness. They perceived flow on customer satisfaction and purchase intentions using playfulness and perceived flow as an outcome (Uzir et al., 2021a). The findings revealed that the customer's perception of playfulness and flow is influenced by the quality of the website (Amin et al., 2020; Ashfaq et al., 2020). Therefore, Participating users create online social networks in e-commerce systems/sites by establishing social relationships with their peers, such as real-world acquaintances, online acquaintances, or like-minded individuals (Sherchan et al., 2013; Khare et al., 2020). Users can share, analyze, and find relevant content using the online social networks that have been built in this way (Shao et al., 2020). Positive referrals within social networks, in particular, boost cognitive trust in the service provider (Kuan, & Bock, 2007; Arora et al., 2017). According to Möllering (2002), cognitive trust

comes before emotional trust, and emotional trust leads to establishing positive or negative expectations about the trustee. Liu and Park (2015) discuss the importance of reviewers' identity and reputation of the vendor as critical in encouraging customers to purchase services online. Therefore, the study proposed the following hypothesis:

Hypothesis 6. Customer satisfaction with online purchasing is positively related to Website continuance purchasing.

2.7 The Moderating Role of Recommendation Word-of-Mouth

A large body of literature investigates the impact of WOM on online consumer behavior, with the valence and volume of WOM being the most widely explored (Dellarocas et al., 2007; Duan et al., 2008a; Bulut & Karabulut, 2018). Nevertheless, some studies displayed that WOM volume positively affects subsequent sales (Duan et al., 2008b; Amblee & Bui, 2011; Al Halbusi & Tehseen, 2018), a sales rank of electronic products (Cui et al., 2012; Gu et al., 2012), books (Chen et al., 2004), and online purchase intention (Park et al., 2007). Some studies find WOM valence has a positive impact on sales rank of electronics (Archak et al., 2011), books and movie box-office performance (Chevalier, & Mayzlin, 2006; Chintagunta et al., 2010), sales of cellphones (Gopinath et al., 2014), consumer package goods (Maslowska et al., 2017), and beer (Clemons et al., 2006). Therefore, this study has identified WOM as the contingent role and a boundary condition concerning customer satisfaction with online purchasing and website continuance purchasing. It is because of the following reasons: because WOM is a significant influencing factor of online driving behavior, WOM can affect online consumers' choices through two effects, namely, awareness effects and persuasive effects (Duan et al., 2008b; Liu et al., 2017). The presence of the product is communicated by WOM, which places it in the choice set of online consumers. The persuasive effects, on the other hand, affect online consumers' views and evaluations of the goods, influencing their decision (Reza Jalilvand et al., 2012).

A study by Lee & Youn (2009) and Qiu et al. (2012) have stated that researchers used attribution theory to understand how WoM influences online customer behavior. Attribution theory examines how people draw causal inferences about why a communicator advocates a particular viewpoint or acts in a particular manner. People frequently attribute compelling information about a stimulus to the stimulus and non-stimulus variables provided by the communicator. However, for many consumers, online or oral reviews have become essential reasoning to develop intentions; the influence of recommendation "word-of-mouth" could be exacerbated by mouth (Arli, & Dietrich, 2017; Pourfakhimi et al., 2020). In the proposed model, the word-of-mouth recommendation is predictable to the model's structure (Liu et al., 2019). It would be one of the moderating constructs being tested to provoke how this variable can augment the relationship between customer satisfaction with online purchasing and Website continuance purchasing online adoption. Word-of-mouth is the most restricted approach to expressing user satisfaction. However, it is powerful and influential as it is a very personal approach, which results in superior in defining the intention of using online technology for purposes (Website continuance purchasing). Nevertheless, to distinguish the recommendation of the word-of-mouth variable as a moderator. It clearly shows the impact of social influence, a common term that describes all types of external influences that affect the customer's perception of using technology for their purchases in the Qatar context:

Hypothesis 7. The recommendation word-of-mouth moderated the relationship between customer satisfaction of online purchasing and website continuance purchasing.

This relationship will be stronger when recommendation word-of-mouth is high than low (see **Figure 1**).

3 METHOD AND PROCEDURES

For this research, the sample is the regular customers who need to purchase and access online services. Thus, we have set inclusion and filtering criteria for the sample during data collection (Aman et al., 2019a; Aman et al., 2019b). These criteria the participants should be 1) Qatari and foreign citizens living inside Qatar, 2) customers who experienced online purchasing services, 3) age at least 18 years old, and 4) no minimum education level required. Thus, the data was gathered by sending a web link. The web link was circulated to emails and social media like WhatsApp, Facebook, Twitter, Instagram, and LinkedIn (Abdelfattah et al., 2022). Thus, out of 600 questionnaires, only 468 responses were returned from the data collection. Subsequently, from the 468 responses, only 455 were valid, with a response rate of 97%. Notably, 13 questionnaires had irregularities, and the study excluded them.

3.1 Variable Measurement

The measures were adapted from various reliable studies, and three academic experts in related subjects double-checked the questionnaire before the significant data collection phase. Furthermore, we used the cognitive interview approach with fifteen people to assess the questionnaire's clarity, readability, and applicability, as indicated by Hulland et al. (2018), where only minimal changes were recommended the questionnaire was approved. Nevertheless, the survey questionnaire was translated from English to Arabic because the respondents' first language was Arabic. Two bilingual speakers translated the items into Arabic following Brislin's (1980a) back-translation procedure. Then two bilingual speakers compared the translated version to the original version to verify the translation (Brislin, 1980b). The differences were resolved through a cycle of retranslation and review, and then an agreement was reached. All items were measured on a five-point Likert scale ranging from 1 for strongly disagree to 7 for strongly agree.

The study measured the hedonic motivation and adapted 3-items from Venkatesh et al. (2012). Example: "I find the use of

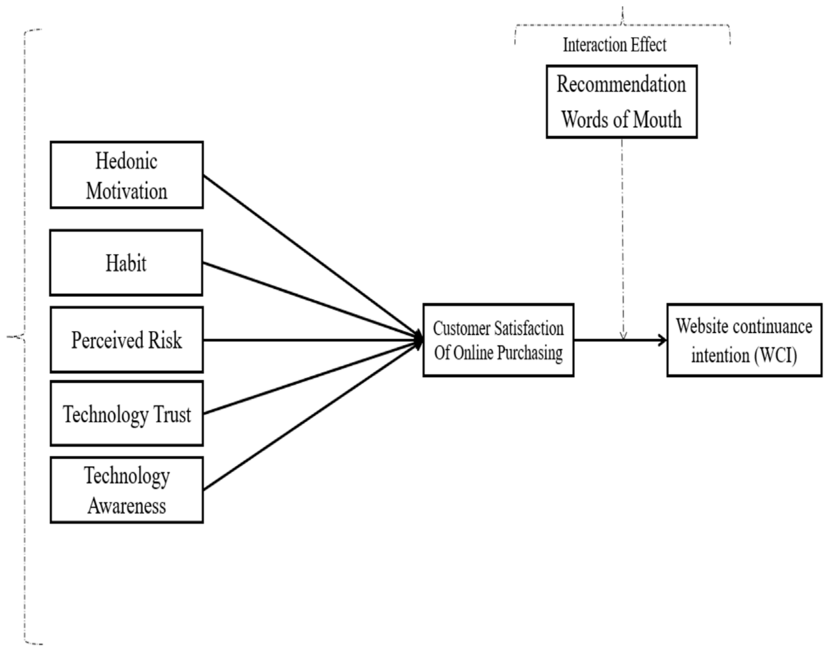

FIGURE 1 | Research model.

online purchasing technology a relaxing experience." Habit refers to the extent to which people tend to perform behaviors automatically because of learning and habit. Thus, we measured habit 4-items and took them from (Venkatesh et al., 2012; Halbusi et al., 2021). For example, the item, "The use of online purchasing service websites has become a habit for me." Perceived risk was measured 7-items was adapted from Corbitt et al. (2003). It is emphasized that customers feel worried about performance, financial, and time risks when buying from the internet and less about social and physiological risks. Example of the item "I believe that online purchases are risky because the products/services delivered may be of inferior quality." The technological trust was assessed with 5-items adapted from Ejdys (2018). The items emphasize trust in technology and show that a person's belief in the development of technology has an impact on the trust in a particular technology. It is already used or will be used in the future. For example, the item, "I can rely on the web system where I purchase the products." This study measured technological awareness and adapted 3-items from Collins (2007). For instance, "I have the technical knowledge required for appearing in an online purchasing" We measured customer satisfaction with online purchasing with 4-items taken from Cao et al. (2018). For example, in the item "The online shopping store provides good customer service quality." Word of mouth (WOM) was measured with 3-items borrowed from Maxham (2001). Typically, WOM provides vital information about a firm, product, and service to consumers that often helps consumers decide whether or not to patronize a firm, product, and service. Example of the item "Given my experience with (online service), I would recommend their service to my friends."

4 DATA ANALYSIS AND RESULTS

The study applied structural equation modeling (SEM) with partial least squares (PLS) Smart PLS 3.3.3 (Ringle et al., 2015). It is crucial because it is ideal for sophisticated causal analyses, including both first- and second-order ideas, and it does not require severe assumptions regarding the variables (Henseler et al., 2009). (Hair et al., 2017). The study investigated the statistical significance of the path coefficients. The PLS analysis used 5,000 subsamples to construct bootstrap t-statistics with n–1 degree of freedom (where n is the number of subsamples).

4.1 Common Method Bias

The issue of common method bias (CMB) may arise since the independent and dependent variables were collected using the same survey. To solve this challenge, we adopted a two-pronged technique using procedural and statistical approaches (Podsakoff et al., 2003; 2012). We used numerous measuring scales in the research instruments on a procedural level in terms of the procedural element (Afthanorhan et al., 2021). We also told the participants that there were no right or wrong answers and that their identities would be kept private. In addition, we used variance inflation factors (VIFs) in the statistical remedies to achieve a comprehensive collinearity test (Kock, 2015). Kock and Lynn (2012) advocated doing such a test to measure vertical and lateral collinearity. Kock and Lynn (2012) stated that when the VIF is more extensive than 3.3 indicates pathological collinearity, suggesting that CMV may contaminate the model. Nevertheless, as shown in **Table 1**, this study is considered free of CMV.

TABLE 1 | Common method variance assessment via full collinearity estimate criteria.

Components	Hedonic motivation	Habit	Perceived risk	Technology trust	Technology awareness	Customer satisfaction of online purchasing	Recommendation words of mouth	Website Continuance Intention (WCI)
VIF	2.113	1.221	1.127	1.223	2.325	1.356	2.311	1.281

VIF, variance inflation factor.

TABLE 2 | Measurement model, loading, construct reliability, and convergent validity.

Variables	Items	Factor loading (>0.5)	CA (>0.7)	CR (>0.7)	AVE (>0.5)
Hedonic Motivation	HM-1	0.762	0.750	0.841	0.570
	HM-2	0.755			
	HM-3	0.800			
Habit	HAB-1	0.785	0.774	0.818	0.531
	HAB-2	0.896			
	HAB-3	0.805			
	HAB-4	0.722			
Perceived Risk	PR-1	0.853	0.747	0.840	0.572
	PR-2	0.770			
	PR-3	0.710			
	PR-4	0.771			
	PR-5	0.807			
	PR-6	0.855			
	PR-7	0.838			
Technological Trust	TT-1	0.831	0.879	0.898	0.543
	TT-2	0.797			
	TT-3	0.833			
	TT-4	0.752			
	TT-5	0.714			
Technological Awareness	TAW-1	0.853	0.883	0.915	0.682
	TAW-2	0.770			
	TAW-3	0.710			
Customer Satisfaction of Online Purchasing	CSOP-1	0.807	0.860	0.891	0.658
	CSOP-2	0.855			
	CSOP-3	0.838			
	CSOP-4	0.831			
WOM	WOM-1	0.733	0.880	0.904	0.603
	WOM-2	0.752			
	WOM-3	0.747			
Website Continuance Intention (WCI)	WCI-1	0.937	0.794	0.881	0.721
	WCI-2	0.812			
	WCI-3	0.798			

CA , Cronbach's Alpha, CR , composite reliability; AVE , average variance extracted.

4.2 Measurement Model Assessment

The measurement model deals with validity and reliability. Therefore, we observed individual item reliability, internal consistency, and convergent and discriminant validity. Concerning item reliability (indictors loading), the results reveal that all items exceed the recommended 0.5 level (Hair et al., 2017) (see **Table 2**). To assess the constructs' internal consistency, we employed Cronbach's Alpha and composite reliability; they ranged from 0.747 to 0.883, higher than the 0.70 cut-offs (Hair et al., 2017). In support of convergent validity, the average variance extracted (AVE) for the constructs ranged from 0.531 to 0.682, above the 0.5 thresholds (Hair et al., 2017) (see **Table 2**).

The study analysis identified no problems with discriminant validity; the AVE for each construct was more significant than the variance shared by each construct with the other latent variables (**Table 3**). (Hair et al., 2017). Henseler et al. (2015) proposed that the Heterotrait-Monotrait ratio (HTMT) of correlations based on a Multitrait-multimethod matrix is more reliable in finding the results. **Table 3** indicated that the HTMT values are less than 0.90, demonstrating that each pair of variables has discriminant validity. All HTMT values are significantly different from one (1), and the 95 percent confidence intervals (CI) do not include 1 (Henseler et al., 2015), signifying that each pair of variables has discriminant validity.

TABLE 3 | Descriptive statistics, correlation matrix, and discriminant validity.

Constructs	Mean	SD	1	2	3	4	5	6	7	8
1. Hedonic Motivation	4.051	0.560	**0.745**	*0.704 [0.662; 0.749]*	*0.392 [0.323; 0.468]*	*0.678 [0.620; 0.731]*	*0.197 [0.157; 0.254]*	*0.087 [0.074; 0.129]*	*0.078 [0.062; 0.137]*	*0.060 [0.052; 0.095]*
2. Habit	3.931	0.441	0.316	**0.766**	*0.543 [0.490; 0.607]*	*0.794 [0.758; 0.827]*	*0.175 [0.156; 0.239]*	*0.084 [0.062; 0.147]*	*0.122 [0.103; 0.175]*	*0.078 [0.074; 0.128]*
3. Perceived Risk	4.206	0.709	0.339	0.164	**0.865**	*0.570 [0.510; 0.631]*	*0.127 [0.103; 0.203]*	*0.102 [0.071; 0.165]*	*0.057 [0.037; 0.11]*	*0.070 [0.036; 0.139]*
4. Technological Trust	4.014	0.521	0.554	0.292	0.246	**0.730**	*0.180 [0.152; 0.247]*	*0.153 [0.108; 0.208]*	*0.089 [0.075; 0.127]*	*0.104 [0.096; 0.139]*
5. Technological Awareness	2.811	0.767	0.049	0.074	0.054	0.074	**0.754**	*0.087 [0.063; 0.132]*	*0.051 [0.030; 0.122]*	*0.118 [0.073; 0.188]*
6. Customer Satisfaction of Online Purchasing	1.274	0.447	0.042	0.076	0.008	0.234	0.047	**0.718**	*0.007 [0.003; 0.083]*	*0.015 [0.002; 0.103]*
7. WOM	3.093	0.999	0.035	0.031	0.002	0.148	0.113	0.057	**0.812**	*0.268 [0.206; 0.331]*
8. Website Continuance Intention (WCI)	2.833	1.150	0.043	0.133	0.047	0.061	0.064	0.041	0.101	**0.742**

SD, standard deviation; n. a = not applicable. Bold values on the diagonal are the square roots of the average variance extracted, shared between the constructs and their respective measures. Off-diagonal elements above the diagonal are the Heterotrait-Monotrait ratios of correlations (HTMT) and their respective confidence intervals at the 95% confidence level. correlation matrix, and discriminant validity.

TABLE 4 | Structural path analysis: direct effect and interaction effect.

Hypothesis	Relationship	Std Beta	Std Error	t-value	*p*-values	Bias and corrected bootstrap 95% CI [Lower Level; Upper Level]	Decision
H-1	Hedonic Motivation- > Customer Satisfaction of Online Purchasing	0.386	0.060	6.467	0.000	[0.275; 0.475]	Supported
H-2	Habit- > Customer Satisfaction of Online Purchasing	0.198	0.066	3.019	0.001	[0.075; 0.293]	Supported
H-3	Perceived Risk- > Customer Satisfaction of Online Purchasing	–0.280	0.070	3.990	0.000	[0.166; 0.404]	Supported
H-4	Technological Trust - > Customer Satisfaction of Online Purchasing	0.045	0.044	1.024	0.153	[0.187; -0.396]	Not Supported
H-5	Technological Awareness- > Customer Satisfaction of Online Purchasing	0.216	0.043	5.020	0.000	[0.147; 0.286]	Supported
H-6	Customer Satisfaction of Online Purchasing - > Website continuance intention (WCI)	0.391	0.046	3.166	0.000	[0.154; 0.386]	Supported
Hypothesis	**Structural Path Analysis: The Interaction Effect (Moderation)**	**Std Beta**	**Std Error**	**t-value**	***p*-values**	**[Lower Level; Upper Level]**	**Decision**
H-7	Customer Satisfaction of Online Purchasing **X** WOM - > Website continuance intention (WCI)	0.231	0.052	4.640	0.000	[0.041; 0.203]	Supported

Std Beta = standard beta, Std Error = standard error.

2.3 Structural Model Assessment (Hypothesis Testing)

This section goes with our direct hypotheses from Hypothesis 1 to Hypothesis 6. According to hypothesis testing, the hedonic motivation was significantly associated with consumer satisfaction with online shopping (= 0.386, t = 6.467, and p 0.000). As a result, Hypothesis H-1 was approved. The second direct effect (Hypothesis 2) of the relationship between habit and customer satisfaction with online purchasing was positively significant with values (β= 0.198, t = 3.019, and $p < 0.001$), therefore, Hypothesis 2 was also supported. Regarding Hypothesis 3, the relation between perceived risk and customer satisfaction with online purchasing was supported as the perceived risk was negative toward customer satisfaction with online purchasing as per (β= -0.280, t = 3.990, and $p < 0.000$). The relationship between technological trust and customer satisfaction with online purchasing was insignificant (β= 0.045, t = 0.044, and $p <$ 0.153). Hence, Hypothesis 4 was not supported. Similarly, for Hypothesis 5, technological awareness was significantly related to the customer satisfaction with online purchasing, so Hypothesis 5 was supported as per (β= 0.216, t = 5.020, and $p < 0.000$). Regarding the final direct effect, Hypothesis 6 showed that customer satisfaction with online purchasing

FIGURE 2 | Interaction plot of customer satisfaction of online purchasing x WOM on the website continuance intention (WCI).

was significantly related to website continuance intention (WCI) with values (β= 0.391, t = 3.166, and $p < 0.000$). **Table 4** shows all the mentioned results.

Following the goals of this study, the moderation test was one of the key contributors to determining if words of mouth recommendation (WOM) moderate the relationship between customer satisfaction of online purchasing and is significantly related to website continuance intention (WCI). Consequently, the interaction between customer satisfaction with online purchasing and words of mouth recommendation (WOM) toward website continuance intention (WCI) revealed a significant interaction, such that (β= 0.231, t = 4.640, and $p < 0.000$). Hence, Hypothesis 7 was supported (see **Table 4**). Generally, it is not entirely clear how a moderation analysis differs for high and low interaction. In other words, the size of the precise nature of this effect is not easy to define from the analysis of the coefficient itself (Dawson, 2014). Hence, this study employed an interaction plot for the interactions to look at the gradient of the slopes. As shown in **Figure 2**, the line labeled 'high words of mouth recommendation (WOM)' has a steeper gradient when compared to 'common words of mouth recommendation (WOM). It indicates that when words of mouth recommendations (WOM) are higher, the positive relationship between customer satisfaction with online purchasing and website continuance intention (WCI) is more substantial (see **Figure 2**).

Regarding the model's explanatory power, R-square values of 0.511 for website continuance intention (WCI) indicated a moderate to large influence (Hair et al., 2017). We have used Stone-Geisser blindfolding sample reuse technique to determine the predictive relevance of the model. It also reveals Q-square values greater than 0, indicating that the research model accurately predicts both customer satisfaction with online purchasing (Q2 = 0.218) and website continuance intention (WCI) (Q2 = 0.245). (Hair et al., 2017). Lastly, the SRMR index value of 0.052 is far below the 0.08 cut-off (Henseler, 2017), and the 95 percent bootstrap quantile is 0.059, or higher than the SRMR value, indicating a good model fit (Hair et al., 2017). Moreover, the discrepancy indices dULS (unweighted least squares discrepancy) and dG (geodesic discrepancy) are both below the bootstrap-based 95 percent percentile (dULS = 1.537; dG = 0.662; HI 95 of dG = 0.981) (Hair et al., 2017). As a result, the difference between the empirical and model-implied correlation matrix is insignificant, and we have no reason to reject the model, which is more likely to be correct (Henseler, 2017).

5 DISCUSSION AND CONCLUSION

This study develops and tests a holistic framework to fill the gaps by integrating the values and attitudes of higher-order constructive formats in the emerging markets context. The current study investigates the antecedents of online purchase intentions during the COVID-19 pandemic. This research will allow online shoppers to understand improved their customers and the factors affecting their online shopping behavior during the pandemic. This study expands the literature on online purchasing by applying the VAB model. It focuses on examining the antecedents of online purchasing in emerging economies during the COVID-19 pandemic. Through this article, online shopping platform providers will be able to prepare for future restrictions and the post-vaccination period by understanding the antecedents of online shopping intentions during quarantine.

This research study explored the reasons that drive emerging-market customers to shop online and website continuance intention (WCI). It considers the elements such as hedonic motivation, habit, perceived risk, technology trust, technology awareness, and customer satisfaction with online purchasing (Alsaad et al., 2017; Ashfaq et al., 2020). Notably, in this study, we have employed recommendation words of mouth contingent on the relationship between customer satisfaction with online purchasing and website continuance intention (WCI). However, our findings confirm the positive and direct effect of the hedonic motivation, habit, perceived risk, and technology awareness on the customer satisfaction of online purchasing and subsequently have a positive effect on the customer satisfaction of online purchasing. Interestingly, recommendation word-of-mouth has significantly moderated the relationship between customer satisfaction with online purchasing and website continuance intention (WCI). The relationship is more robust when WOM is high than low.

In terms of the theoretical implications, this study makes a significant contribution to the knowledge by examining the factors like hedonic motivation, habit, perceived risk, technology trust, technology awareness, and customer satisfaction of online purchasing toward website continuance intention (WCI). Significantly, this also analyzed the moderating role of recommendation words of mouth (WOM) on the relationship between customer satisfaction with online purchasing and website continuance intention (WCI). It is because WOM is particularly important in marketing and e-commerce since intangible products are difficult to judge prior to consumption. They give more information about the product to help make a more informed decision. They will feel

delighted and satisfied with higher reviews than with moderate or lower ratings.

In terms of policy implications, the current findings of this study have ramifications for policymakers, marketing managers, and academics concerned with Qatar as a developing market. For public authorities to reduce their negative views of online shopping, they must first understand the challenges that online shoppers face, such as a lack of trust (Al-Khulaifi et al., 2001). Therefore, governments can concentrate their efforts on enhancing security and data privacy legislation to maximize the benefits of internet shopping. The degree of uncertainty, risk, and complexity in establishing internet channels is higher in an emerging-market scenario. As consumers in emerging nations become more aware of the advantages of online shopping, online businesses must work to reduce risk perceptions. Consumers believe that the information provided by online reviews is useful. As a result, businesses can focus on creating marketing tactics that encourage customers to provide information that positively influences their buy intentions via web pages. Online retailers should pay attention to online reviews of their products and services to foster the development of trust and encourage their consumers to contribute qualified information. Online retailers should improve the usability of online reviews to encourage consumers to post high-quality online reviews (Luo & Ye, 2019; Uzir et al., 2020). In addition, online merchants can use better and more secure transaction mechanisms, such as mobile wallets, internet security protocols, or secure approval signs to minimize risk perception and encourage individuals to buy online (Ventre & Kolbe, 2020).

A fundamental limitation of this study is that the data came from a single source. However, the study used two surveys and models of direct and moderated variables less likely to be affected by common method bias (Podsakoff et al., 2012; Al Halbusi et al., 2020; Halbusi et al., 2021; Alnoor et al., 2022; Abdelfattah et al., 2022), so CMB cannot be eliminated. In addition to the potential impact of CMB, the consistency of empirical results may have been exposed as self-reported data were used to measure intent, which can be a complex issue. Therefore, socially expected response bias cannot be completely ruled out. Future research should collect data from as many sources as possible, such as the sell-side and buy-side. A second limitation is that the results of this study are based on samples from Middle Eastern cultural contexts such as Qatar. Perhaps, specific cultural characteristics of this context, which include strong adherence to values and different cultural perspectives and structures (Moaddel, 2010), may have influenced the results of this study. Indeed, word-of-mouth (WOM) differences are likely to be replicated in cultural contexts (Triandis et al., 1988). However, it can be seen that further research is needed to assess the contextual sensitivity of these findings (Whetten, 2009) by analyzing other cultures where the importance of religious beliefs and cultural characteristics is similar to those applicable to other settings such as the West. Third, this study did not consider other external factors as it sought to explain continuation intentions. The intention is a complex observation influenced by many organizational, personal, and external variables. Therefore, caution must be exercised when making inferences from this study to the extent that a simplified version of the continuation intent is provided by focusing on a few variables, such as Arabic culture (Al Halbusi et al., 2022).

Additionally, a second limitation is that the study highlights Qatar's online buying behavior. Upcoming research should compare the findings with other emerging markets in the Gulf. We also recommend looking at other aspects to decide online purchases, as other important variables may influence the Qatari website's stay-on-line (WCI) intent. Therefore, we recommend evaluating other structures, such as social support or social commerce, for future research. In terms of perceived harm, a better understanding of behavioral elements in emerging markets is needed, as well as identifying possible modifiers, such as the frequency of online purchases. Finally, this survey is primarily quantitative; however, given the wide range of personalized customer buying experiences, qualitative research can better understand the underlying psychosocial and contextual structures that can influence behavioral intentions across different customer segments. Additionally, research on website interactivity, quality of service, privacy, and tour package customization can be conducted to understand better, how these factors affect customers' willingness to use the website.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Vishal Dagar,
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Ali Junaid Khan,
Islamia University of Bahawalpur, Pakistan
Sami Ullah,
Shandong University, Weihai, China

*CORRESPONDENCE
Raheel Akhtar,
mianraheel19@gmail.com
Adeel Akhtar,
adeel.akhtar@bzu.edu.pk

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Mediation effect of environmental performance in the relationship between green supply chain management practices, institutional pressures, and financial performance

Xin Ma[1], Raheel Akhtar[1]*, Adeel Akhtar[2,3]*, Raema Abdullah Hashim[3] and Muhammad Sibt-e-Ali[4]

[1]School of Management and Economics, North China University of Water Resources and Electric Power, Zhengzhou, China, [2]Department of Commerce, Bahauddin Zakariya University, Multan, Pakistan, [3]Putra Business School, Universiti Putra Malaysia, Selangor, Kuala Lumpur, Malaysia, [4]School of Business, Zhengzhou University, Zhengzhou, China

Pakistan is an agricultural country that uses a huge number of pesticide chemicals and is confronting environmental and economic issues. Firms need to comprehend the integration of green supply chain management (GSCM) practices in their supply chain. The current study intends to analyze the mediation effect of environmental performance (ENP) in the relationship between GSCM practices, institutional pressures (IP), and financial performance (FNP). Therefore, GSCM-IP-ENP-FNP model was developed with the help of an extensive literature review and then proved with the help of data collected from pesticide chemical firms working in Pakistan. Data were collected through a questionnaire from 500 senior-level managers of the pesticide firms of Pakistan. However, 468 responses were retained for analysis keeping in view the limitations of the current study. SPSS version 22 and SmartPLS 3.0 were used for data analysis. Results of the study indicated strong relationships among all variables. It was also concluded that GSCM practices, IP, and ENP have a positive and statistically significant relationship with a firm's FNP. This study is an important contribution to theory and practice. The study is unique and has significant contributions because it developed and proved the GSCM-IP-ENP-FNP model. The model helped to prove the mediation effect of ENP in the relationship between GSCM practices, IP, and FNP in the pesticide sector of Pakistan, which would be highly beneficial for the managers of pesticide firms as well as for the government to understand the importance of GSCM practices for improving the ENP as well as the FNP of pesticide firms in Pakistan as well as worldwide, especially in developing countries. This study recommends that the management of firms should implement GSCM practices to protect the environment. Government, consumers, and other institutions should exert pressure and the government should provide subsidies, if necessary, to the firms for successful implementation of GSCM practices. Furthermore, it is recommended to conduct further studies in other countries by using the

mixed methodology in the pesticide sector as well as in other sectors of the economy to increase the generalizability of the current study.

KEYWORDS

green supply chain management, institutional pressures, environmental performance, financial performance, pesticide firms

1 Introduction

Over the last decade, firms, as well as governments of various countries, have been highly concerned regarding environmental issues (Zelazna, Bojar and Bojar, 2020). The growing trend of implementing green supply chain management (GSCM) practices is highly stimulated by institutional pressures to achieve the target of greening the industrial operations (Tseng et al., 2019). GSCM practices from supplier to customer encompass the whole value chain as organizations try to reduce the negative impacts of their operations on the natural environment (Ahmed et al., 2020). Pressure from the global industry is to implement the GSCM practices to become competitive in the global market, which also provides export opportunities for manufacturers (Al-Ghwayeen and Abdallah, 2018). The institutional pressures accompanying globalization have prompted enterprises to improve their environmental and financial performance (Helm, 2020). The pressure on businesses to increase environmental performance also comes from globalization (Tang et al., 2020). Increasing environmental concern has become a part of the pesticides sector as well. GSCM practices including internal and external practices have a positive and significant effect on the firm's financial growth (Liao and Zhang, 2020).

Firms implementing GSCM practices under institutional pressures can be assessed on environmental and firm's financial performance. All over the world, global warming and environmental change is an important issue (Ali et al., 2021; Rehman et al., 2021). The recent studies suggest that further investigations are required to find the relationship between environmental practices and financial performance, which may include reduced use of toxic materials and reduced wastage of water, materials, and electricity and firm's financial growth, especially in the developing countries (Vanalle et al., 2017). Most of the studies are carried out in developed countries, so a research gap exists in developing countries (Geng, Mansouri and Aktas, 2017). Most of the GSCM studies included single informants from each organization, but future researchers must include multiple responses from each organization from different levels of employees (Habib et al., 2020). Therefore, this study aims to analyze the relationship between GSCM practices, institutional pressures, environmental and firm's financial performance in the Pakistani pesticide sector by having multiple responses from each organization from different levels of employees. This research has a vital contribution to the existing literature because it has proved the mediation effect of environmental performance in the relationship between GSCM practices, institutional pressures, and financial performance in the pesticide sector of Pakistan, which would be helpful for the managers of pesticide firms as well as for the government to understand the importance of GSCM practices for improving the environmental as well as the financial performance of pesticide firms in Pakistan as well as worldwide, especially in developing countries. Moreover, it is one of the rare studies, which includes GSCM practices; internal (IGSCM) practices like eco-design (ECD) of product and internal environmental management (IEM), and external (EGSCM) practices like green purchasing (GP), cooperation with customers (CWC) and reverse logistics (RL), institutional pressures (IP), environmental (ENP) and firm's financial performance (FNP).

This research is conducted using the resource-based view (RBV) theory and the institutional theory. The RBV theory emphasizes that the resources and capabilities always play important role in achieving competitive advantage (Bu et al., 2020). Adoption of GSCM practices may also be one of the competitive advantages. RBV theory focuses on a firm's internal and external strategies to improve the firm's financial performance (Kamasak, 2017). IP plays an important role in the adoption of GSCM practices to improve environmental performance (Chu et al., 2017), which is linked with institutional theory. Institutional theory dimensions clear the boundaries of best GSCM practices (Dedoulis, 2016). The institutional theory theoretically supports explaining the GSCM practices (internal GSCM practices and external GSCM practices). The institutional theory also supports the relationship between institutional pressures and environmental performance (Yang, 2018).

Pakistan's agricultural sector has a great contribution to the GDP of Pakistan. Pakistani farmers use large amounts of pesticide chemicals for improving agricultural outputs, whereas pesticide producers are adopting effective GSCM practices for improving their environmental and financial performance (Akhtar and Soratana, 2021). Most of the farmers in Pakistan use pesticides for growth in agricultural production. Pesticides have many negative effects on the environment (Hakeem et al., 2016). More use of pesticides and fertilizers harms the environment and is becoming a major challenge for the improvement of environmental performance (Hakeem et al., 2016; Dagar et al., 2020). The agriculture sector, which contributes 18.9% of Pakistani GDP,

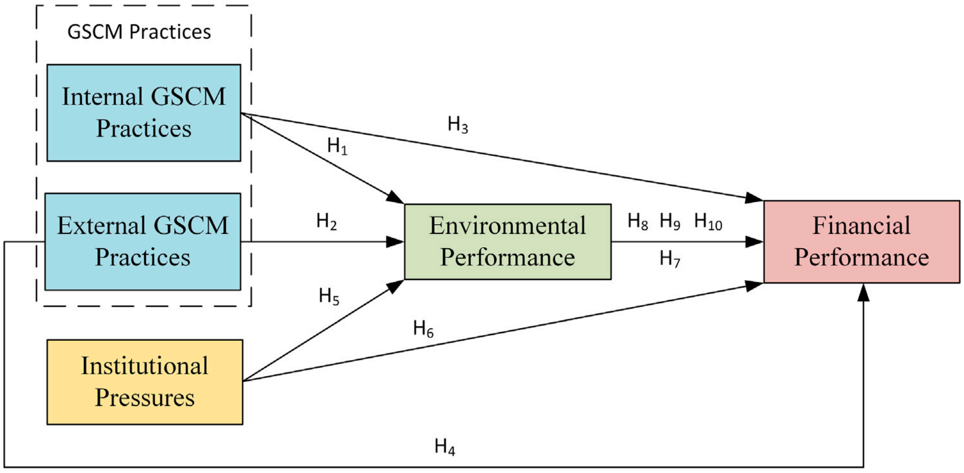

FIGURE 1
GSCM-IP-ENP-FNP model.

can benefit from China Pakistan Economic Corridor (CPEC) by upgrading the nexus of the backward and forward supply chain (Yar et al., 2021). CPEC is one of the flagship projects of China's Belt and Road Initiative, which had an initial worth of $47 billion and currently has $62 billion (Ali et al., 2020). CPEC is one of the major FDIs in the history of Pakistan (Ali et al., 2020). Due to CPEC projects, hundreds of companies are doing investments in Pakistan and many more companies are willing to invest; most of those companies are implementing green practices but still, the environmental threat should not be ignored (Khan, 2020). FDI was criticized for the rise in environmental pollution through unsustainable production practices due to a lack of environmental regulations by host countries (Asif et al., 2020). More regulations (institutional Pressures) are required to improve the environmental performance of Pakistani firms (Kouser, Subhan and Abedullah, 2020). Thus, the current study aims to analyze the mediation effect of environmental performance in the relationship between GSCM practices, institutional pressures, and financial performance in the pesticide sector of Pakistan through the lens of RBV theory and institutional theory.

2 Literature review

A detailed examination of the literature was conducted with particular attention paid to GSCM practices, institutional pressures, firm's environmental and financial performance. A model GSCM-IP-ENP-FNP (Figure 1) was developed after an extensive literature review. The literature review findings are given below:

2.1 Relevant theories of the study

2.1.1 Resource based view theory

RBV theory focuses on indispensable, rare, valuable, and non-sustainable firms' capabilities and resources to attain sustainable and competitive advantage in the form of environmental improvement (green and better quality products) and competitive financial performance (resources optimization) as compared to competing firms (Barney, 1991). Tangible assets and intangible assets both include the firm's important resources like GSCM practices, environmental and financial performances (Vitorino Filho and Moori, 2020). A temporary competitive advantage is provided by tangible resources because competitors can copy these resources easily. Although, the competitors cannot copy the intangible resources because it is gained by the experience (Kamasak, 2017). It is difficult to copy the GSCM practices of the competitors because it gains from the experience. For example, competitors cannot easily copy the positive reputation of firms that is earned by the successful implementation of GSCM practices (Yildiz Çankaya and Sezen, 2019). Therefore, RBV is one of the most appropriate theories for the investigation of the relationship between GSCM practices, environmental and financial performances.

2.1.2 Institutional theory

Institutional theory is utilized to comprehend the many external variables that compel any firm to launch or implement any new practice. The pressure which firms put on one another in the adoption of more sustainable green practices in the supply chain is known as institutional pressures (Saeed et al., 2018). External pressures which can influence

organizational activities are known as institutional pressures (DiMaggio and Powell, 1983). This theory can be used to examine and explain the cause and extent of implementing the firm's green practices (Touboulic and Walker, 2015).

2.2 Green supply chain management practices and environmental performance

GSCM practices are implemented to improve environmental performance (Zhu, Sarkis and Lai, 2012). A sustainable environment can be achieved by adopting innovative environmental-related technologies like GSCM practices (Khan M. K. et al., 2022). The Implementation of GSCM (internal and external) practices causes a reduction in environmental accidents, which improves the firm's performance as well as society's well-being (Das, 2018). The environmental performance of the firm demonstrates its ability to reduce hazardous components, environmental accidents, pollution, and solid waste. (Esfahbodi, Zhang and Watson, 2016). GSCM practices cover internal GSCM practices and external GSCM practices (Ming Heng et al., 2018). Internal GSCM practices include deliberate performance-related activities, which means these practices have a valuable contribution to a firm's performance (Vanalle et al., 2017). Internal GSCM practices include the practices like eco-design (ECD) and internal environmental management (IEM) (Choi, Min and Joo, 2018; Al-Sheyadi, Muyldermans and Kauppi, 2019). External GSCM covers practices like green purchasing (GP), cooperation with customers (CWC) and reverse logistics (RL) have a significant relationship with the environmental performance of the firm (Zaid, Bon and Jaaron, 2019). Internal and external GSCM practices have a significant relationship with environmental performance (Marhamati and Azizi, 2017). GSCM (Internal and external) practices have a significant relationship with environmental performance (Al-Sheyadi, Muyldermans and Kauppi, 2019). Therefore, the following hypotheses are proposed:

H1: Internal GSCM practices have a significant effect on the firm's environmental performance.

H2: External GSCM practices have a significant effect on the firm's environmental performance.

2.3 Green supply chain management practices and financial performance

Financial performance includes an increase in return on investment, increase in earnings per share, increased profit margin, raise in product price, raise in sales, and enhanced market share (Golicic and Smith, 2013). In previous studies, limited research was conducted to investigate the relationship between GSCM (internal and external) practices and financial performance (Siddiqui and Siddiqui, 2020). Recent studies find a direct and significant relationship between GSCM (internal and external) practices and organizational performance (Chin, Tat and Sulaiman, 2015). If GSCM practices are combined with the supply chain of a firm, they will lead to an increase in profit and competitive advantage (Chan, He and Wang, 2012). The overall change in financial performance is due to indicators related to GSCM practices (Shahzad et al., 2022). A study conducted on the supply chain situation paradox collected data from 284 individuals from each firm and concluded that GSCM (internal and external) practices have a significant and positive effect on a firm's financial performance (Schmidt, Foerstl and Schaltenbrand, 2017). There are mixed results found in the previous studies indicating the relationship between GSCM (internal and external) practices and a firm's financial performance (Geng, Mansouri and Aktas, 2017). Adoption of GSCM (internal and external) practices is vital for the top management to achieve a competitive advantage (Banasik et al., 2017). Effective GSCM practices cause an improvement in financial performance (Golicic and Smith, 2013). Therefore, the following hypotheses are proposed:

H3: Internal GSCM practices have a significant effect on the firm's financial performance.

H4: External GSCM practices have a significant effect on the firm's financial performance.

2.4 Institutional pressures, environmental and firm's financial performance

Institutional pressures from governments, competitor firms, customers, and other pressure groups have a significant impact on firms for the successful implementation of GSCM practices (Zhang et al., 2020). GSCM practices can be influenced by institutional pressures, which include pressure from domestic regulatory bodies, government regulations, stakeholders, customers, competitors, non-government organizations, and employees (Zhang et al., 2020). Pressure from competing firms encourages organizations to implement GSCM practices as it allows the firms to compete by delivering green products and staying agile with improvements in environmental commitments (Choi, Min and Joo, 2018). Institutional pressures from governments and other pressure groups have a positive and significant effect on a firm's environmental performance (Phan and Baird, 2015). Environmental regulations play an important role in the improvement of environmental performance (Murshed et al., 2021). Research conducted on 248 enterprises concluded that the institutional pressures had a significant impact on a firm's environmental and financial performance (Aharonson and Bort, 2015). Environment and financial performance have a negative relationship, so the

government needs to provide subsidies and tax exemptions to encourage eco-friendly products (Ullah and Ali, 2022). Effective governance may improve environmental performance (Nadeem et al., 2022). Institutional pressures have a significant and noteworthy relationship with GSCM (internal and external) practices (Mitra and Datta, 2014). Therefore, we proposed the following hypotheses:

H5: Institutional pressures have a significant and noteworthy effect on the firm's environmental performance.
H6: Institutional pressures have a significant and noteworthy effect on the firm's financial performance.

2.5 Firm's environmental performance and financial performance

Environmental performance includes environmental compliance improvement, a decrease in consumption of energy and water, minimum use of hazardous material and environmental accidents, and a decrease in carbon emissions (Yook, Choi and Suresh, 2018). Firms implementing GSCM practices minimize firm costs and improve environmental performance by protecting the environment (Shafique, Asghar and Rahman, 2017). A firm's GSCM practices cause environmental improvement and have a significant and noteworthy effect on a firm's financial performance (Yang, 2018). Change in a climate affects the industrial financial performance (Ali et al., 2021). Environmental concerns to achieve firm performance have an important impact on society (Luo, Ullah and Ali, 2021). Earlier studies have clear evidence of a remarkable relationship among the environmental and firm's financial performance (Al-Sheyadi, Muyldermans and Kauppi, 2019; Weimin et al., 2022). A firm's financial performance improvement can happen through the successful implementation of GSCM (internal and external) practices (Al-Sheyadi, Muyldermans and Kauppi, 2019). Therefore, we proposed the following hypothesis:

H7: Firm's environmental performance has a significant and noteworthy effect on the firm's financial performance.

2.6 Mediating role of environmental performance between green supply chain management practices, institutional pressures, and firm's financial performance

Environmental performance can be measured by waste reduction, prevention of pollution, or other items related to environmental performance (Tseng et al., 2019). Firms should adopt GSCM practices, but how they can improve environmental and financial performance is not clear yet (Zhu, Sarkis and Lai, 2019). Internal GSCM practices like ECD and IEM can reduce the use of toxic materials, energy, and water waste, which has a remarkable role in minimizing environmental impacts and enhancing firm financial performance by cost-cutting (Al-Ghwayeen and Abdallah, 2018). Financial performance improves as the firms successfully implement GSCM practices (Zailani et al., 2012). According to a study done in China on 126 automobile manufacturers, the indirect influence of GSCM practices on a firm's financial performance might be mediated by a firm's environmental performance (Feng et al., 2018). The rise in environmental performance minimizes pollution due to the successful implementation of GSCM (internal and external) practices, which results in the improvement of financial performance because of a reduction in costs (Esfahbodi et al., 2017). Environmental practices have a remarkable relationship with institutional pressure and green practices (Jianguo et al., 2022). The green growth objective cannot be achieved without the sustainable use of material resources (Xie et al., 2022). A firm's environmental performance mediates the relationship among GSCM practices and financial performance in manufacturing companies (Al-Ghwayeen and Abdallah, 2018). A firm's environmental performance also mediates the relationship among the institutional pressures and a firm's financial performance (Gupta and Gupta, 2021). Future studies should be conducted to investigate the direct influence of institutional pressures on the environment and the indirect effect on firm financial performance (Yang, 2018). More studies are required to examine the impact of environmental performance, GSCM (internal and external) practices, institutional pressures, and financial performance in manufacturing firms (Saeed et al., 2018). Therefore, based on the above-stated studies we proposed the following hypotheses:

H8: Firm's environmental performance has a mediating role between internal GSCM practices and a firm's financial performance.
H9: Firm's environmental performance has a mediating role between external GSCM practices and a firm's financial performance.
H10: Firm's environmental performance has a mediating role between institutional pressures and a firm's financial performance.

2.7 Research model of the study

After an extensive literature review, Figure 1, GSCM-IP-ENP-FNP Model was developed. The model shows that internal GSCM, external GSCM, and institutional pressures have a significant, direct as well as indirect effect, on a firm's financial performance having the mediating role of environmental performance. The rationale for the GSCM-IP-

ENP-FNP model is inspired by recent studies (Saeed et al., 2018), (Ahmed, Najmi and Khan, 2019; Marri, Sarwat and Aqdas, 2021).

The Figure 1 indicates that internal GSCM, external GSCM, and institutional pressures have a significant, noteworthy, direct, and indirect, effect on financial performance with mediating role on environmental performance.

3 Materials and methods

It is a quantitative study and a survey questionnaire was utilized to collect data. Multi-stage sampling was done. In the 1st stage, purposive sampling was applied for the selection of firms and at 2nd stage, convenient sampling was used to get responses from senior employees of the selected firms. Cross sectional design was followed for data collection due to time and cost constraints. There are 52 corporate-level pesticide chemical firms registered with Pakistan Crop Protection Association (PCPA). Out of those 52 firms, 22 firms are located in district Multan, Punjab, which accounts for 44% of the total corporate-level firms. Therefore, Multan is considered a hub for the pesticide chemical firms operating in Pakistan. That's why 22 corporate-level pesticide chemical firms, located in district Multan, were selected for the collection of data by using the purposive sampling method.

3.1 Sampling techniques

Sampling is the process of selecting a subset from a defined sampling frame or the complete population. Sampling can be used to draw conclusions about a population or to make generalizations on current theory (Taherdoost, 2016). Generally, sampling is divided into two categories; probability sampling and non-probability sampling. By using probability sampling, every item in the population has an equal chance of being included in the sample. One method for doing probability sampling would be for the researcher to first create a sampling frame and then use a random number generating computer program to choose a sample from the sampling frame (Taherdoost, 2016). Probability sampling includes; simple random, systematic sampling, stratified random, and cluster sampling. Probability sampling is not appropriate for the current study because it is not possible to list down all the employees working in pesticide chemical firms in a short time and low budget.

Non-probability sampling techniques such as convenience sampling and purposive sampling are used by researchers to choose a sample of subjects/units from a population. Although non-probability sampling has several drawbacks owing to the subjective nature of sample selection, it is beneficial when randomization is difficult, such as when the population is very massive (Etikan, 2016). It can be beneficial when the researchers' resources, time, and labor are limited. So, the non-probability sampling is appropriate for the current study.

3.2 The sample size of the study

This study has five variables with 39 items to evaluate the conceptual framework of the study. Internal GSCM practices were measured with 10 items (Al-Sheyadi, Muyldermans and Kauppi, 2019), External GSCM Practices were measured with 09 items (Yildiz Çankaya and Sezen, 2019), Institutional Pressures was measured with 07 items (Chu et al., 2017; Kalpande and Toke 2020), Environmental performance was measured with 06 items (Pinto, 2020), (Banasik et al., 2017) and Financial performance was measured with 07 items (Flynn et al., 2010; Zhang et al., 2020). According to (Israel, 1992) for the selection of sample size where the population is greater than 100,000 and the level of confidence is 95% with a p-value = 0.05 sample size should be 400 (Singh and Masuku, 2014). Researchers suggests that at least the 05 to 01 ratio should be taken (Memon et al., 2020). In another study, the "10-times rule" is stated as a favorite for data collection due to its simple application (Kock, 2018) its most widely used in PLS-SEM studies (Kock and Hadaya, 2018). This rule is based on that the sample size should be greater than 10 times the maximum number of items in the scale. The requirement for a sufficient sample size is 5–20 responses against one item (Maurischat, 2006). Based on these studies the targeted sample for the current study was 390 respondents from 22 Pesticide firms located in district Multan, Pakistan.

3.3 Data collection

Data were collected using Google Forms. An online link was shared with respondents through WhatsApp, Facebook, email, and personal visits. The link was sent to senior executives of the companies and they further forwarded it to their senior-level colleagues. Responses were collected from 10 July 2021 to 10 November 2021. The minimum required sample size was 390 by using the 10 times rule for data collection (Kock, 2018), which is a suitable technique for using SmartPLS (Kock and Hadaya, 2018). However, to ensure quality, a total of 500 responses were collected. 468 responses were retained for further analyses, whereas 32 responses were eliminated due to study limitations (responses from firms having less than 100 employees or the firm's age was not more than 10 years). Descriptive analysis was conducted using SPSS version 22. Other statistical analyses including reliability and validity, discriminant validity, multicollinearity, correlation analysis, and hypothesis testing were performed by using Partial Least Square Structural Equation Modelling through SmartPLS 3.

TABLE 1 Demographics analysis.

Category	Frequency	%	Category	Frequency	%
Gender			**Experience in pesticides**		
Male	445	95.10%	less than 1 year	27	5.80%
Female	23	4.90%	1–3 years	51	10.90%
Total	468	100%	3–5 years	111	23.70%
Age of Respondent			5–10 years	136	29.10%
Less than 25	24	5.10%	more than10 years	143	30.60%
between 25–30	69	14.70%	Total	468	100%
between 30–35	104	22.20%	**Experience at current position**		
between 35–40	161	34.40%	less than 1 year	61	13%
more than 40	110	23.50%	1–3 years	123	26.30%
Total	468	100%	3–5 years	128	27.40%
Education			5–10 years	87	18.60%
Undergraduate	66	14.10%	more than10 years	69	14.70%
Graduate	281	60%	Total	468	100%
MS/MPhil	116	24.80%	**ISO 14000 Certification**		
PhD	5	1.10%	Yes	287	61.30%
Total	468	100%	No	181	38.70%
Job Title			Total	468	100%
CEO/President	8	1.70%	**Environmental Certification**		
Manager (Operations related)	108	23.10%	Yes	459	98.10%
Manager (Productions related)	66	14.10%	No	9	1.90%
Manager (Supply Chain related)	149	31.80%	Total	468	100%
Manager (Environment related)	34	7.30%			
Top Level Manager	45	9.60%			
Middle Level Manager	28	6%	**Firm's Number of Employees**		
First Level Manager	24	5.10%	Between 100 and 200	51	10.90%
Other	6	1.30%	Between 201 and 300	84	17.90%
Total	468	100%	Between 301 and 400	53	11.30%
Benefits form CPEC Projects			Between 401 and 500	104	22.20%
Yes	445	95.10%	more than 500	176	37.60%
No	23	4.90%	Total	468	100%
Total	468	100%	**Age of Firm**		
Problems due to CPEC Projects			Between 10 and 15 years	163	34.80%
Yes	1	0.20%	Between 15 and 20 years	106	22.60%
No	467	99.80%	more than 20 years	199	42.50%
Total	468	100%	Total	468	100%

4 Analysis and findings

4.1 Demographic analysis

Demographic analysis was conducted to generalize and check the study limitations (Table 1), and the bold text is the subsection of demographics using SPSS version 22. As the study was limited to corporate-level pesticide chemical firms, having more than 10 years of firm age along with more than 100 employees. 500 responses for the current study were received from which 32 responses were excluded because those responses belonged to firms, which had less than 100 employees or the firm's age was not more than 10 years. There were 445 male (95.1%) and 23 female (4.9%) participants. 161 (34.4%) respondents had an age between 35–40. 402 (85.9%) respondents were having at least graduate or higher-level educational qualifications. 143 (30.6%) respondents had more than 10 years of experience in pesticide firms, whereas 128 respondents (27.4%) had working experience at their current job. 287 (61.3%) respondents belonged to such firms, which were having ISO 14000 certification. 459 (98.1%) respondents belonged to those firms, which were having ISO 14000 certification and/or any other environmental

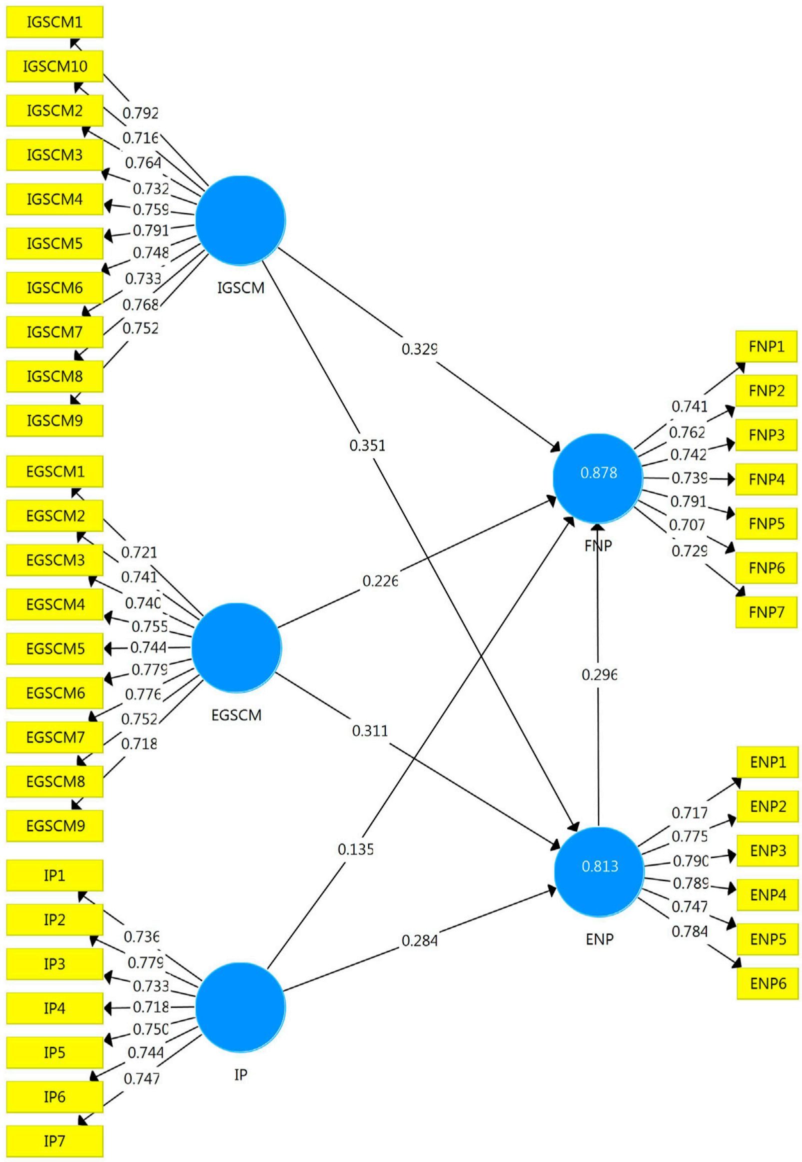

FIGURE 2
Measurement model.

certification. 445 (95.1%) respondents indicated that pesticide firms had benefited from CPEC projects and 467 (99.8%) respondents indicated that pesticide firms in Pakistan did not have any problems due to CPEC projects as shown in Table 1.

4.2 Validity and reliability analysis

This section encompasses two parts. 1st part, Figure 2, shows the measurement/outer model, whereas, the 2nd part, Figure 3, depicts the structural (inner model). Association between variables is indicated in the measurement/outer model (Xiang et al., 2022). For the determination of the constructs' reliability and validity, it is necessary to estimate the outer model at 1st stage (Ringle et al., 2015). To examine the validity as well as reliability of constructs, an analysis of the outer model was performed to confirm that the items of the survey questionnaire were measuring what they were supposed to measure.

4.3 Quality criteria for measuring instrument

To estimate the validity as well as reliability of the constructs and items, outer model analysis is used as the

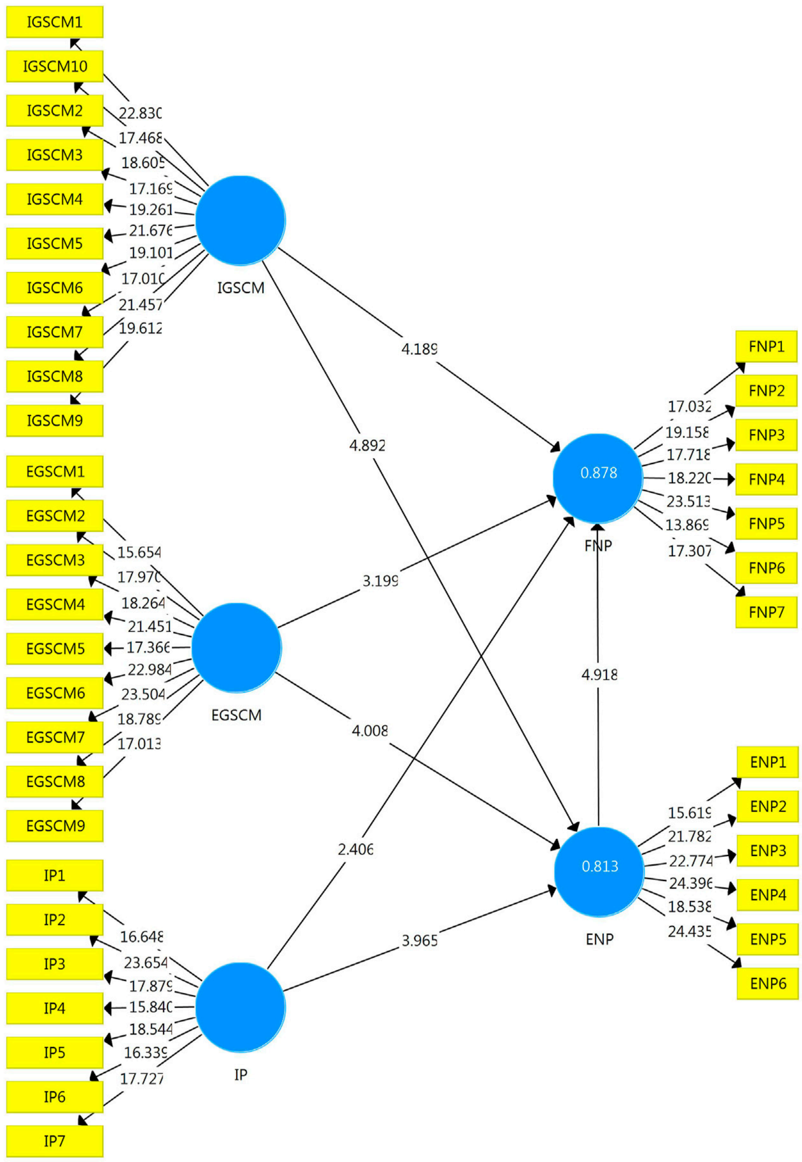

FIGURE 3
Structural model (GSCM-IP-ENP-FNP).

"Quality Criteria for Measuring Instrument" (Henseler, Hubona and Ray, 2016). Cronbach's Alpha values were >0.70 and Composite Reliability values also were >0.70, which confirmed the reliability of the outer model (Table 1). In the current study convergent validity was ensured by using average variance extracted (AVE) measuring >0.50 as the rule of thumb (Henseler, Hubona and Ray, 2016). As the outer loadings of all items were >0.70 (Table 1), therefore, further analyses were conducted to test the study hypotheses.

4.4 Discriminant validity

One of the important methods to evaluate discriminant validity is cross-loading analysis (Khan M. T. et al., 2022), which confirms that the items measuring the variable are measuring what they are intended to measure (Hair et al., 2014), (Vanalle et al., 2017). The cross-loading analysis yielded sufficient data for discriminant validity in the current investigation as shown in Table 2.

TABLE 2 Quality criteria for measuring instrument.

Variables	Measures	Measure's Outer loading	Cronbach's Alpha	rho_A	Composite Reliability	Average variance Extracted (AVE)
IGSCM	IGSCM1	0.792	0.916	0.917	0.930	0.571
	IGSCM2	0.764				
	IGSCM3	0.732				
	IGSCM4	0.759				
	IGSCM5	0.791				
	IGSCM6	0.748				
	IGSCM7	0.733				
	IGSCM8	0.768				
	IGSCM9	0.752				
	IGSCM10	0.716				
EGSCM	EGSCM1	0.721	0.901	0.902	0.919	0.559
	EGSCM2	0.741				
	EGSCM3	0.740				
	EGSCM4	0.755				
	EGSCM5	0.744				
	EGSCM6	0.779				
	EGSCM7	0.776				
	EGSCM8	0.752				
	EGSCM9	0.718				
IP	IP1	0.736	0.866	0.867	0.897	0.554
	IP2	0.779				
	IP3	0.733				
	IP4	0.718				
	IP5	0.750				
	IP6	0.744				
	IP7	0.747				
ENP	ENP1	0.717	0.860	0.861	0.896	0.589
	ENP2	0.775				
	ENP3	0.790				
	ENP4	0.789				
	ENP5	0.747				
	ENP6	0.784				
FNP	FNP1	0.741	0.866	0.868	0.897	0.555
	FNP2	0.762				
	FNP3	0.742				
	FNP4	0.739				
	FNP5	0.791				
	FNP6	0.707				
	FNP7	0.729				

4.5 Multicollinearity analysis

Multicollinearity of the data should be checked before the analysis of the structural model of the study (Hair et al., 2017). Table 3 shows the maximum multicollinearity value of 2.510, which is within the normal range. That's why multicollinearity is not the problem of the current study (Henseler, Hubona and Ray, 2016).

4.6 Structural model

Because of recommended bootstrap samples of 5000 (Vanalle et al., 2017), the current study conducted bootstrap analysis at 5000 samples. The relationship was examined between independent variables (IGSCM, EGSCM, institutional pressures), mediating variable (environmental performance), and dependent variable (financial performance). The bootstrapping method was used to measure the path coefficients, significance, t-value, and standard error through SmartPLS 3. Bootstrapping results are presented in Figure 3.

Results in Figure 3 show that all measures had a t-value > 1.96 and a p-value < 0.05 therefore, all the measures were statistically significant (Marri, Sarwat and Aqdas, 2021).

All items of financial performance were highly correlated with GSCM practices (internal as well as external practices), institutional pressures, and environmental performance, which means that GSCM practices (internal and external), institutional pressures, and environmental performance have a strong relationship with firm's financial performance as shown in Table 4, and the value of IGSCM1= 2.510 is highest value and ENP1=1.551 is the lowest value.

To estimate the adequacy of the model it is necessary to calculate the "coefficient of determination (R^2)" (Marri, Sarwat

TABLE 3 Cross loadings.

Items	EGSCM	ENP	FNP	IGSCM	IP
EGSCM1	**0.721**	0.635	0.644	0.651	0.701
EGSCM2	**0.741**	0.601	0.634	0.689	0.611
EGSCM3	**0.740**	0.679	0.673	0.636	0.634
EGSCM4	**0.755**	0.650	0.680	0.692	0.652
EGSCM5	**0.744**	0.602	0.654	0.689	0.656
EGSCM6	**0.779**	0.628	0.699	0.665	0.705
EGSCM7	**0.776**	0.713	0.696	0.639	0.664
EGSCM8	**0.752**	0.664	0.681	0.684	0.657
EGSCM9	**0.718**	0.668	0.648	0.620	0.610
ENP1	0.659	**0.717**	0.671	0.602	0.654
ENP2	0.692	**0.775**	0.668	0.699	0.616
ENP3	0.665	**0.790**	0.713	0.660	0.651
ENP4	0.666	**0.789**	0.714	0.666	0.712
ENP5	0.676	**0.747**	0.676	0.624	0.606
ENP6	0.646	**0.784**	0.658	0.714	0.658
FNP1	0.612	0.606	**0.741**	0.650	0.617
FNP2	0.665	0.697	**0.762**	0.711	0.643
FNP3	0.699	0.646	**0.742**	0.666	0.618
FNP4	0.666	0.728	**0.739**	0.709	0.625
FNP5	0.735	0.729	**0.791**	0.699	0.680
FNP6	0.661	0.616	**0.707**	0.624	0.671
FNP7	0.615	0.611	**0.729**	0.611	0.620
IGSCM1	0.725	0.672	0.689	**0.792**	0.649
IGSCM10	0.580	0.660	0.645	**0.716**	0.602
IGSCM2	0.631	0.699	0.701	**0.764**	0.662
IGSCM3	0.676	0.598	0.638	**0.732**	0.602
IGSCM4	0.707	0.659	0.720	**0.759**	0.667
IGSCM5	0.772	0.672	0.773	**0.791**	0.668
IGSCM6	0.667	0.695	0.682	**0.748**	0.676
IGSCM7	0.630	0.638	0.612	**0.733**	0.541
IGSCM8	0.619	0.616	0.647	**0.768**	0.594
IGSCM9	0.676	0.593	0.656	**0.752**	0.605
IP1	0.659	0.588	0.617	0.616	**0.736**
IP2	0.667	0.709	0.659	0.618	**0.779**
IP3	0.641	0.658	0.668	0.582	**0.733**
IP4	0.652	0.605	0.612	0.688	**0.718**
IP5	0.618	0.634	0.641	0.591	**0.750**
IP6	0.678	0.610	0.652	0.642	**0.744**
IP7	0.649	0.599	0.616	0.599	**0.747**

Bold values shows the significant values.

TABLE 4 Collinearity statistics (VIF).

Outer VIF values			
Indicators (measures)	VIF	Indicators (measures)	VIF
IGSCM1	2.510	IP1	1.819
IGSCM2	2.069	IP2	1.874
IGSCM3	1.971	IP3	1.664
IGSCM4	2.011	IP4	1.720
IGSCM5	2.319	IP5	1.859
IGSCM6	2.021	IP6	1.707
IGSCM7	1.848	IP7	1.853
IGSCM8	2.169	ENP1	1.551
IGSCM9	2.101	ENP2	1.942
IGSCM10	1.869	ENP3	2.017
EGSCM1	1.819	ENP4	1.994
EGSCM2	2.018	ENP5	1.781
EGSCM3	1.939	ENP6	1.933
EGSCM4	2.111	FNP1	1.744
EGSCM5	2.060	FNP2	1.793
EGSCM6	2.271	FNP3	1.733
EGSCM7	2.121	FNP4	1.711
EGSCM8	1.938	FNP5	1.958
EGSCM9	1.760	FNP6	1.621
		FNP7	1.665

TABLE 5 Latent variable correlations.

Variables	EGSCM	ENP	FNP	IGSCM	IP
EGSCM	1.000	0.870	0.894	0.886	0.876
ENP	0.870	1.000	0.891	0.862	0.847
FNP	0.894	0.891	1.000	0.897	0.858
IGSCM	0.886	0.862	0.897	1.000	0.831
IP	0.876	0.847	0.858	0.831	1.000

and Aqdas, 2021). The coefficient of determination (R^2) was used to evaluate and measure the structural model. R^2 values of 0.75 indicate strong, 0.50 indicates moderate and 0.25 indicates the weak effect of the independent variable(s) on the dependent variable (Akter, Fosso Wamba and Dewan, 2017). The variance in the dependent variable due to the independent variable is measured with R^2. Results of R^2 for environmental performance and financial performance are shown in Table 5, and the value =1.000 shows the perfect correlation. Results showed that environmental performance had R^2 = 0.813, whereas Financial Performance had R^2 = 0.878, which indicated that there was a strong effect on environmental performance and financial performance due to GSCM (internal and external) Practices and institutional pressures (see Table 6).

4.7 Hypothesis testing

This study tested the hypotheses using SmartPLS 3. Hypotheses testing and final decision for internal green supply

TABLE 6 R square.

Variables	R square	R square adjusted
ENP	0.813	0.811
FNP	0.878	0.877

TABLE 7 Hypotheses testing results and decision.

Hypothesis	Path/ Relationship	Original sample (O)	Sample mean (M)	Standard deviation (stdev)	T statistics (|O/ STDEV|)	*p* values	Decision
H1	IGSCM - > ENP	0.351	0.351	0.072	4.892	0.000	Supported
H2	EGSCM - > ENP	0.311	0.312	0.077	4.008	0.000	Supported
H3	IGSCM - > FNP	0.433	0.436	0.086	5.060	0.000	Supported
H4	EGSCM - > FNP	0.318	0.323	0.070	4.560	0.000	Supported
H5	IP - > ENP	0.284	0.282	0.072	3.965	0.000	Supported
H6	IP - > FNP	0.219	0.211	0.068	3.207	0.001	Supported
H7	ENP - > FNP	0.296	0.292	0.060	4.918	0.000	Supported

chain management (IGSCM) practices, external green supply chain management (EGSCM) practices, institutional pressures (IP), environmental performance (ENP), and financial performance (FNP) result shows in Table 7.

$\mathbf{H_1}$ results (Internal GSCM Practices - > Environmental Performance) indicated a "Relationship coefficient" (β) = 0.351, "T-statistics" = 4.892 with "*p*-value" = 0.000. So, our H_1 is supported with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, there was a "positive and significant relationship proved between internal GSCM practices and environmental performance". $\mathbf{H_2}$ results (External GSCM Practices - > Environmental Performance) indicated a "Relationship coefficient" (β) = 0.311, "T-statistics" = 4.008 with "*p*-value" = 0.000. So, our H_2 is accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, there was a "positive and significant relationship proved between external GSCM practices and environmental performance". $\mathbf{H_3}$ results (Internal GSCM Practices - > Financial Performance) indicated a "Relationship coefficient" (β) = 0.433, "T-statistics" = 5.060 with "*p*-value" = 0.000. So, our H_3 was accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, there was a "positive and significant relationship proved between internal GSCM and firm's financial performance". $\mathbf{H_4}$ results (External GSCM Practices - > Financial Performance) indicated a "Relationship coefficient" (β) = 3.18, "T-statistics" = 4.560 and "*p*-value" = 0.000. So, our H_4 was accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, there was a "positive and significant relationship proved between external GSCM practices and firm's financial performance". $\mathbf{H_5}$ results (Institutional Pressure - > Environmental Performance) indicated a "Relationship coefficient" (β) = 0.284, "T-statistics" = 3.965 with "*p*-value" = 0.000. So, our H_5 is supported with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, there was a "positive and significant relationship proved between institutional Pressure and environmental performance". $\mathbf{H_6}$ (Institutional Pressure - > Financial Performance) indicated a "Relationship coefficient" (β) = 0.219, "T-statistics" = 3.207 with "*p*-value" = 0.001. So, our H_6 was accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Therefore, a "significant and positive relationship between institutional pressures and firm's financial performance was proved". $\mathbf{H_7}$ results (Environmental Performance - > Financial Performance) indicated a "Relationship coefficient" (β) = 0.296, "T-statistics" = 4.918 and "*p*-value" = 0.000. So, our H_7 was accepted with "T-statistics > 1.96 with *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, there was a "positive and significant relationship proved between firm's environmental performance and firm's financial performance".

4.8 Mediation analysis and results

This study tested the mediation effect of environmental performance using SmartPLS 3. Table 8 shows the results of the mediation analysis and final decision on mediating role of a firm's environmental performance between GSCM (IGSCM and EGSCM) practices, institutional pressure, and the firm's financial performance.

$\mathbf{H_8}$ results (Internal GSCM Practices - > Environmental Performance - > Financial Performance) indicated a "Relationship coefficient" (β) = 0.104, "T-statistics" = 3.640 with "*p*-value" = 0.000. Therefore, our H8 was accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba

TABLE 8 Mediation testing results and decision.

Hypothesis	Path/ Relationship	Original sample (O)	Sample mean (M)	Standard deviation (stdev)	T statistics (|O/ STDEV|)	*p* values	Decision
H8	IGSCM - > ENP - > FNP	0.104	0.102	0.029	3.640	0.000	Supported
H9	EGSCM - > ENP - > FNP	0.092	0.091	0.031	2.993	0.003	Supported
H10	IP - > ENP - > FNP	0.084	0.083	0.028	3.010	0.003	Supported

and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, "environmental performance had a positive mediating role between GSCM (internal practices) and firm's financial performance". H9 results (GSCM External Practices - > Environmental Performance - > Financial Performance) indicated a "Relationship coefficient" (β) = 0.092, "T-statistics" = 2.993 with "*p*-value" = 0.003. So, our $\mathbf{H_9}$ was accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, "environmental performance had a mediating role between external GSCM practices and firm's financial performance". $\mathbf{H_{10}}$ results (Institutional Pressures - > Environmental Performance - > Financial Performance) indicated a "Relationship coefficient" (β) = 0.084, "T-statistics" = 3.010 with "*p*-value" = 0.003. So, our H_{10} was accepted with "T-statistics > 1.96 and *p*-value < 0.05" (Akter, Fosso Wamba and Dewan, 2017), (Akhtar and Soratana, 2021). Hence, "environmental performance had a mediating role between institutional pressures and firm's financial performance".

5 Conclusion

According to the findings of the study, the strong, positive, and statistically significant association between GSCM (IGSCM and EGSCM) practices, institutional pressures, environmental performance, and a firm's financial performance was established. GSCM (IGSCM and EGSCM) practices and institutional pressures had a significant relationship with the environmental as well as with the firm's financial performance (Wei, Ayub and Dagar, 2022). As implementing the GSCM practices there is a visible decline in consumption of natural resources. Consumption of natural resources and energy has a significant effect on environmental performance (Dagar et al., 2022). There was a mediating role of environmental performance in the relationship between GSCM practices, institutional pressure, and financial performance. Moreover, the environmental performance had also a significant positive effect on a firm's financial performance.

The current study has a great contribution to theory and practice. The GSCM-IP-ENP-FNP model was developed with the help of an extensive literature review and then proved with the help of data collected from pesticide chemical firms working in Pakistan. The resource-based view (RBV) theory and institutional theory were used to prove the mediation effect of a firm's environmental performance in the relationship between GSCM (IGSCM and EGSCM) practices, institutional pressures, and financial performance in the pesticide sector of Pakistan (Khan M. T. et al., 2022). These findings would be helpful for the managers of pesticide firms as well as for the government to understand the importance of GSCM practices for improving the environmental as well as the financial performance of pesticide firms in Pakistan as well as worldwide, especially in developing countries. More specific rules and government guidelines are needed for environmental improvement (Choi, Min and Joo, 2018). In terms of application, this research helps pesticide chemical firm executives to better grasp the significance of GSCM practices and institutional pressures in improving environmental and financial performance. The conclusions of this study are important for the government and other stakeholders to keep pressure on pesticide firms and other businesses to adopt GSCM practices.

This study has some limitations also. The study included pesticide chemical firms because Pakistan is an agricultural country and the use of pesticide chemicals is necessary for the improvement of agriculture production (Akhtar and Soratana, 2021). The study included only corporate-level firms having 10 years of firm age and a minimum of 100 employees because small firms do not have enough resources to adopt GSCM practices in their business operations (Geng, Mansouri and Aktas, 2017). The study is limited to GSCM practices, institutional pressures, environmental performance, and financial performance. Government, consumers, media, and other pressure groups have emphases on implementing GSCM practices and improving environmental performance; on the other hand, firms have concerns regarding financial performance (Ullah and Ali, 2022). The quantitative research approach is followed because the quantitative method is suitable for theory testing by examining the relationship among variables of the study (Ming Heng et al., 2018). A quantitative approach is used because it helps collect larger data in a short time. Future research may be conducted using a mixed research methodology including questionnaires as well as in-depth interviews to get further insights.

The current study recommends that GSCM practices (internal and external) should be adopted and implemented by the management of the firms to protect the atmosphere and

improve the environmental and financial performance. GSCM-related practices like energy-efficient use, and minimum fossil fuel consumption can lead to improvement in environmental and financial performance (Ullah and Nadeem, 2022). To eliminate unsustainable activities and improve environmental quality, policymakers are advised to raise public pressure on political leadership (Zhang et al., 2022). Government, consumers, media, and other institutions should exert pressure on pesticide chemical firms and other firms to adopt the GSCM (internal and external) practices for the improvement of environmental performance. Government should also pay attention to facilitating and providing subsidies, if necessary, to the firms for the successful implementation of GSCM practices for environmental protection.

The results may be generalized to the pesticide firms and other firms operating in other countries with similar features. The findings of this study can be applied in developing countries as well as in developed countries. The current study is limited to the variables of the study due to particular emphasis on the mediation effect of environmental performance, whereas financial performance is a major concern of firms. Data collection was also limited to Pakistan only. It is recommended for future researchers to conduct more studies in other countries by focusing on additional variables like technological shift, innovation, and social performance. It is strongly recommended that future studies may be conducted using a mixed methodology. The study concludes that a firm's environmental and financial performances are affected by the GSCM (internal and external) practices as well as by institutional pressures, moreover, environmental performance mediates the relationship between GSCM practices, institutional pressures, and financial performance.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

For this research article, four authors have their contributions. The contributions from authors include "Conceptualization, XM, RA, and AA; methodology, RA and AA; software use, validation, formal analysis, RA, AA, and RH; investigation, resources, data curation, writing—original draft preparation, RA; supervision, project administration, funding acquisition, XM; writing-review and editing, XM, AA, RH, and MS. All authors have read and agreed with the terms to the published version of the manuscript. Authorship is limited to those who have contributed substantially to the work reported."

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Vishal Dagar,
Great Lakes Institute of Management, India

REVIEWED BY
Muhammad Kamran Khan,
Northeast Normal University, China
Muhammad Owais Khan,
University of Agriculture, Peshawar, Pakistan

*CORRESPONDENCE
Qing Lu,
luqingwzvcst@outlook.com,
luqing@wzvcst.edu.cn

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Energy consumption and pollution control from the perspective of industrial economic activity: An empirical study of China's coastal provinces

Qing Lu*

School of Economics and Trade Management, Wenzhou Vocational College of Science and Technology, Wenzhou, China

From the perspective of production performance, energy supply are the basic material conditions. However, greenhouse gas, air pollution and waste water are also produced in the process of production. If the undesired characteristics are ignored in the process of performance evaluation, the production efficiency will be misestimated. Based on this, this study uses Data Envelopment Analysis (DEA) to evaluate the undesired output, and discusses the production efficiency with thermal consumption in Chinese port cities, especially with severe shipping emissions, during 2015–2019. The empirical results show that the efficiency declines first (2015–2017) and then increases (2018–2019) when considering the undesired output of wastewater and SO_2 generated by thermal consumption.

KEYWORDS

pollution, undesired output, energy supply, economic, efficiency

Introduction

Since China's power supply is mainly fossil fuel power generation, since 2014, China has vigorously promoted the implementation of *Ultra-Low Emissions and Energy Conversation Projects* in its coastal power plants in order to effectively reduce environmental pollution (Wang and Li, 2019; Zhang et al., 2021a; Lei Zhang et al., 2022). Stricter standards for energy efficiency and environmental protection have been introduced, and the emission concentration of air pollutants from newly built generating units should basically meet the emission limits for gas turbine units, with the focus on developing clean combustion technologies (Han et al., 2018; Zhang et al., 2021b; Yansong Zhang et al., 2022). For example, the application of pressurized fluidized bed combined cycle (PFBC) power generation technology, integrated coal gasification combined cycle (IGCC) power generation technology and high efficiency ultra-supercritical (USC) coal-fired power generation technology and coupling power generation technology based on

coal generators, etc. (Qian et al., 2021; Wei et al., 2021). And other different types of fuel oil units in service will implement ultra-low emission transformation, such as adding desulfurization, denitration and dust removal devices and other technical means on the original unit to reduce the discharge of industrial pollutants such as wastewater and sulfur dioxide. But some scholars mentioned that thermal production caused by the undesirable output (e.g., shipping emission) in the port city is still prominent (Rezaei et al., 2019; Gregoris et al., 2021; Chen et al., 2022).

Sulfur dioxide and nitrogen oxide emissions from ship fuel burning have been major air pollutants in port cities. The most commonly used marine fuels include light diesel oil, heavy diesel oil, fuel oil and residual fuel oil. Specific include: 0# diesel, −10# diesel, 20# heavy wood, 4# fuel oil, 120# fuel oil, 180# fuel oil, 380# fuel oil (Kondrasheva et al., 2018; Fang et al., 2021; Jing Chen et al., 2021). Depending on the tonnage of the ship (the size and type of engine used), different ships need different marine fuels. In Shanghai, for example, sulfur dioxide and nitrogen oxide emissions from ships accounted for 12.4% and 11.6% of the local total emissions in 2012, while the figures rose to 25.7% and 29.4% in 2015, respectively, according to the Shanghai Environmental Monitoring Center. Data from Hong Kong's Environmental Protection Department showed that in 2016, ships accounted for 49% of sulfur dioxide, 37% of nitrogen oxide, 38% of PM10 and 44% of PM2.5 emissions (Chen et al., 2019; Ma et al., 2022; Yang et al., 2022). Therefore, it is necessary to evaluate the undesirable output of energy consumption in coastal area.

In this study, the power supply is analyzed from the perspective of electricity and heating supply, and an economic model is used to discuss. Different from the previous traditional efficiency model, energy consumption activities in coastal areas are economic behaviors that have both positive impacts on economic production and negative impacts on environmental conservation. If the output value of pollution generated by energy consumption activities is not taken into account in the analysis process, there will be an error in the estimation. Based on the above discussion, this paper therefore studies the situation of energy consumption and environmental pollution in coastal cities. From the perspective of undesired output, this paper discusses the production efficiency of cities in Fujian, Zhejiang and Jiangsu provinces of China. On the basis of estimating output efficiency, Malmquist Productivity Index is further applied to discuss the correlation between output and productivity.

Literature review

Models such as Tobit model, spatial Durbin model, GMM panel estimation and multiple regression analysis are often used to evaluate the impact mechanism of industrial environmental efficiency (Emrouznejad and Yang, 2016; Yang and Li, 2017; Young and Lipták, 2018; Zhang et al., 2020; Sunari Magar et al., 2021). For example, Wang et al. (2019), Hanafiah et al. (2017), Qiu et al. (2022a) used Tobit model to conduct regression analysis and explore the relationship between economic growth, energy consumption and industrial environmental sustainability. Qiu et al. (2022b), Quan et al. (2022), Miao et al. (2020) studies the impact of energy consumption and environmental pollution on technological innovation efficiency of industrial enterprises by using GMM model based on panel data of industrial enterprises in 30 provinces of China. Scholars such as Zhang et al. (2021c), Khan et al. (2019) and Zia et al. (2021) used spatial Durbin model and multiple regression analysis method to study the influence mechanism of industrial transfer and environmental regulation factors on industrial energy and ecological efficiency of provinces in China. Wang and Luo (2022), Cheng et al. (2019) used the prefecture-level data of urban agglomerations in Yangtze River Delta from 2003 to 2016 and the spatial Tobit model to consider the spatial spillover effect. Further regression analysis showed that industrial structure, environmental regulation and innovation level were positively correlated with industrial technology costs. However, foreign direct investment is not conducive to the growth of industrial technology costs (Teng et al., 2021; Wang et al., 2022; Wu et al., 2021). The popularity of these studies leads to more studies on the measurement of industrial environmental efficiency. The research mainly involves the construction of index system and the selection of measure model (Yin et al., 2021; Lirong Yin et al., 2022). Some studies take capital investment and consumption of various resources as input indexes and gross economic output value as output indexes to construct the index system of industrial resource and environmental efficiency (Alvarado et al., 2018). For example, Shahbaz et al. (2021) selects total energy investment and energy resource utilization as input indicators. Scholars such as Zakari et al. (2021) and choose energy consumption, capital and labor input as the input index of industrial sectors, and total industrial output value as the output index of industrial sectors, so as to study the energy efficiency of China's industrial sectors. Importantly, most studies add industrial pollutant emissions as undesired output, making its efficiency measurement more scientific and reasonable. For example, Emrouznejad et al. (2019) analyzed China's manufacturing industry by using carbon emission reduction as an unintended output, so as to maintain the productivity index and reduce carbon emissions at the same time. Han et al. (2021) not only adds industrial waste water and SO_2, but also adds industrial soot and industrial waste emissions as undesired output, so as to calculate the value of China's regional industrial ecological efficiency. However, these current studies generally focus on the overall national situation and rarely make classification judgment for regions, and seldom study the situation of cities with ports as the leading industry. Because in theory, the situation in coastal port cities could be more important because of the presence of high-polluting industries such as shipping.

As for the estimation of industrial resource and environmental efficiency, many scholars currently use ecological footprint method, Stochastic Frontier Analysis (SFA), life cycle method and decoupling model. For example, Cao et al. (2022), Bibi et al. (2022), Chishti et al. (2021), Dagar et al. (2022), Chandel et al. (2022) used the SFA model to explore the energy efficiency of industrial sectors in India north. However, the method of Data Envelopment Analysis (DEA) has increasingly been adopted to measure the efficiency of industrial resources and environment. The early experts and scholars mostly measure the efficiency based on CCR and BCC models. In 1978, Charnes, Cooper and Rhode put forward the first DEA model—CCR model. Then Banker, Charnes and Cooper put forward another basic form of DEA model—BCC model. DEA model does not need any subjective enactment of significant and small cost, nor does it need to set production function in advance, and it can simultaneously measure the efficiency of multiple decision-making units of the same type. Scholars such as Godil et al. (2022), Islam et al. (2021), Zeng et al. (2019), Yang and Zhu (2022) used the traditional CCR-BCC model to calculate the energy efficiency of five Central Asian countries and the Yangtze River Economic Belt respectively. Currently, the improved DEA-SBM model or super-efficiency DEA model and other methods are often used to measure. Muhammad and Khan (2022), Oryani et al. (2021), Oryani et al. (2022), Qin et al. (2021), Rehman et al. (2022), Yufeng Chen et al. (2021) calculates the industrial energy efficiency and industrial environmental efficiency values of 30 provinces and regions in China in different years by constructing the SBM model. Ni Ni Yin et al. (2022) evaluated the industrial energy efficiency of areas along the “Belt and Road” in China by using the SBM model containing unintended outputs. For example, Yang et al. (2020) took undesired outputs in shipping industry into consideration and conducted an empirical analysis of 25 provinces using simple linear programming. In this study, when the linear programming method is used to measure efficiency, the purpose of considering the undesirable output is to get closer to the real efficiency. Moreover, Cecchini et al. (2018), Zakari et al. (2021), Zhang et al. (2021d), Zia et al. (2021), Weimin et al. (2022) used data envelopment analysis (DEA) model to discuss the efficiency including undesired outputs. After the inclusion of undesired outputs, the efficiency value obtained will be lower than the efficiency value estimated in the traditional way, indicating that if the phenomenon of undesired outputs is ignored in the empirical estimation, the efficiency evaluation will be misestimated. Then it affects the judgment of input and production behavior strategy of the object. Gao et al. (2021) measured the green total factor energy efficiency and the effects of urban agglomerations in the Yangtze River Delta. The empirical results show that, under environmental regulation, excessive pollutant emissions led to a decrease in the growth rate of energy and technical efficiency. They believe that the ignorance of the sustainable technology improvement led to the decrease of the growth rate of energy technology progress. And the cumulative growth rate of technical efficiency, GDP, exhaust emissions per unit GDP, and energy consumption have different degrees of influences on energy efficiency. Zhao et al. (2020) used the DEA method and spatial spillover methods to show the infrastructure level and industrial efficiency cities in Pearl River Delta region of China. The results show that regional infrastructure has significant promotion effect and spatial spillover effect on industrial efficiency. However, there are significant differences in the effects of different infrastructures among the three regions. Overall, there are many literatures on environmental efficiency at present but the research on environmental efficiency in coastal areas is relatively rare. In this paper, DEA method is used to reveal the efficiency difference between coastal areas in combination with the practical situation of China’s coastal areas, providing reference for improving the environmental efficiency of China.

Materials and Methods

Data Envelopment Analysis (DEA) mainly constructs a nonparametric broken line surface and boundary from observed data in the way of linear programming. The relative efficiency of each required estimation sample compared with this boundary is calculated accordingly. Traditionally, the observed data are constructed into a nonparametric broken line surface and boundary by linear programming method, and the relative efficiency between samples is compared. In the production activity category, there are I producers, and each producer has n inputs to carry out the production activity and produce the final output M. For the *i*th producer, these output and input data can be represented by vector qi and xi respectively. Where N×I and M×I represent input matrix X and output matrix Q respectively. DEA makes mathematical planning for the comparison of all outputs and inputs of each producer by using the productivity ratio pattern. Therefore, the estimation model is the vector form expressed in the following Eq. 1:

$$\begin{gathered} \max_{\theta,\lambda} u' q_i / v' q_i \\ \text{s.t.} \\ u' q_j / v' q_j \le 1 \\ u, v \ge 0 \\ j = 1, 2, \ldots\ldots\ldots, I \end{gathered} \tag{1}$$

Through linear programming of Eq. 1, all producers are solved to find the most favorable weight for each producer’s input distribution. By introducing Eq. 1 into the dual pattern, the output guiding pattern of Eq. 2 can be obtained:

$$\begin{gathered} \text{Max}_{\theta,\lambda} \theta \\ \text{s.t.} \\ \theta q_j \le Q\lambda \\ \theta x_i \ge X\lambda \\ \lambda \in R^+ \end{gathered} \tag{2}$$

Eq. 2 is the most commonly used type of datagram analysis, where θ is a scalar. λ is a constant vector with dimension $I \times 1$. The θ value obtained is the production efficiency of the i-th producer, and the θ value is between 0 and 1. If it is 1, it represents the point on the boundary. The producer is defined as an efficient operator. According to Eq. 2, the number of samples to be studied (for example, there are I samples) is determined to solve the production efficiency values respectively.

Considering the existence of undesirable outputs in reality, if the estimation equation is still estimated in accordance with Eq. 2, it is possible to misestimate the efficiency result of undesirable outputs. Therefore, we need to distinguish output Q from desired output Q and from undesired output B. In order to distinguish it from λ of Eq. 2, we assume that the constant vector ϑ, the desired output vector O_Q, and the undesired output value O_B are taken into account. Where, $O_Q + O_B = Y$ indicates that the total output is the sum vector of desired output value and undesired output value. Therefore, Eq. 2 is extended to Eq. 3 as follows:

$$\begin{gathered} Max\,Scores \\ \text{s.t}\ X\vartheta + Scoresg_x \le x_k \\ Q\vartheta - ScoresO_Q \ge y_k, \\ B\vartheta - ScoresO_B \ge b_k, \vartheta \ge 0 \end{gathered} \tag{3}$$

Where, the production may be set as:

$$S = \{(x, y) | x \ge X\vartheta, y \le Q\vartheta, b \ge B\vartheta\} \tag{4}$$

Eq. 4 represents that in the case of given desired and undesired output value, the production behavior must weigh the proportion of the two to find the optimal efficiency result. Finally, it can be concluded through linear programming:

$$\begin{gathered} \text{Max}\,\theta \\ \text{s.t.} \\ \theta Q \le Q\vartheta \\ \theta B = B\vartheta \\ x_j \ge X\vartheta \\ \vartheta \in R^+ \end{gathered} \tag{5}$$

Eq. 5 is the relative ratio of efficiency values in each period. When the value is less than 1, it means that productivity increases relative to the previous period; when the value is greater than 1, it means that productivity decreases relative to the previous period. The empirical data in this paper are extracted from the Statistical Yearbook of Chinese Cities regularly published by the Department of Urban Social and Economic Survey of the National Bureau of Statistics from 2015 to 2020, which includes the statistical data of urban construction and other aspects of 656 cities (including prefecture-level and above cities and county-level cities) in China. In the present research, we used the data of 33 coastal cities in Fujian, Zhejiang and Jiangsu provinces revealed by the yearbook from 2015 to 2019. In the selection of variables, the economic activity variables were taken as the output variables of urban GDP (Unit: million RMB), PM2.5 (annual average concentration of fine suspended particulates in 2.5 microns) and sulfur dioxide (Unit: ton), among which PM2.5 and sulfur dioxide were the undesired output. Secondly, employees (Unit: 10,000 people), industrial electricity consumption (Unit: 10,000 KWH) and fixed asset investment (Unit: million RMB, excluding agricultural products) are input variables. In addition, in order to analyze the impact of environmental governance and economic conditions on production efficiency, we also consider urban per capita income and environmental fiscal expenditure. The descriptions of relevant variables are summarized in Table 1.

Results

According to the estimated results of Eqs 2, 3, we can obtain the production efficiency of each city from 2015 to 2019 considering environmental pollution. Table 2 lists the production efficiency values of each province over the years by year and province. Firstly, it can be found that by province, taking into account the undesirable output of PM2.5 and sulfur dioxide generated in industrial heating activities, Jiangsu Province has the highest production efficiency, followed by Fujian Province, and Zhejiang Province has the lowest. For example, from the perspective of annual changes, the production efficiency of all samples showed a trend of decreasing first (2015–2017) and then increasing (2018 and 2019). The empirical results show that with the evolution of time, the production efficiency of China's coastal cities over the years has improved as a whole.

Table 3 collates productivity changes over the years according to Eq. 4. As can be seen from the figure, productivity pointer less than 1 means productivity declines relative to the previous period, while productivity pointer greater than 1 means productivity increases relative to the previous period. It can be found that the productivity indicator showed a downward trend from 2015 to 2017 and an upward trend from 2018 to 2019. The results in Table 3 are consistent with those in Table 2. Such estimation results show that the production performance of industrial economic activities in cities decreases first and then rises, taking into account the output value generated by electric heating supply and pollution problems.

Figure 1 further depicts the changes of each region in Table 3. It can be found that, although Jiangsu province has the best performance in production efficiency on the whole, from the perspective of productivity change, Fujian Province has the best productivity change on the whole, showing an increase since 2017. One possible reason for the downward trend and then upward trend is that China has been vigorously promoting the implementation of ultra-low emission and energy saving renovation projects in domestic power generation since 2014. In our opinion, this reflects that the adjustment of the thermal policy made local industries first face the pain period and the stage of transformation of production mode, and the efficiency declined during 2015–2017. After the completion of the transformation stage, the overall efficiency and productivity gradually improved. This proves that the promotion of policy

TABLE 1 Definition of variables and the descriptive statistics.

Variable	Mean	Std. dev.	Unit
Gross value of production (Desired output value)	27701	2214	10 million RMB
Sulfur dioxide (undesired output value)	126	164	Kiloton
PM2.5	58.453	23.312	CBM cubic meter
Employee	71.694	56.047	10,000
Electric and heating consumption	1096436	11048	Million KWH
Fixed investment	15111	1115	10 million RMB
Per capita	4.101	1438	10,000
Environmental protection expenditure	422.4	2721	10 million RMB

TABLE 2 Production efficiency estimation results.

Category	Mean	Std. dev.
Region		
Zhejiang	0.701	0.782
Jiangsu	0.783	0.689
Fujian	0.725	0.336
Year		
2015	0.737	0.335
2016	0.710	0.314
2017	0.689	0.784
2018	0.705	0.668
2019	0.768	0.441
Total	0.724	0.586

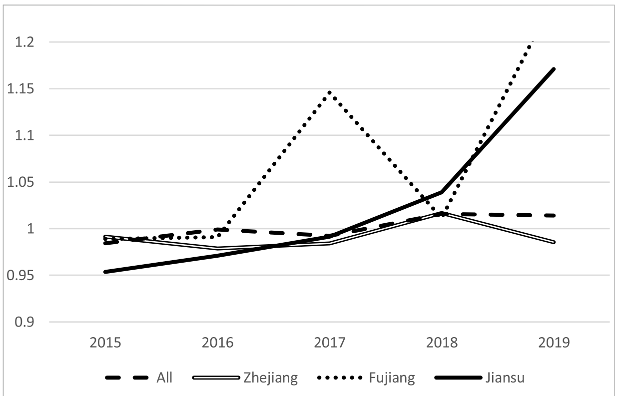

FIGURE 1
Productivity changes over years.

TABLE 3 Productivity changes.

Year	All	Zhejiang	Fujiang	Jiansu
2015	0.9843	0.9914	0.9889	0.9536
2016	0.9992	0.9787	0.9909	0.9711
2017	0.9924	0.9843	1.146	0.9914
2018	1.0157	1.0167	1.0111	1.0388
2019	1.0141	0.9857	1.246	1.171

has improved the efficiency value of production input, and this change has achieved the result of curbing environmental pollution while pursuing production capacity.

Conclusion

Through considering undesired output, this paper explores the production efficiency of 33 Chinese coastal cities dominated by coastal industry and shipbuilding industry from 2014 to 2019 considering the undesired output. Considering the undesired output of air pollution generated in industrial energy consumption activities, Fujian Province has the highest production efficiency, followed by Jiangsu Province, and Zhejiang Province has the lowest. From the perspective of annual change, the production efficiency of coastal cities showed a changing trend of decreasing first (2015–2017) and then increasing (2018–2019), reflecting the thermal production regulation and the input level has reached a certain balance, thus driving the increase of efficiency.

According to the policies of the National Energy Administration of China, the state has formulated a number of supporting policies, such as electricity price, power generation and sewage charge, in order to mobilize the enthusiasm for the renovation of shipping industry and coastal industry. At present, China pays 0.5 cent for electricity and 1 cent for heat for new and active units that achieve ultra-low emission levels. Where the pollutant discharge concentration is more than 50% below the limits set by the State or local authorities, the policy of halving the pollutant discharge fee shall be earnestly implemented. The empirical results show that the efficiency decreases first and then increases, which should be related to the adjustment of China's electric and heating power policy in recent years.

It can be seen that energy-intensive industries are easy to manage and produce quick results, and they can be channeled through policies such as electricity and heating prices. This paper suggests that in the future, the industries such as shipping should continue to take the lead in carrying out ultra-low emission transformation and greatly reduce the emission of air pollutants, which can not only contribute to the control of air pollution, but also explore ways for other energy-intensive industries to implement ultra-low emission transformation in the future, and help promote the cleaner thermal combustion in China. The empirical results of this paper confirm that the policy promotion has improved the efficiency value of economic production input level on the one hand, and on the other hand, the promotion of environmental protection policy has brought positive effects on economic activities and sustainable environmental development under the attempt to improve the air pollution problem. However, it is needed to point out the limitations of this paper. Since this paper focuses on the situation before COVID-19, future follow-up studies may further include comparative studies before and after the epidemic (Emrouznejad and Yang, 2016; Sunari Magar et al., 2021; Yang and Li, 2017; Young and Lipták, 2018; Zhang et al., 2020).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

QL contributed to the study conception and design. Material preparation, data collection, and analysis were performed by QL, and QL commented on previous versions of the manuscript. QL read and approved the final manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Cem Işık,
Anadolu University, Turkey

REVIEWED BY
Xiaodong Yang,
Xinjiang University, China
Yang Shi,
Shandong University of Finance and Economics, China

*CORRESPONDENCE
Mingyue Du,
mydu@st.btbu.edu.cn

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Does environmental regulation develop a greener energy efficiency for environmental sustainability in the post-COVID-19 era: Role of technological innovation

Mingxia Zhang[1] and Mingyue Du[2]*

[1]School of Business, Henan Normal University, Xin Xiang, China, [2]School of Economics, Beijing Technology and Business University, Beijing, China

Improving green energy efficiency (GEE) and promoting green economic transformation are important goals for China to achieve sustainable economic development in the post-COVID-19 era. Based on panel data of 27 manufacturing industries in China, this paper uses GMM model and threshold model to study the impact of environmental regulation and technological innovation on green energy efficiency. Our findings show that technological innovation promotes green energy efficiency in both pollution-intensive and clean industries, and its promotion effect is more pronounced in pollution-intensive industries. Environmental regulation not only directly improves the green energy efficiency of polluting industries and clean industries, but also plays a positive intermediary role between technology and green energy efficiency. The impact of technological innovation on GEE has a threshold effect of environmental regulation. When environmental regulation did not cross the threshold, technological innovation does not significantly promote GEE. The promotion effect of technological innovation on GEE will increase with the strengthening of environmental supervision. Therefore, the government should formulate reasonable environmental regulations according to the industry heterogeneity to vigorously promote the green energy efficiency of the manufacturing industry.

KEYWORDS

environmental regulation, technological innovation, green energy efficiency, China, environmental sustainability

1 Introduction

Since the 21st century, environmental problems such as environmental pollution, energy shortage and greenhouse effect have not only hindered the sustainable development of the world economy, but also run counter to the public's demands for healthy living conditions (Ahmad et al., 2021a; Akram et al., 2021; Rehman et al., 2021).

The excessive exploitation and wanton destruction of natural resources by human beings have exceeded the carrying capacity of the earth, making the economy and society face severe resource and environmental bottleneck constraints (Rees, 2017; Irfan et al., 2021; Khan et al., 2021). To solve the irreversible negative externalities caused by human economic activities to the environment, the 178 parties in world signed the "Paris Agreement" that pledged to limit the rise in average global temperatures to less than 2°C (Ari and Sari, 2017; Vandyck et al., 2018). However, the 26th United Nations Climate Change Conference (COP26) stated that even if current carbon reduction commitments are fully realized, global temperatures could rise by 2.2°C by the end of the century. How to transform from the traditional development model to green development and achieve a win-win situation between economic development and environmental protection has become an important problem that countries around the world need to solve urgently (Ahmad et al., 2021b; Isik et al., 2021). How to transform from the traditional development model to green development and achieve carbon peaking and carbon neutrality goals has become an important action that countries around the world urgently need to solve in the post-COVID-19 era (Zhou et al., 2022).

Manufacturing is the foundation of economic development and the backbone of industrialization (Fu et al., 2021). However, the economic growth mode that relies on energy input has brought a serious "ecological deficit" to China, which has caused China to face great constraints on resources and the environment (Wang A. et al., 2021; Yang et al., 2021b). The development of manufacturing is the main source of environmental pollution and resource consumption. Authoritative data show the ratio of manufacturing energy consumption to China's total energy consumption is 70%, while the industrial added value accounted for only 31.9%% of the national GDP. Therefore, the manufacturing industry needs to transform from extensive development to green and intensive development with low energy consumption and high green energy efficiency (Liu et al., 2018).

Technological innovation reduces environmental pollution, and realizes the recycling of raw materials and wastes (Chen and Lei, 2018; Ren et al., 2021; Ulucak, 2021). In particular, green technology is expected to be a dominant factor that can theoretically contribute to over 60% of targeted carbon emission reduction (IEA, 2013). Green technology innovation not only improves enterprises' productivity and competitiveness, but also benefits environmental protection (Wang M. et al., 2021); Cao et al., 2021). Existing studies have shown that environmental regulation is an important driving force for technological innovation (Cai et al., 2020; Shao et al., 2020; Mbanyele and Wang, 2022). Moreover, environmental regulation is an effective way to improve energy efficiency and actively develop renewable energy. To achieve pollution control and ecological protection, China has promulgated many environmental protection laws since 1979, including the "Energy Conservation Law", "Air Pollution Prevention and Control Law" and "Environmental Protection Law". It can directly affect the configuration of factors in the production process, and affect energy efficiency by affecting the production cost of enterprises (Georg et al., 1992). However, there are different research views on whether environmental regulation can effectively improve green energy efficiency. On the one hand, environmental regulation can force enterprises to upgrade sewage equipment and improve energy efficiency by raising the entry threshold for polluting industries and levying high pollution taxes (Li et al., 2020). Moreover, environmental regulation accelerates factor flow of resources from low-productivity firms to high-productivity firms, which is conducive to promote industrial transformation and the efficiency of economic growth (Ouyang et al., 2020). On the other hand, some scholars oppose the government's environmental policy, and suggest that strict environmental regulation can promote technological research and development, but the cost of regulation far exceeds the effect of innovation (Lanoie et al., 2011). Controlling pollution emissions may crowd out corporate technology research and development funds, which means that the positive relationship between environmental regulation and technology research and development does not hold (Chintrakarn, 2008). Because these two effects work in opposite directions, which effect is dominant will determine the final impact of environmental regulation on GEE (Wang A. et al., 2021). However, due to the difficulty in designing statistical indicators, few studies have examined the correlation between technological innovation and GEE from the perspective of environmental regulation.

To identify heterogeneous effects of environmental regulation on energy efficiency. Our research divides manufacturing into pollution-intensive and clean industries, and studys the impact of environmental regulation on green energy efficiency different industries. Furthermore, we discuss the role of technological innovation between environmental regulation and GEE, and calculate the optimal range of environmental regulation intensity for mobilizing the enthusiasm of enterprises to innovate. Compared with existing research, the main contributions of our study are as follows. First, the relationship between technological innovation and GEE is rarely covered by previous literature. Therefore, we incorporate the three into the same model to discuss the impact of corporate n technological innovation on GEE heterogeneity from the perspective of environmental regulation. Second, from the research methods, the systematic GMM method is applied to perform benchmark model regression in order to effectively overcome the endogeneity problem caused by the existence of bidirectional causal relationships between variables. Besides, with environmental regulation as the threshold variable, we construct a threshold model to investigate the threshold effect and influence mechanism of environmental constraints in the

impact of technological innovation on GEE. Third, although the assumption of homogeneous industries has been frequently emphasized in previous studies, there are significant differences in resource consumption and pollution emissions among different industries. It means that the implementation of unified regulatory policies may adversely affect the development of the industry. Therefore, in our study, manufacturing is divided into pollution-intensive industries and cleaning industries. Our research findings can provide important references for governments to formulate differentiated regulatory policies.

The rest of the article is organized as follows: Section 2 reviews the relevant literature. Section 3 is the model and data. Section 4 is mainly about empirical results and discussion. The conclusion is in the final section.

2 Literature review

2.1 Environmental regulation and technological innovation

Environmental regulation refers to the environmental management and control measures introduced by the government to reduce pollution emissions (Tietenberg, 1990). Generally, its main regulatory tools roughly include executive order regulation, market regulation and voluntary regulation (Wu et al., 2020). Command-type market regulation mainly uses direct administrative means to prevent and control corporate emissions, including pollutant discharge standards and restrictions on pollutant discharge concentrations (Zhang and Ke, 2015). Market-based regulation mainly motivates enterprises to increase pollution discharge equipment and green technology research and development through collection of pollution discharge fees, subsidies for environmental protection technology innovation, and issuance of pollution discharge licenses (Fowlie et al., 2016). The measurement methods of environmental regulation can be roughly divided into four types: 1) cost indicators. It includes environmental taxes and sewage charges (Kim, 2010). 2) Input indicators: fiscal expenditure on environmental protection, investment in pollution control (Naso et al., 2017). 3) Performance indicators. It indirectly reflects the results of environmental regulation through the effectiveness of environmental governance, including carbon emissions per unit of industrial output, pollution emissions, and the number of pollution inspections published by the media (Alpay et al., 2010). 4) Comprehensive indicators. It usually covers multiple environmental indicators and is widely used by scholars (Walter and Ugelow, 1979). In the face of unprecedented difficulties in global environmental governance, many scholars have done some research on the relationship between environmental regulation and technological innovation, but the conclusions are inconsistent and divergent. First, traditional economic theories suggest that the contradiction between ecological protection and economic growth is insurmountable. Therefore, the strict environmental laws introduced by the government improve the quality of the ecological environment, but bring adverse effects on enterprises (Millimet and Roy, 2016). Environmental regulation increases the cost of pollution control compliance for enterprises. Enterprises usually reduce the investment in research and development to purchase green sewage equipment. The "crowding-out effect" caused by environmental regulation not only reduces the productivity of enterprises but also reduces the technological innovation of enterprises. In addition, many scholars have pointed out that environmental regulation may adversely affect the development of enterprises in the short term, but in the long run, environmental regulation will bring "innovation compensation effect" to enterprises (Li et al., 2021). Appropriate environmental regulation can motivate enterprises to optimize resource allocation and stimulate the innovation compensation effect of enterprises (Shapiro and Walker, 2018). In addition, some scholars have conducted a comprehensive study of the above two viewpoints, arguing that the impact of environmental regulation on technological innovation is uncertain. It depends on the strength of the two effects of "compliance cost" and "innovation compensation" (Shen et al., 2019).

2.2 Technological innovation and energy efficiency

With the increasingly serious problem of energy shortage, the government and scholars pay more and more attention to the research of energy efficiency, and derived various energy efficiency measurement methods. Single factor energy efficiency is generally measured by energy intensity (Cheng et al., 2020; Wang and Ma, 2022). It is usually measured by energy consumption per unit of output (Zhang et al., 2011). Based on the theory of total factor productivity, green total factor energy efficiency considers the substitution effect between energy and production factors, which is more in line with the actual production process (Lee and Lee, 2022). Green energy efficiency can be measured by parametric method (Stochastic Frontier Method (SFA)) and nonparametric method (Data Envelope Method (DEA)) (Yao et al., 2021). Compared with SAF, DEA method is widely used because it does not require more subjective assumptions (Liu and Xin, 2019). Moreover, it can measure the factor utilization efficiency of multiple inputs and multiple outputs (Xie et al., 2021). With the global extreme climate change and ecological destruction, scholars have begun to consider environmental effects in calculating energy efficiency, that is, green energy efficiency (Ren et al., 2022). Technological innovation is the main source of technological progress, and it affects energy efficiency by promoting technological progress. Whether technological innovation can

significantly promote the improvement of energy efficiency depends on the bias of technological progress. In the research of technological innovation, Solow (1957) constructed an exogenous economic growth model with technological progress as an exogenous variable. It is found that technological progress can promote the increase of per capita output. Once the economy reaches a steady state, the rate of technological progress is the only factor that determines the growth of per capita output. Arrow (1971) studied the technology spillover effect from the perspective of externality, and believed that due to the existence of learning effect, low-tech enterprises can obtain the technology spillover of those R&D enterprises with advanced technology through imitation and learning. Romer (1986) suggests that technology is not an exogenous variable, but an endogenous one. In the long-term growth model, technology is considered as the same input factor as labor and capital, and the marginal productivity of technology is increasing. Therefore, technological progress can promote the increase of productivity. Whether technological innovation can significantly promote the improvement of energy efficiency depends on the technological progress bias (Chen and Liu, 2021). Therefore, if technological innovation promotes energy-biased technological progress, it can effectively reduce energy consumption and significantly improve energy efficiency when output and non-energy factors remain unchanged (Liao and Ren, 2020). However, if technological innovation promotes energy-consuming technological progress, it will reduce the relative marginal productivity of the energy factor. Further, it may cause the substitution of energy factors for non-energy factors and increase the input share of energy factors, which may lead to a decrease in energy efficiency.

3 Methodology and data

3.1 Econometric models

3.1.1 Basic model

To investigate the effect of environmental regulation (ER) on GEE, the base panel econometric model is conducted as follows:

$$GEE_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_k X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{1}$$

GEE_{it} is the green energy efficiency of manufacturing; ER_{it} is the environmental regulation. X represents a series of control variables, including capital structure, sales value, energy consumption structure, import size, export competitiveness. α_0 is the constant term. α_1 is the main parameter to be estimated. μ_i and υ_t are the industry and year fixed effects. ε_{it} is the random disturbance term. For the heteroscedasticity and collinearity of the control model, all metrics are logarithmic.

As economic theory and reality show, green energy efficiency is cumulative and dynamic. That is, current green energy efficiency may be affected by previous efficiency changes. Therefore, we include a lagged one-period term of green energy efficiency (GEE_{it-1}) in the model to eliminate the path dependence of the variables. The dynamic panel model is set as follows.

$$GEE_{it} = \alpha_0 + \alpha_1 GEE_{it-1} + \alpha_2 ER_{it} + \alpha_3 X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{2}$$

3.1.2 Mediation effect model

The mediating effect model can study the process and mechanism of the influence of independent variables on dependent variables. Compared with studies that only examine the influence of independent variables on dependent variables, the study of mediation variables can not only explain the mechanism behind the relationship, but also integrate existing theories, which has significant theoretical and practical significance. To verify the transmission mechanisms of ER impacts on energy efficiency, the mediation effect model is constructed according to the stepwise regression method proposed by Baron and Kenny (1986).

$$TI_{it} = \beta_0 + \beta_1 ER_{i,t-1} + \beta_k X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{3}$$

$$GEE_{it} = \gamma_0 + \gamma_1 GEE_{i,t-1} + \gamma_2 TI_{it} + \gamma_3 ER_{it} + \gamma_k X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{4}$$

The Eq. 3 estimates the impact of ER on the mediation variable (*technological innovation*). Eq. 4 is used to further examine the impact of technological innovation and ER on the green energy efficiency. The meanings of the relevant variables and parameters are consistent with Eqs 1, 2.

3.1.3 Threshold panel model

The effect of technological innovation on energy efficiency may be affected by the intensity of environmental regulation. That is, differences in the intensity of ER may lead to a threshold effect on the impact of technological innovation on GEE. To further test the non-linear relationship between ER, technological innovation and GEE, the dynamic threshold model is used to study the threshold mechanism.

$$GEE_{it} = \beta_0 + \beta_1 TI_{it} \bullet I(q_{it} \le \gamma) + \beta_2 TI_{it} \bullet I(q_{it} > \gamma) + \beta_3 X_{it} + \lambda_i + \varepsilon_{it} \tag{5}$$

Among them, q_{it} is the threshold variable (environmental regulation). γ is the threshold value.

3.2 Variables selected

1) Environmental Regulation. Existing studies often measure environmental regulation by the ratio of the sum of waste gas and wastewater treatment costs to the main business income. However, it cannot truly reflect the pollution burden at

current pollution levels. Therefore, referring to the method of Wang A. et al. (2021), the indicators constructed in this article are as follows:

$$pcc = \sum_{i=1}^{2} \frac{\cos_i}{emi_i} \frac{fac_i}{fac_1 + fac_2}$$

Among them, cos_1 and cos_2 represent the industry wastewater treatment costs and waste gas treatment costs, and respectively. emi_1 and emi_2 represent waste water discharge and exhaust gas discharge. fac_1 and fac_2 are wastewater treatment facilities and waste gas treatment facilities.

2) Technological innovation. Previous studies have frequently used patent grants to measure technological innovation. However, patent licensing can be influenced by political factors. Also, patents are often applied to production processes before they are officially granted. Therefore, the patent applications are stable and timely than the number of patent grants, and can better reflect the real level of innovation. Referring to the research of Liu et al. (2020), we use the number of industrial invention patent applications to measure technological innovation.
3) Green energy efficiency. Accurately measuring the GEE is an important basis for the following empirical research (Yang et al., 2021a). The "data envelopment analysis" (DEA) can evaluate the efficiency of multiple decision-making units with multiple inputs and multiple outputs. However, in actual production process, inputting production factors (labor, capital, and energy) produce industrial products, as well as undesired outputs. Compared with the traditional DEA, the EBM-DDF model is a developed method with the advantages of combining radial and non-radial, which can capture green energy efficiency information more accurately. Hence, to effectively avoid the shortcomings of the CCR model and the SBM model, the directional distance function (DDF) is defined based on the EBM model proposed by Tone and Tsutsui (2010). Suppose there are n decision-making units (j = 1, ⋯, n) with m kinds of inputs and s kinds of outputs, the EBM model is constructed as follows:

$$\gamma^* = min\theta - \epsilon_x \sum_{i=1}^{m} \frac{W_i S_i}{X_{i0}}$$

$$s.t. \begin{cases} \theta_{X_0} - X\lambda - s = 0 \\ \lambda Y \geq 0 \\ \lambda \geq 0 \\ 0 \leq \gamma^* \leq 1 \\ s \geq 0 \end{cases}$$

In the model, γ* is the optimal efficiency value, which satisfies $0 \leq \gamma^* \leq 1$, W_i is the weight of the input element i and satisfies $\sum_{i=1}^{m} W_i = 1$ $(W_i \geq 0)$, θ is the radial efficiency value, and S_i is the slack variable of the input element i, ϵ_x is a parameter of composite radial θ and non-radial slack variables, and λ is the relative importance of the reference decision-making unit. $X = \{x_{ij}\} \in R^{m\times n}$ is the input vector, $Y = \{x_{ij}\} \in R^{s\times n}$ is the output vector, and X > 0, Y > 0. We introduce the GML index based on the EBM model to measure the GEE. The expression of GML index is:

$$GML^G(X^t, Y^t, B^t, X^{t+1}, Y^{t+1}, B^{t+1}) = \frac{1 + \vec{D}^G_{EBM}(X^t, Y^t, B^t)}{1 + \vec{D}^G_{EBM}(X^{t+1}, Y^{t+1}, B^{t+1})}$$

Where, B^t and B^{t+1} represent the undesired output of the decision-making unit in period t and t + 1, respectively. We define the global production possibility set (PPS) as: $PPS^G_D = conv\{PPS^1_D, PPS^2_D, \ldots, PPS^T_D\}$, and the directional distance function. $\vec{D}^G_{EBM}(X^t, Y^t, B^t) = max\{\beta: (Y^t + \beta Y^t, B - \beta B) \in PPS^G_D\}$

The input variables include capital stock (k), labor (L) and energy consumption (E); desirable outputs variable is industrial sales output value; undesirable output variables include chemical oxygen demand (COD), SO_2 emissions, CO_2 emissions, solid waste emissions. The variable measurement method is shown in Table 1.

4) Control variables. Some control variables were introduced into the model to reduce the error in the results. The capital structure is expressed by the ratio of foreign investment in various industries to paid-in capital (Wang et al., 2018). The energy consumption structure is expressed by the ratio of coal consumption to total energy consumption. We use manufacturing sales output value to measure the operation of enterprises. The level of imports is expressed as the ratio of the value of sub-industry imports to the value of industrial sales. The trade export is expressed by the ratio of the industry's total export value to the industry's total output value. We reclassify the manufacturing industry according to the National Economic Industry Classification (2011) promulgated by the National Bureau of Statistics. Since the statistical caliber is different from the past, in order to maintain the authenticity of the data as much as possible, we have consolidated the sub-categories of some manufacturing sectors. Specifically, we merged the rubber and plastic products industry prior to 2012 into the rubber and plastic products industry. After 2012, the automobile industry and transportation equipment such as railways and ships are merged into the transportation equipment manufacturing industry. Considering the availability of data, we excluded the metal products industry and equipment repair industry, and the comprehensive utilization of waste resources. Finally, we sorted out 27 two-digit coding manufacturing industries (GB/T4754-2011). The statistical results of all variables are shown in Table 2.

4 Results and analysis

4.1 Benchmark model

OLS, FE and RE regression equations were adopted to examine the impact of technological innovation and green

TABLE 1 China's green total factor energy efficiency.

Attribute layer	First-class index level	Method and data source
Input variable	Capital stock (K)	The perpetual inventory method
	labor (L)	The annual average number of employees in industrial firms above designated size
	Energy consumption (E)	The total energy consumption of industrial firms above designated size
Desirable outputs	Industrial sales output value	Considering the availability of data, industrial sales output value is used as a substitute variable for expected output
Undesirable output	Chemical oxygen demand (COD)	—
	SO_2 emissions (SO_2)	—
	Carbon emission (CO_2)	Carbon emissions are estimated using 8 commonly used energy consumption and their carbon emission coefficients, carbon oxidation factors and calorific value
	Solid waste emissions	—

TABLE 2 The statistical description of variables.

Variable	Definition	Obs	Mean	Std. Dev.	Min	Max
GEE	Green energy efficiency	351	0.8741	0.2577	0.4011	2.0264
ER	Environmental regulation	351	15.5953	19.5905	0.2159	113.3026
CS	Capital Structure	351	0.2863	0.1529	0.0005	0.7638
ECS	Energy consumption structure	351	0.4576	0.2215	0.0672	0.8566
TI	Technological innovation	351	212.4502	137.9494	22.7476	774.1671
IM	Trade import	351	0.1286	0.2516	0.0009	1.9850
EX	Trade export	351	0.2387	0.3193	0.0046	1.6387
SS	Sales scale	351	19263.01	18112.45	1079.377	86308.14

energy efficiency. Besides, considering the variable endogeneity, we also introduce the hysteresis of green technology innovation, and adopt the GMM method to estimate Eq. 1. The p-values of AR 2) and Hansen report that the second-order serial correlation of the model does not hold, and instrumental variables are appropriate. Table 3 reflects that technological innovation can increase GEE, and this result is consistent with the findings of Sun et al. (2021). The development of green energy is an inevitable choice for energy transformation. It plays an important role in reducing the pressure of energy shortage, effectively solving environmental problems and improving energy consumption structure. Particularly, promoting technological innovation in energy conservation and emission reduction is an important way to achieve clean and low-carbon development of energy (Hanley et al., 2009). In the long run, technological innovation can not only continuously improve the competitiveness and economic benefits of energy production, but also promote the transformation and upgrading of enterprises to a certain extent, which provides new momentum for the improvement of energy ecological efficiency. Technological innovation improves energy efficiency from three aspects. First, from the perspective of energy production structure, with the continuous breakthrough of energy exploration and exploitation and equipment technology, the backward production capacity of coal power will be gradually eliminated, and the production of clean energy will continue to increase. Second, technological innovation can directly improve energy efficiency. Technological innovation investment (R&D funding and scientific research personnel) accelerates technology diffusion and improves energy efficiency. Finally, technological innovation can improve the level of industrialization, adjust the industrial structure and optimize the energy structure (Wang L. et al., 2021). Specifically, in the process of energy production, enterprises improve overall energy efficiency by introducing advanced technologies and high-efficiency equipment in the energy industry to reduce energy consumption in the production process and reduce energy intensity. In addition, technological innovation improves energy efficiency by optimizing the industrial structure and changing the structure of energy production and consumption. Our research also found that compared to the cleaning industry, the impact of technological innovation on energy efficiency is greater in highly polluting industries.

TABLE 3 Basic results.

Variables	RE	FE	GMM	Cleaning industry	Polluting industry
LNGI	0.0755***	0.0736***	0.0407***	0.0450***	0.1763**
	(3.40)	(3.01)	(6.70)	(6.57)	(2.36)
LNSV	−0.1406***	−0.1026***	−0.1070***	−0.1417***	−0.3689***
	(−8.69)	(−3.87)	(−15.01)	(−5.79)	(−4.17)
LNES	0.0907***	0.1283***	−0.2175***	−0.0594***	0.2301
	(3.14)	(4.14)	(−11.06)	(−2.69)	(1.43)
LNEXP	0.0426	0.1146***	−0.1290***	−0.1058***	0.1972***
	(1.64)	(3.05)	(−7.24)	(−2.97)	(3.45)
LNIMP	−0.0565***	−0.0574***	0.0246**	0.0088	0.0613
	(−3.12)	(−2.60)	(1.98)	(0.72)	(1.27)
LNSS	0.0152	0.0098	0.0151	0.0197	0.0333
	(0.61)	(0.32)	(0.95)	(0.42)	(0.40)
L.GEE			0.7430***	0.3834***	
			(32.83)	(3.34)	
_CONS	1.8358***	1.6689***	0.6240***	1.3953***	4.0073***
	(9.68)	(7.16)	(8.33)	(4.95)	(4.36)
R^2	0.4597	0.4668		0.4363	0.5908
AR(2)/p-value			1.20/[0.229]		
Hansen test/p-value			25.27/[0.613]		
F/Wald test			6343.40***		
N	351	351	351	234	117

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; t or z statistics in (); p value in [].

4.2 Environmental regulation and GEE

Table 4 presents the estimated results of the impact of environmental regulation (ER) on energy efficiency. Columns (1) and (2) are the results of the OLS and FE econometric models, respectively. We find that the estimated coefficient of the direct impact of ER on green energy efficiency is significantly negative at the 1% level, indicating that ER can improve energy efficiency and play an innovative compensation effect. This result is consistent with Lin and Xu (2017), and Mandal (2010), but different from the research findings of Wu et al. (2020), who proposed there is a "U" relationship between environmental regulation and energy efficiency. To deal with the path dependence of energy efficiency, we employ the system generalized method of moments (SYS-GMM) to estimate a dynamic panel metering model. According to the SYS-GMM regression results in column (3), the coefficient of the lag term in the first period is significantly positive at the level of 1%, reflecting that energy efficiency is affected by the previous period. The results of Hansen's test and AR (2) test accept the null hypothesis at the 10% significance level, indicating that all instrumental variables used in this paper are valid and that the second-order serial correlation is not satisfied in the error term. The estimated coefficient of ER on energy efficiency is 0.0135, which is statistically significant at the 1% level. It is consistent with the results of static panel regression. The impact of ER on green energy efficiency is also a hot topic in academic discussions. From the perspective of the long-term dynamic process, appropriate environmental regulation can encourage enterprises to carry out technological innovation, improve the production technology and production methods of polluting enterprises, and thus improve the technical level and production efficiency. Although the cost of technological improvement and pollution control has increased in the process of environmental control, the lagging "innovation compensation effect" can offset the "compliance cost" of enterprises. Therefore, environmental regulation can achieve the purpose of improving environmental quality, increasing output and improving energy efficiency through efficiency improvement and technological progress.

4.3 Mediation effect results

The above regression results show that the positive impact of environmental regulation (ER) on energy efficiency has been demonstrated, but its indirect impact mechanism needs further examination. According to the constructed mediation effect model, we study the transmission mechanism of ER on green

TABLE 4 Basic results.

Variables	OLS	FE	GMM	Cleaning industry	Polluting industry
LNER	0.0373***	0.0394***	0.0103***	0.0013	−0.0646**
	(4.21)	(3.93)	(5.61)	(0.54)	(−2.14)
LNSV	−0.1718***	−0.1707***	−0.0759***	−0.0788***	−0.2276**
	(−16.81)	(−12.72)	(−13.60)	(−3.69)	(−2.56)
LNES	−0.1365***	-0.1421***	−0.1479***	-0.0967***	0.4714***
	(−5.62)	(−5.66)	(−7.40)	(−5.30)	(2.82)
LNEXP	−0.0742***	−0.0737***	−0.0927***	−0.03667	0.2017***
	(−5.78)	(−5.56)	(-8.76)	(−1.37)	(3.21)
LNIMP	−0.0185*	−0.0194*	0.01782*	−0.03557***	−0.00287
	(−1.75)	(−1.71)	(1.79)	(−4.95)	(−0.06)
LNSS	0.0488***	0.0478***	0.0260***	0.0423*	0.2517***
	(3.71)	(3.53)	(2.86)	(1.90)	(3.39)
_CONS	2.1447***	2.1074***	0.6308***	0.8179***	−37.3463
	(20.78)	(17.01)	(8.96)	(3.13)	(−1.53)
L.GEE			0.7704***	0.6221***	
			21.37	5.58	
R^2	0.4920	0.4983			0.8889
AR(2)/p-value			0.96/[0.336]		
Hansen test/p-value			23.48/[1.000]		
F/Wald test			1642.61***	11545.51***	
N	351	351	351	234	117

Note: $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$; t or z statistics in ().

energy efficiency from the perspective of technological innovation. The results are reported in Table 6. Columns (1) and (2) in Table 5 report the estimated results of technological innovation as a mediating variable. The results in column (1) show that ER can significantly improve energy efficiency (0.010). The estimation results in column (2) show that the estimated effect of ER on technological innovation is positive and statistically significant (0.076), and column (3) reports the estimated effect of ER and technological innovation on energy efficiency. We found that technological innovation still had a positive impact on energy efficiency at the 1% level. Therefore, it can be concluded that ER can increase green energy efficiency, and its increased benefit can be attributed to the improvement of technological innovation capacity. The mediating effect of technology level is mainly manifested in three aspects. 1) Improving the intensity of environmental regulation will increase the production cost of enterprises in a short period of time. Environmental regulation forces enterprises to purchase more advanced sewage equipment and machines and introduce foreign green production processes, which is conducive to the improvement of energy efficiency. 2) The government's strict environmental regulation will accelerate the technological innovation of enterprises, improve the efficiency of resource allocation, and improve the internal structure of enterprises. It reduces the amount of pollutants and promotes the improvement of productivity and energy efficiency. 3) With the gradual advancement of technology, industrial enterprises can use energy more efficiently and reduce energy demand. Further, the decline in energy demand will also reduce energy prices, which encourages energy companies to carry out a new round of technological innovation. Therefore, the promotion effect of environmental regulation on energy efficiency is mainly realized by improving the technical level.

4.4 Threshold effect

Previous studies have shown China has a huge regional and regional dimension in environmental governance. Therefore, the increase effect of the environmental regulation on energy efficiency may show a nonlinear relationship. To verify the potential nonlinear effects between technological innovation and energy efficiency, this paper extends the procedure of Hansen (1999) and uses Wald's test for self-sampling (Bootstrap) to detect threshold effects. According to the existence test of threshold effect, different levels of ER are used as threshold variables for self-sampling. After 300 self-sampling results, the impact of environmental regulation presents nonlinear threshold characteristics.

TABLE 5 Mediation effect results.

Variables	GEE	GI	GEE
L.DEP	0.770***	0.532***	0.886***
	(21.375)	(79.938)	(27.029)
GI			0.065***
			(12.382)
LNER	0.010***	0.076***	−0.008***
	(5.613)	(9.256)	(−2.700)
LNSV	−0.076***	0.008	−0.044***
	(−13.605)	(0.438)	(−5.629)
LNES	−0.148***	−0.181***	−0.068***
	(−7.402)	(−7.021)	(−6.419)
LNEXP	−0.093***	−0.183***	−0.066***
	(−8.763)	(−3.776)	(−4.931)
LNIMP	0.018*	0.174***	−0.001
	(1.790)	(7.273)	(−0.143)
LNSS	0.026***	−0.021	0.024**
	(2.856)	(−0.662)	(2.299)
_CONS	0.631***	2.061***	−0.005
	(8.962)	(10.979)	(−0.049)
AR(2)/p-value	0.96/[0.336]	−1.91/[0.056]	1.24/[0.216]
Hansen test/p-value	23.48/[1.000]	26.90/[0.415]	25.14/[0.865]
F/Wald test	1642.61***	60227.47***	67566.13***
N	351	351	351

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; t or z statistics in ().

Further, we employ a robust standard deviation test to estimate a panel threshold model to overcome the undesired effect of heteroskedasticity. The corresponding estimation results are shown in Table 6. Based on the estimation results of model (1), it is found that the coefficients of each interval of technological innovation variables under the threshold model are significantly negative, indicating that there is a significant dynamic nonlinear relationship between technological innovation and green energy efficiency. From the threshold test results, when the ER value is lower than 3.465, the estimated coefficient of green finance is 0.1324, but not significant, indicating that it is necessary to show that the government appropriately strengthens environmental regulation. If the regulatory intensity is relatively relaxed, it will not be enough to form effective incentives for green innovation, and even increase investment in pollution control, thereby crowding out R&D investment. When the value of the ER index exceeds 3.465, the coefficient of technological innovation increases to 0.1550 and is significant, indicating that the efficiency improvement effect of technological innovation still exists, and the promotion intensity has increased. It is not difficult to find that as the intensity of environmental regulation increases, the efficiency improvement effect of technological innovation shows a significant positive nonlinear characteristic.

TABLE 6 Threshold regression results.

Variables	Coef.	Std. Err.	t	P>|t|	95% Conf. Interval
LNSV	0.2593	0.0395	6.57	0.000	[0.1816, 0.3370]
LNES	−0.1831	0.0455	−4.02	0.207	[−0.2726, −0.0935]
LNEXP	−0.0365	0.0551	−0.66	0.508	[−0.1450, 0.0719]
LNIMP	0.0744	0.0323	2.30	0.022	[0.0108, 0.1380]
LNSS	−0.0524	0.0449	−1.17	0.244	[−0.1408, 0.0359]
_CONS	−0.6002	0.3419	−1.76	0.080	[−1.2729, 0.0725]
GI_1	0.0765	0.0544	1.41	0.159	[−0.0230, 0.1831]
GI_2	0.1550	0.0358	4.33	0.000	[0.0846, 0.2254]
R^2	0.6043	Sigma_u	0.2250		
F value	69.17***	Sigma_e	0.1602		

5 Conclusion and recommendations

Based on panel data of 27 manufacturing industries in China, this paper uses GMM model and threshold model to study the impact of environmental regulation and technological innovation on green energy efficiency. Our findings show that technological innovation promotes green energy efficiency in both pollution-intensive and clean industries, and its promotion effect is more pronounced in pollution-intensive industries. Environmental regulation not only directly improves the green energy efficiency of polluting industries and clean industries, but also plays a positive intermediary role between technology and green energy efficiency. The impact of technological innovation on GEE has a threshold effect of environmental regulation. The promotion effect of technological innovation on GEE will increase with the strengthening of environmental supervision. Therefore, the government should formulate reasonable environmental regulations according to the industry heterogeneity to vigorously promote the green energy efficiency of the manufacturing industry.

For different industries, the government needs to formulate differentiated environmental regulation policies. For pollution-intensive industries, the government needs to relax environmental regulations and policies to avoid occupying the production, operation and R&D funds of enterprises. When formulating high-intensity environmental regulations, the government should give companies a certain amount of pollution control compensation, and guide pollution-intensive industries to increase investment in pollution control research and development by means of financial subsidies and low-interest loans. It is necessary to promote the transformation of enterprises from traditional industries to green industries. The government should supervise the environmental technology and pollution prevention and control enterprises that do not meet the standards. The government should shut down those small enterprises with low technical capabilities and serious pollution, which promotes the concentration of factor resources in enterprises with high technical level and good environmental benefits. For polluting industries, the

government should appropriately strengthen environmental regulations and force enterprises to find the best technical path for energy conservation and emission reduction. It is conducive to giving full play to the driving role of environmental regulation in the substantive innovation of enterprises and promoting the green development of the manufacturing industry.

Technological innovation is an effective means to improve energy efficiency. Considering the existence of "cost effect" and "innovation compensation effect", the promotion effect of technological innovation on improving energy efficiency may not be obvious in the short term. However, as the "innovation compensation effect" of later-stage enterprises compensates for the cost effect exceeding environmental regulation, technological innovation will promote the improvement of energy efficiency. Therefore, the government should continue to encourage enterprises to strengthen technological innovation and fundamentally improve energy efficiency. In addition, the government should rely on technological progress to solve resource and environmental problems. It is necessary for the government to comprehensively use fiscal, tax, credit, subsidies, and environmental policies to increase support for green production and scientific research and encourage innovation. It can improve the energy efficiency and clean production capacity of enterprises, and guide the technological progress to change in the direction of energy saving and environmental improvement.

To guide enterprises to increase the research and development of invention patents, the government should cultivate the environmental protection awareness of enterprise executives. On the one hand, the government should use industry associations and executive training courses to publicize environmental protection policies and laws and regulations to enterprises, thus improving the environmental protection awareness of enterprise management and enhancing environmental protection responsibility. On the other hand, the government can increase the publicity of green consumption and guide the masses to adjust their consumption structure and choose low-carbon products. It is necessary to increase the environmental protection knowledge training for other staff of the enterprise to enhance the implementation effect of environmental regulations. Enterprises should strictly abide by environmental laws and regulations, actively abide by environmental regulations and policies, attach importance to green technology innovation, and achieve cleaner production.

This paper makes an exploration of the influence of environmental regulation and technological innovation on GTFEE, but there are still limitations that can be further expanded in the future. First, due to the availability of data, we use indirect methods to measure the intensity of environmental regulation. We also did not analyze the heterogeneous impact of technological innovation on the energy efficiency relationship under different types of environmental regulatory policies (eg, market-based policies and command-and-control policies). Future research can further subdivide environmental regulation according to policy characteristics, and study the heterogeneous impact of different environmental regulation types on energy efficiency. Second, technological innovation and technological introduction are the two main paths of technological progress. This paper only examines how environmental regulation affects the relationship between technological innovation and energy efficiency, without examining whether environmental regulation can affect energy efficiency by changing technology introduction. Therefore, future research can expand the analysis from the perspective of technology introduction.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

MZ: Conceptualization, Project administration, Formal analysis, Writing—original draft, Funding acquisition, Supervision. MD: Writing—review editing, Methodology, Data curation, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Vishal Dagar,
Great Lakes Institute of Management, India

REVIEWED BY
Muhammad Sibt E. Ali,
Zhengzhou University, China
Muhammad Owais Khan,
University of Agriculture, Pakistan

*CORRESPONDENCE
Nudrat Fatima,
nudratfatima91@gmail.com

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Globalization, institutional quality, economic growth and CO_2 emission in OECD countries: An analysis with GMM and quantile regression

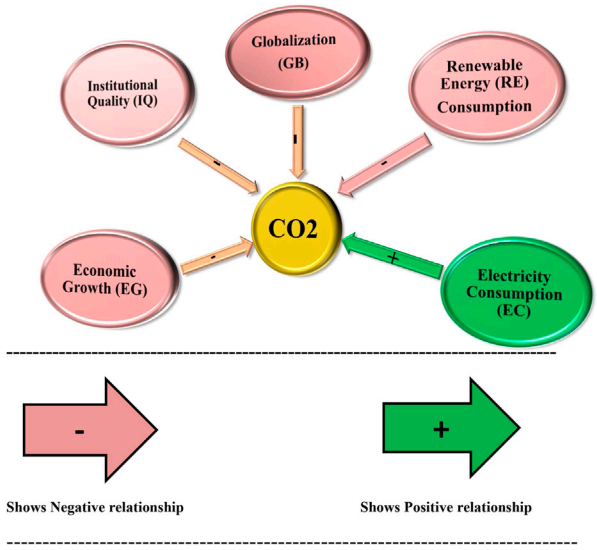
Nudrat Fatima*, Yanting Zheng and Ni Guohua

Beijing Technology and Business University, Beijing, China

This research used the dynamic panel model and QR (Quantile Regression) to examine the effect of globalization (GB), Institutional Quality (IQ), Economic Growth (EG), Electricity Consumption (EC), and Renewable Energy (RE) consumption on Carbon dioxide (CO_2) emission from 1991 to 2018 in thirty-six (OCED) countries. Panel unit root tests have been employed to examine the stationarity of the study variables; the results, which included the Harris and Tzavalis (Journal of econometrics, 1999, 91 (2), 201–226) and Levin et al. (Journal of Econometrics, 2002, 108 (1), 1–24) tests, indicate that all of the variables used are a combination of I (0) and I(I). Cointegration in the study variables has been examined using the cointegration tests devised by Westerlund, Kao, and Pedroni; the results suggest that cointegration exists in the research variables. Findings of the one-step difference GMM, One-step system GMM and two-step system GMM reveal that RE consumption, GB, and IQ negatively affect the CO_2 emission in (selected OECD) countries that help to reduce CO_2 excretion. In contrast, EC consumption and EG become responsible for the climatic and environmental loss. Further, this study checked the robustness by using SQR (Simultaneous quantile regression) and PQR (Panel Quantile Regression). The evaluated study findings of QR (Quantile Regression) reveal that RE consumption, GB, and IQ help to reduce the CO_2 emission while EG and EC consumption becomes responsible for the climatic and environmental loss. Further recommendations are suggested based on the findings.

KEYWORDS

economic growth, institutional quality, globalization, renewable energy consumption, quantile regression



GRAPHICAL ABSTRACT
This research used the dynamic panel model and quantile regression to examine the effect of globalization, institutional quality, economic growth, electricity consumption, and renewable energy consumption on Carbon dioxide (CO_2) emission from 1991 to 2018 in 36 Organization for Economic Cooperation and Development countries

Introduction

Natural disasters are mainly caused by the climatic and environmental loss; both developing and developed countries are facing climatic and environmental loss (Baiardi and Morana, 2021) that are mainly caused by the reduction of resources (Kabir and Salim, 2019) such as soil, water, and air; the destruction of the ecosystems; habitat demolition; the destruction of wildlife and greenhouse gasses (Saud et al., 2020). Greenhouse gases are known main climatic and environmental loss element that adversely impacts the world. Riti et al. (2017a), Sheraz et al. (2022a) reveals that degradation of the climatic atmosphere is mainly caused by natural disasters such as floods, forest fires and hence negatively affect infrastructure, agricultural land and natural resources as well as human beings. OECD (2020) report also suggested that the main cause of greenhouse gases is CO2 emission around the globe. Canada is toped ranked country in CO_2 emission by contributing 15.5% tones/capita followed by Australia, United States and Luxembourg, contributing 15.3, 14.9 and 14.8%, respectively, and it is steadily rising.

Khan and Hou (2021), Shen et al. (2022a) investigated the effect of consumption of traditional energy sources and IQ on CO_2 emission in South African countries. Results showed that climatic atmosphere quality in African region improves with IQ. Salman et al. (2019), Shen et al. (2022b) examined the association between IQ and CO2 emission. Study findings reveal that CO_2 emission and IQ are positively correlated. Authors concluded that effective institutions are important aspects of the legislation that will assist in taking a low level the climatic and environmental loss and enhance the EG. However, the study of Wu and Zhu (2021); Obobisa et al. (2022) reveals that CO_2 emission has a negative effect by enhancement in the IQ from African perspective.

On the contrary, Hassan et al. (2019), Lei et al. (2021) investigated the effect of IQ on CO_2 emission in Pakistan. Their results show that CO_2 emission has a positive effect of IQ. Asongu and Odhiambo (2019), Chen X. et al. (2021); Quan et al. (2021) reveal that country follow rules and regulations regarding the climatic atmosphere with high IQ. Results indicate that the climatic atmosphere improves with an enhancement in IQ.

Sarkodie et al. (2020a); Chen Y. et al. (2021); Quan et al. (2022) showed that in African economies, RE consumption assists in reducing climatic and environmental loss. According to Pilatowska et al. (2020) by enhancing the climatic atmosphere, RE consumption helps health facilities, education, and the gender gap. Destek and Aslan (2020) and Sarkodie et al. (2020b) examined the impact of RE consumption on CO_2 emission in China. Results demonstrate that biomass consumption of traditional energy sources takes a low-level CO_2 emission.

Khan et al. (2019), Qin et al. (2022), Liu S. et al. (2022) investigated the effect of consumption of traditional energy sources on CO_2 emission in Pakistan. Study findings reveal that energy consumption and CO_2 emission are positively correlated. Similarly, another study by Khan et al. (2020)

concluded that CO_2 emission has a positive influence on the consumption of traditional energy sources and EG. Adedoyin et al. (2020), Munir et al. (2020), Liu Y. et al. (2022), Yin et al. (2022) also checked the impact of EG on CO_2 emission and concluded that EG and CO_2 are positively correlated in Asian countries.

Anwar et al. (2020) examined the effect of coal usage and EG on CO_2 in Pakistan. They concluded that coal consumption and EG impact CO_2 emission positively. Several distinct research studies Yoo (2006), Akinlo (2008), Khan et al. (2018), Bashir et al. (2019), Ali et al. (2019), Eyuboglu and Uzar (2020) and Wang Q. et al. (2020) investigated the relationship among energy consumption, EG, and CO_2 excretion. Their study results conclude that the consumption of traditional energy sources becomes responsible for boosting the climatic and environmental loss. The study of Awodumi and Adewuyi (2020); Shang et al. (2021); Wang and Luo (2022) applied non-linear autoregressive distributed lag to evaluate the influence of consumption of traditional energy sources on the CO_2 emission in African region.

Findings of the study reveal that consumption of traditional energy sources and CO_2 excretion. Salahuddin et al. (2018) and Naz et al. (2019) studied the impact of EC, EG, and FDI on CO_2 emissions in Kuwait. Results reveal that EC, EG, and FDI are positively correlated with CO_2 excretion. Similarly, another study results of Salahuddin et al. (2018) demonstrate that Consuming EC and EG for industrial processes reduces CO_2 emissions in GCC nations.

In many research studies, domestic credit to the private sector is used as a proxy to measure financial development (Komal and Abbas, 2015; Park et al., 2018) found; that many research projects employed stock market indicators as a proxy for financial progress. To reveal the presence of a climatic and environmental loss Kuznets curve (EKC), Shahbaz et al. (2017) analyzed the association between GB and CO_2 excretion in China by employing time series data from 1970 to 2012. Their study result indicates that GB is positively related to CO_2 emissions from excessive consumption in advanced economies are being shifted to developing economies, and emerging economies are willing to accept the problem of climatic and environmental deterioration in exchange for economic success.

Sheraz et al. (2021) showed that GB's economic, political, and social aspects influence everyone around the world. The world's developing countries are linked to developed countries with the goal of attracting funds for EG. In Pakistan, Khan et al. (2019a) used time-series data to assess the influence of GB on CO_2 excretion. Findings indicate that GB and CO_2 are positively linked with each other; moreover, developed countries are investing in Pakistan because of the country's consistent and increasing investment opportunities for international investors, as well as its economic development. Early research focused on the effects of GB or IQ with other economic variables, while this study examines the effects of GB and IQ with other economic variables. This study used GB and IQ both variables together along with other economic variables to check their impact on CO_2. However, several variables such as GB, IQ, EC consumption, RE consumption, and EG were entirely ignored in early studies that employed dynamic panel models to assess the impact of the stated variables on CO_2 emissions, such as one-step difference GMM, one step system GMM, and two-step system GMM. To investigate the robustness, this study employed SQR and PQR. For the first time, panel data from 36 OECD countries (see Appendix Table A1) were used from 1991 to 2018. The basic concern of this research study is to see how GB, IQ, energy consumption, EC use, and EG affect CO_2 emissions. Countries are chosen depending on their EG and energy consumption to conduct economic activities; pollution is a significant issue in many countries because of their high energy consumption, causing concern among policymakers and energy experts. This study employs cross-sectional dependence studies such as Kao cointegration Kao (1999), and Pedroni cointegration Pedroni (1999), Pesaran (2004), Westerlund (2005).

Literature review

Hdom (2019) used the ARDL model to examine the influence of EC production on CO_2 emissions in South America from 1980 to 2010. The study's findings reveal that EC and EG production are positively related to CO_2 emissions in the short run, although RE consumption assists in environmental improvement. It is also suggested that sample countries should use RE in CO2 reduction. The study of Ridhosari and Rahman (2020) illustrates that EC consumption is a significant contributor to the growth in CO_2 emissions. Hamdi et al. (2014) evaluated the relationship between EC consumption, EG, and FDI in Bahrain. Study findings reveal that EC consumption and EG are correlated with each other. Liddle and Sadorsky (2017) examined the effect of EC generation on CO_2 emission. The study results reveal that 1% increase in EC production contributes to about 0.82% reduction in CO_2 emission. Cowan et al. (2014) evaluated the effects of EC consumption on CO_2 excretion. Results indicate that EC consumption contributes to the invalidity of the Granger causality test for measuring CO_2 excretion.

Sheraz et al. (2022b) explored the role of intelligence on climatic and environmental degradation in BRI countries. Results show that IQ contributes in CO_2 emission reduction. Furthermore, existing studies showed that CO_2 emission and trade openness are positively correlated. Similarly, they also conducted another survey and revealed that IQ is a solution for a clean climatic atmosphere and that IQ is important to improve the quality of the climatic environment. Akif and Asumadu (2019) investigated how IQ affects CO_2 emissions in newly industrialized countries. Results of the study demonstrated that IQ contributes to reducing CO_2 emissions

TABLE 1 Variables Description.

Variables	Description	Source
CO_2 Excretion	Metric Tons per Capita	selected OECD
RE consumption	Total primary energy as a percentage	selected OECD
EC consumption	Gigawatt-Hours in Total	selected OECD
EG	Gross Domestic Product (GDP) (Constant 2010 USD)	WDI
IQ	Stability in government, democratic accountability, bureaucratic excellence, corruption, and law and order	ICRG
GB	KOFI GB Index	KOFI

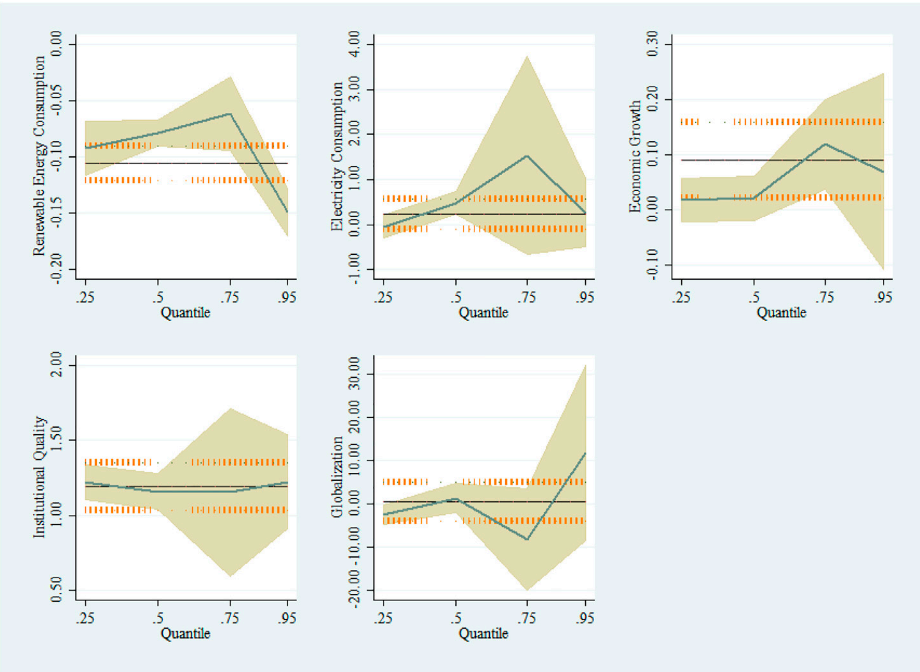


FIGURE 1
Quantile graphs.

and that standards linked with the law help for the improvement of the climate.

Liu et al. (2020) examined the impact of GB in G-7 economies to verify the EKC hypothesis. Findings showed that GB helps to reveal the presence of the EKC hypothesis in G-7 economies. Further evaluated results show that EG is positively significant with environmental degradation, While the consumption of RE and environmental degradation are negatively associated with each other. Rehman et al. (2019) examined the effect of GB RE usage on CO_2 emissions. Results demonstrated that GB and RE consumption helps to reduce the CO2 emission while negatively affected the environmental degradation and hence consumption of traditional energy sources becomes responsible to an enhancement the CO_2 excretion. Zaidi et al. (2019) studied the effect of GB on CO_2 emissions in the APEC (Asia Pacific Economic Cooperation). Results of the study validate that GBs contributes in the reduction of CO_2 emission. Akadiri et al. (2019) evaluated the impact of GB on the CO_2 emission. Results indicated that GB helps to lessen the CO_2 emission in Turkey. Ziaei (2015) evaluated the impact of RE consumption on CO_2 emission. Results demonstrated that RE consumption helps to take a low level the CO_2 excretion. Godil et al. (2020) studied the impacts of IQ, traditional energy consumption, and RE use on CO_2 emissions in South African countries. Results showed that RE consumption and IQ help in the reduction of CO_2

emission in South Africa. Riti et al. (2017b) explored the correlation between financial development and RE use.

Study results revealed that financial development, population, and RE consumption is negatively related to CO_2 emission while the results of traditional consumption of traditional energy sources increase the CO_2 emission. In Asian economies, RE consumption and value-added agricultural production contribute in the reduction of CO_2 emissions in Asian economies, while the finding of consumption of energy sources indicates a positive influence on climatic and environmental degradation (Liu et al., 2017).

Research methodology

This study examines the impacts of EG, RE, and EC consumption, as well as GB and IQ, on CO_2 emissions in 36 OECD states using a balanced panel dataset from 1991 to 2018. The variables in this study have been chosen based on previously published research. CO_2 emissions have been used as a proxy for measuring the degradation of the environment by W. Cowan et al. (2014), Paramati et al. (2017), Xu et al. (2020) employed EC consumption as a main indicator for climatic and environmental degradation; Dreher (2006); Cowan et al. (2014); Hafsaoui et al. (2019); Wang Z. et al. (2020) evaluated the effect of EG on CO_2 emission. As a result of this investigation, the following fundamental equation is generated and initiated.

$$\begin{aligned} \boldsymbol{CarbonDioxideEmission_{it}} = \boldsymbol{\beta_0} & + \boldsymbol{\beta_1 RenawableEnergyConsumption_{it}} \\ & + \boldsymbol{\beta_2 ElectricityConsumption_{it}} \\ & + \boldsymbol{\beta_3 EconomicGrowth_{it}} \\ & + \boldsymbol{\beta_4 InstitutionalQuality_{it}} \\ & + \boldsymbol{\beta_5 Globalization_{it}} + \boldsymbol{\varepsilon_{it}} \end{aligned} \tag{1}$$

The letter t denotes time frame from 1991 to 2018, and the letter "i" denotes selected OECD countries that have been selected. Table 1 illustrate a detail description of the variables.

Materials and Methods

This study evaluated the effects of RE consumption, EC consumption, EG, IQ, and GB on the emission of CO_2 in sample countries. Study results have been validated using GMM (one-step difference and one and two-step system) models. SQR and PQR have been employed to evaluate the results' robustness. Endogeneity, heteroskedasticity, serial correlation control, and heterogeneity. Are all concerns that the QR (Quantile Regression) and panel dynamic models intend to avoid (Baltagi, 2005; Kripfganz and Schwarz, 2019; Neagu and Teodoru, 2019).

The dynamic panel model, commonly known as the GMM model, is examined by employing instrumental models that have an advantage over the traditional two-stage least squares (2SLS) approach. GMM model is well suited model for dynamic panel model. GMM estimators are unbiased. Arellano and Bond (1991) examined the performance of several GMM, OLS, and WG estimators. They concluded that GMM estimators possess low variations and biasness by using stimulations. According to Fumio Hayashi (2011), GMM models employ orthogonality requirements to achieve successful estimation results in the presence of heteroscedasticity induced mostly by the unknown form. Therefore, for our formal analysis, we adopted a type of dynamic panel with lagged levels of CO_2 excretions using Arellano and Bond (1991)'s GMM estimators. Based on Equations, the following is a proposed model for the GMM estimator (1).

$$\begin{aligned} & \boldsymbol{Carbon\ dioxide\ emission_{2i,t}} \\ & = \boldsymbol{\beta_0 Carbon\ dioxide\ emission_{i,t-1}} + \boldsymbol{\beta_1 Renewable\ energy\ consumption_{i,t}} \\ & + \boldsymbol{\beta_2 Electricity\ consumption_{i,t}} + \boldsymbol{\beta_3 Economic\ Growth_{i,t}} + \boldsymbol{\beta_4 Institutional\ Quality_{i,t}} \\ & + \boldsymbol{\beta_5 Globalization_{i,t}} + \sum_{j=1}^{6} \boldsymbol{\theta_j Z_{i,t}} + \boldsymbol{\mu_{i,t}} + \boldsymbol{\varepsilon_{i,t}} \end{aligned} \tag{2}$$

In the above Eq 2 β_0 is the element that is to be investigated by controlling for a vector of core explanatory variables, μ specifies country-specific effects, ε reveal the error term. Additionally, $\beta_1\ to\ \beta_5$ are the elements to be capture the effect of RE consumption, EC consumption, EG, IQ and GB respectively. This study used a model to indicate the form of the dynamic panel data models proposed by Arellano and Bond (1991). The above-mentioned Eq 2 suggests the model that includes the lagged dependent variables of CO_2 emission that is correlated with the error term.

Further robustness was checked with quantile regression. PQR and SQR have investigated the impact of RE consumption, EC consumption, EG, IQ, and GB on CO_2 excretion. PQR equation is based on Eq 1.

$$\begin{aligned} & \boldsymbol{Q_{Carbon\ dioxide\ emissioni.t}} (\boldsymbol{\tau_k / \beta_i, X_{i,t}}) \\ & = \boldsymbol{\beta_0 + \beta_1 renewabl\ energy\ consumption_{i.t} + \beta_2 electricity\ consumption_{i.t}} \\ & + \boldsymbol{\beta_3 institutional\ quality_{i.t} + \beta_4 economic\ growth_{i.t} + \beta_5 globalization_{i.t}} \\ & + \boldsymbol{\epsilon_{i.t}} \end{aligned} \tag{3}$$

The above PQR equations indicates that "I" denote sampled countries and t represents time period of 1991–2018. β_i represents the unobserved specific effect, τ indicates the conditional distribution's number of quantiles. The variables used to investigate the impact of these components i.e (RE consumption, EC consumption, IQ, EG, and GB) on CO_2 excretion. In addition, the coefficients have been examined using the following equation to determine the τth quantile of the conditional distribution.

$$\boldsymbol{\widehat{\beta(\tau)} = argmin \sum\nolimits_{i=1}^{n} \rho_\tau (y_i = x_i^\tau \beta} \tag{4}$$

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
CO2 Excretion	1,008	8.435	4.212	2.100	29.000
RE consumption	1,008	14.366	15.675	0.280	89.750
EC Consumption	1,008	4.890	0.682	3.003	6.6220
EG	1,008	2.631	3.229	−14.814	25.163
IQ	1,008	0.010	1.637	−6.205	2.0890
GB	1,008	1.888	0.057	1.615	1.9610

TABLE 3 Correlations Matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
CO2 Excretion	1.000					
RE consumption	−0.283	1.000				
EC Consumption	0.136	−0.263	1.000			
EG	0.024	−0.008	−0.110	1.000		
IQ	0.358	0.258	0.004	−0.095	1.000	
GB	0.213	0.015	0.173	−0.078	0.457	1.000

TABLE 4 VIF Test.

Variables	VIF	1/VIF
IQ	1.38	0.724,553
GB	1.32	0.757,890
RE Consumption	1.16	0.858,915
EC Consumption	1.12	0.889,623
Economic Growth	1.02	0.978,520
Mean VIF	1.2	

Note: VIF, is Variance Inflation Factor.

In Eq 4 $\rho_\tau(u) = u(\tau - I(u<0)), I(u<0) = \begin{cases} 1, u<0 \\ 0, u>0 \end{cases}$ Specifies to examine the function and I (.) is an indicator function.

The Pesaran (2004) CD test has been employed to determine cross-sectional dependency in this research. The HT (Harris-Tzavalis) test and the LLC (Levin-Lin-Chu) test have been employed to determine stationarity, respectively. Pedroni (1999), Pedroni (2004) and Westerlund introduced cointegration, which has been investigated using cointegration tests.

Results and discussion

Results of descriptive statistics have been reported in Table 2. Study findings reveal that the average CO_2 emission is 8.435, with maximum and minimum values of 2.1 and 29, respectively. The descriptive statistics show that the least and biggest RE consumption amounts are 0.28 and 89.750, with an average of 14.366. The average quantity of EC consumed is 4.89, with low and high values of 3.003 and 6.622, respectively. The minimum and maximum EG values are -14.814 and 25.163, respectively, with a mean value of 2.631. The mean IQ value is 0.01 with a maximum value of 2.089 and a minimum value of -6.205; the mean GB value is 1.888 with a maximum value of 1.615 and a minimum value of 1.961.

The correlations matrix has been established, as shown in Table 3. Findings reveal that CO_2 emissions have a positive link with EC consumption, EG, IQ, and GB, but a negative relationship with RE consumption in selected OECD countries. The results of the correlations matrix reveal that RE consumption helps to minimize the climatic and environmental loss in several OECD countries. Still, EG and EC consumption cause a rise in the climatic and environmental loss.

The VIF has been applied to analyze the multicollinearity problem in the variables listed in Table 4. The VIF results show that there is no problem with multicollinearity in the variables. All variables have a significance level of more than 0.20, and the VIF values are less than 5, indicating that the variables are not multicollinear.

The analysis of the Levin-Lin-Chu and the Harris-Tzavalis Unit root tests on the Panel Unit root test is summarized in Table 5. CO_2 emissions and RE consumption are not stationary at the level, but they become stationary at the first difference, but EC consumption, EG, IQ, and GB do not have a unit root problem at the level or the first difference. While consumption of RE, GB, and EC is not stationary at the level, it is stationary at the first difference, CO_2, EG, and IQ are stationary both at the level and at the first difference.

The cross-sectional dependence findings are summarized in Table 6. The findings show that the research variables are stable, rejecting hypothesis H0. Cross-sectional reliance test demonstrates that every country has a cross-sectional dependency.

Table 7 presents the findings of the Westerlund, Kao, and Pedroni cointegration tests. The Westerlund, Kao, and Pedroni cointegration tests have been used to detect cointegration in the research variables. The cointegration results are significant, indicating that the tested variables are cointegrated.

The findings of GMM models are summarized in Table 8. The basic purpose of this research is to examine the impact of EC consumption, RE consumption, EG, IQ and GB on CO_2 excretion in selected sample countries. The results of the GMM models reveal that RE consumption has a negative and considerable influence on CO_2 emissions in OCED countries. The data show that in several OECD countries, consumption of RE reduces CO_2 emissions.

The analyzed data reveal that increases in RE consumption reduce CO_2 emissions by 0.21, 0.10, and 0.10%, respectively. Results of the RE consumption are in

TABLE 5 Panel Unit Root Test.

	Levin-lin-Chu		Harris-Tzavalis	
	At Level	At Difference	At Level	At Difference
CO2 Excretion	−4.7878	−21.6722***	−2.2105*	−46.4064***
RE consumption	3.4798	−19.3778***	2.9469	−61.2288***
EC Consumption	−11.4941***	−21.9518***	0.9198	−48.5811***
Economic Growth	−20.4808***	−34.4661***	−29.4314***	−61.0233***
IQ	−11.4508***	−23.2201***	−7.1010***	−43.3475***
GB	−17.2299***	−19.9598***	0.1097	−34.9762***

Where *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 6 Cross-sectional Dependence Test.

Variable	CD-Test	*p*-value	Corr	abs (corr.)
CO2 Excretion	33.46	0.000	0.252	0.511
RE consumption	66.51	0.000	0.501	0.672
EC Consumption	77.17	0.000	0.581	0.668
EG	58.35	0.000	0.439	0.448
IQ	30.82	0.000	0.232	0.376
GB	126.19	0.000	0.95	0.95

TABLE 7 Panel Cointegration Test.

Kao Cointegration Test		
	Statistic	***p*-Value**
MDF t (Modified Dicky Fuller)	−0.7524	0.2259
DF (Dicky Fuller t)	−1.6763	0.0468
ADF (Augmented Dicky Fuller t)	−1.7461	0.0404
UMDF (Un-adjustable Modified Dicky Fuller t)	−3.2613	0.0006
UDF (Un-adjustable Dicky Fuller t)	−3.1758	0.0007
Pedroni Cointegration Test		
MPP (Modified Phillips-Perron t)	2.3093	0.0105
PP (Phillips-Perron t)	−6.1605	0.000
ADF (Augmented Dicky Fuller t)	−4.3362	0.000
Westerlund Cointegration Test		
Variance ratio	−1.8602	0.0314

line with those of earlier studies. Muhammad et al. (2021) investigated the effect of RE use on global climate and environmental degradation. They claimed that using RE contributes to lower CO_2 emissions. Teng et al. (2020) investigated how RE consumption affects CO_2 emissions. The results of the study show that the use of RE reduces CO_2 emissions. Using time-series data, Usman et al. (2020) investigated the asymmetric effect of consumption of traditional energy sources on CO_2 emission in Pakistan. They proved that consuming sustainable energy reduces CO_2 emissions in Pakistan. The effect of RE consumption on CO_2 emission is also investigated by Chiu and Chang (2009), Al-Mulali and Ozturk (2015), Shafiei and Salim (2013), and Bento and Moutinho (2016). They claimed that RE consumption contributes to keep CO_2 emissions to a minimum level. Dogan and Seker (2016) investigated causes of climatic and environmental degradation. The data show that the use of RE aims to reduce climatic and environmental degradation, but traditional consumption of traditional energy sources increases climatic and environmental degradation. Jebli et al. (2016) investigated the effect of using RE on CO_2 emissions. Results show that consumption of RE contributes to minimize CO_2 emissions. Findings of the GMM (one-step difference and system) show EC consumption has a positive and considerable effect on CO_2 emissions in a number of OECD countries. According to the investigated findings of power consumption, a one percent increase in EC consumption has a positive effect on CO_2 emission and is responsible for increasing CO_2 emission by 1.46 and 0.22%, respectively. Results on EC consumption are similar to those of the following researchers.

In a group of countries, Asongu et al. (2020) investigated the effect of consumption of traditional energy sources and urbanization on CO_2 emissions. The data show that consumption of EC has a positive effect on CO_2 emissions. According to, increased EC consumption increases CO_2 emissions, which results in climatic and environmental degradation. Munir and Riaz (2020) looked at the asymmetric influence of consumption of traditional energy sources on CO_2 emissions in South Asian economies. The data indicated that increased EC consumption in South Asian countries had a positive effect on CO_2 emissions. Salahuddin et al. (2018) also

TABLE 8 Dynamic Panel GMM Results.

	One-step difference GMM	One-step system GMM	Two-step system GMM
CO2 Excretion$_{t-1}$	0.790***	0.983***	0.971***
	(37.84)	(214.35)	(151.47)
RE consumption	−0.212***	−0.108***	−0.107***
	(−36.94)	(−101.33)	(−12.75)
EC Consumption	1.468***	0.220***	0.336
	(7.40)	(9.20)	(1.43)
EG	0.00698	0.0987***	0.103***
	(1.40)	(19.24)	(23.4***
IQ	−0.294***	−1.238***	−1.121***
	(−6.18)	(−110.12)	(−22.68)
GB	−1.095	−0.0872	−0.303
	(−1.62)	(−0.28)	(−0.30)
_cons		8.472***	7.317***
		(14.46)	(3.46)
AR(1)	0.142	0.180	0.630
AR(2)	0.333	0.222	0.446
N	972	1,008	1,008

t statistics in parentheses.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

TABLE 9 Robustness check QR (Quantile Regression) Results.

	SQR			QRPD	
	Q25	Q50	Q75	Q95	
RE consumption	−0.0920***	−0.0787***	−0.0617***	−0.149***	−0.0502***
	(−8.97)	(−11.31)	(−4.12)	(−18.15)	(−8.26)
EC Consumption	−0.0477	0.479***	1.542	0.257	0.980***
	−0.34)	(4.25)	(1.61)	(1.21)	(19.82)
EG	0.0177	0.0209	0.119*	0.0695	−0.0383***
	(0.98)	(1.09)	(2.00)	(1.08)	(−3.24)
IQ	−1.220***	−1.160***	−1.156***	−1.223***	−0.997***
	(−16.94)	(−16.29)	(-3.65)	(−9.18)	(−20.36)
GB	−2.397*	1.359	−8.163	11.78	−8.111***
	(−2.39)	(0.77)	(−1.05)	(1.67)	(−10.92)
_cons	12.01***	3.628	18.26	−5.645	
	(5.97)	(1.17)	(1.42)	(−0.42)	
Pseudo R2	0.2115	0.1724	0.1068	0.2360	
N	1,008				1,008

t statistics in parentheses.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

concluded similar conclusions. They indicated that increasing EC usage causes more pollution.

EG is positively and significantly related to degradation of environment in selected OECD countries. According to findings of GMM model (one-step difference and one-step system), one percent increase in EG is responsible for increases in excretion of CO_2 is 0.098 percent and 0.103 percent, respectively, in 36 OECD countries. Results on EG and CO_2 emissions are consistent with prior studies. Muhammad et al. (2021) showed that global EG is significantly important for climatic and environmental degradation. Another recent study by Teng et al. (2020) found that economic activities have a positive effect on climatic and environmental loss. In Pakistan, Khan et al. (2019) Khan et al. (2019a), Khan et al. (2019b) employed a dynamic ARDL simulation time series model to demonstrate that economic activities reduce CO_2 emissions. Economic activities boost CO_2 emissions; they also say that EKC is beneficial to the world's industrialized economies.

The findings of the GMM models in 36 OECD nations show that IQ has a negative and significant influence on CO_2 emissions. One-step difference GMM, one-step system GMM, and two-step system GMM all show a 29, 1.23, 1.12% reduction in carbon emission by 1% increase in IQ, 1.23 percent, and 1.12 percent, respectively. According to Ibrahim and Law (2014), IQ strengthens the rules and regulations that support the reduction of CO_2 emissions. IQ has a detrimental impact on CO_2 excretion Ali et al. (2019). Intelligence contributes to the mitigation of climatic and environmental harm, according to Tamazian and Rao (2010), Lau et al. (2014), and Al-Mulali and Ozturk (2015). IQ has a positive impact on EG but a negative impact on climate change and environmental harm (Bhattacharya et al., 2017).

GB and CO_2 are negatively and significantly correlated with each other in sample OECD countries. According to results of the GMM models. Teng et al. (2020) showed that GB has a negative effect on climatic and environmental degradation in the long run. GB (Balsalobre-Lorente et al., 2019), contributes in the reduction of climatic and environmental degradation. According to Shahbaz et al. (2019), as GB increases, climatic and environmental loss decreases. In Pakistan, Khan et al. (2019a) showed that GB increases climatic and environmental degradation. Study findings of Sheraz et al. (2021) and Twerefou et al. (2017) reveal that GB contributes in increased climatic and environmental degradation.

QR (Quantile Regression) i.e., SQR (Simultaneous quantile regression) and PQR (Panel Quantile Regression), were used to check the robustness of the evaluated results. Table 9 demonstrates results of the robustness check QR results.

The results of the SQR and PQR findings indicated that RE consumption and environmental loss are significantly negative correlated in sample countries. The results of the SQR show that increasing RE consumption CO_2 reduces by one percent while climatic and environmental loss by 0.092%, 0.078%, -0.061%, and 0.149% in the selected OECD countries, respectively, from quantile 25 to quantile 95. On the contrary, results of the panel quantile regression indicate that 1% increase in consumption of RE reduces CO_2 excretion by approximately 0.050% in the sample OECD nations.

According to the results of the simultaneous quantile regression, consumption of EC and environmental degradation are significantly and positively related to each other in the selected OECD countries with quantile 50. On the contrary, the panel QR yielded the same conclusions. According to results of the panel quantile regression, the consumption of EC consumption has a positive and substantial effect on climatic and environmental degradation in the selected OECD countries and accounts for 0.98% of the climatic and environmental degradation.

Results reveal that EG impacts climatic and environmental degradation positively and significantly in the OECD countries with quantile 75. According to the quantile 75 results, a 1% increase in economic development leads to 0.119% increase in climatic and environmental loss in selected OECD countries. While the results of the panel quantile regression reveal that EG in the selected OECD countries contributes to the mitigation of climatic and environmental degradation. Results show that employing advanced technology in economic activities helps to mitigate climatic and environmental degradation in developed countries throughout the world.

Results of the IQ and GB show that the selected OECD countries have a negative and considerable influence on climate and environmental degradation. Results of the SQR show that IQ contributes in the reduction of CO_2 emissions in the OECD economies. The results of the panel QR reveal that in the selected OECD countries, IQ and GB contribute to mitigating climatic and environmental degradation. Further graphs for QR in Figure 1 for all variables are as follow.

Conclusion

The impact of GB, IQ, RE consumption, EG, and consumption of EC on CO_2 excretion has been investigated in sample of OECD 36 countries. Quantile regression methods; PQR and SQR has been employed to analyze the relationship among study variables. To assess the stationarity of variables Panel Unit Root test; HT, and LLC tests have been used. The results of these tests reveal that at both the level and the first difference, the variables are stationary. Westerlund, Pedroni, and Kao tests results indicate that cointegration exists among variables.

According to study results of the GMM models, In OCED nations, RE usage has a negative and considerable impact on CO_2 emissions. The findings show that using RE helps to cut CO_2 emissions in a number of OECD nations. The investigated data show that increased consumption of RE reduces

CO2 emissions by 0.21%, 0.10%, and 0.10%, respectively. The results of the GMM (one-step difference) and GMM (one-step system) show that EC usage has a favorable and significant influence on CO_2 emissions in several OECD countries. According to the results of the EC consumption, 1% increase in EC consumption has a positive effect CO_2 emission and is responsible for proliferation of 1.46 and 0.22%, respectively.

GMM system's results indicate that EG has a significant and positive influence on climatic and environmental degradation in sample countries. According to results one percent increase in EG generates 0.098 and 0.103% rise in CO_2 excretion in sample countries, respectively. Findings of GMM difference and system indicate that IQ has a negative and significant impact on CO_2 emission. Results reveal that 1% increase in IQ contributes 29, 1.23, and 1.12% decrease in CO_2 emission, respectively. According to these results, GB and CO_2 emissions are negatively and insignificantly correlated with each other.

Quantile regression; SQR and PQR have been employed to confirm the robustness of the analyzed results. The evaluated findings of these results reveal that consumption of RE is negatively associated with climatic and environmental degradation. Results indicate that 1% increase in consumption of RE contributes 0.092%, 0.078%, -0.061 and 0.149% reduction in climatic and environmental degradation respectively from 25 to 95 quantile. On the contrary, findings of PQR indicate that a 1% increase in consumption of RE reduces 0.05% CO_2 emission in the sample countries. Results of SQR indicate that EC consumption and environmental degradation are positively and significantly related to each other in sample countries with quantile 50. While PQR also reported similar results. These results indicate that EC consumption and environmental degradation are positively and significantly related with each other and contributes 0.98% climatic and environmental degradation in OECD countries.

The evaluated findings indicate that with quantile 75 EG and environmental degradation are positively and significantly correlated. It indicates that a 1% increase in EG becomes responsible for enhancing climatic and environmental degradation by about 0.119% in selected OECD countries. On the contrary, findings of PQR confirm that in sample countries, EG helps to reduce climatic and environmental degradation. Evaluated results demonstrate that use of high technologies for economic activities contributes in climatic and environmental degradation in developed countries. Results of IQ and GB demonstrate a negatively significant impact on climatic and environmental degradation. The study also confirms that IQ contributes in CO_2 excretion reduction in selected OECD countries. Results of PQR (quantile regression) demonstrate that IQ and GB help to reduce climatic and environmental degradation.

According to the results of this study, consumption of EC for economic activities is the primary source of CO2 emission. A few OECD countries are attempting to protect EG by adopting a variety of energy resources to compete with the world's developed countries, which is resulting in increased CO_2 emissions and climatic and environmental degradation. The study findings call for formulating effective policies to encourage green financing for environmental upgradation. In order to address economic concerns and to achieve sustainable development goals, policymakers must introduce such policies that stimulate a sustainable climatic environment. To achieve the Sustainable Development Goals for cost-efficient and clean energy and water, and sanitation the OECD countries must enhance public-private partnerships in specialized energy projects for a sustainable environment. The use of fossil fuels for economic purposes has a positive effect on climatic and environmental degradation in several OECD countries. Policymakers in a number of OECD countries must stimulate investment in thermal, solar, and wind power. They must also enhance clean energy productivity and guarantee that everyone has access to clean energy in order to accomplish the SDGs by 2030. Policies that promote globalization, economic growth, institutional quality to support green infrastructure, and energy generation utilizing renewable energy sources are recommended. By expanding and upgrading infrastructure and technology-based energy resources, EG and a clean climate can be attained. A few OECD countries' governments should support climate policies and regulations as well as give incentives for the investment to the investors and clean energy projects that will improve the environment. They are expected to promote strategic collaborations with other countries at different level to promote green innovations.

Data availability statement

Used data are publically available on the OECD Statistics website under https://stats.oecd.org/.

Author contributions

Globalization, Institutional Quality, Economic Growth, and CO_2 Emission in OECD Countries: An analysis with GMM and quantile regression: NF Conceived and designed the analysis Collected the data Contributed data or analysis tools Performed the analysis Wrote the paper Other contribution: ZY Conceived and designed the analysis Collected the data Contributed data or analysis tools Performed the analysis Wrote the paper Other contribution: NG Conceived and designed the analysis Collected the data

Contributed data or analysis tools Performed the analysis Wrote the paper Other contribution.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

TABLE A1 List of countries.

Austria	Hungary	New Zealand
Australia	Italy	Netherland
Belgium	Iceland	Portugal
Chile	Ireland	Poland
Czech Republic	Israel	Swedenf
Canada	Japan	Slovak Republic
Denmark	Korea	Spain
Estonia	Lithuania	Switzerland
France	Luxembourg	Slovenia
Finland	Latvia	Turkey
Greece	Mexico	United States
Germany	Norway	United Kingdom

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EDITED BY
Cem Işık,
Anadolu University, Turkey

REVIEWED BY
Mubeen Abdur Rehman,
The University of Lahore, Pakistan
Haitao Wu,
Beijing Institute of Technology, China

*CORRESPONDENCE
Jinhao Liang,
liangjinhao@wxit.edu.cn
Xiaowei Song,
songxiaowei@stu.ouc.edu.cn

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Can green finance improve carbon emission efficiency? Evidence from China

Jinhao Liang[1]* and Xiaowei Song[2]*

[1]School of Management, Wuxi Institute of Technology, Wuxi, China, [2]School of Management, Ocean University of China, Qingdao, China

The improvement of carbon emission efficiency and the realization of the goal of "carbon peaking and carbon neutrality" are the key issues that China needs to solve urgently at this stage. The green and low-carbon transformation of the economy requires sufficient financial support. Whether green finance is an opportunity to improve China's carbon emission efficiency is worth studying. For the aim, based on the macro-panel data of 30 provinces in China from 2010 to 2019, this paper uses fixed effect model and spatial Durbin model to study the impact of green finance on regional carbon emission efficiency. The results show that: First, the development of green finance can improve the carbon emission efficiency; Second, in addition to the "local effect", the influence of green finance on carbon emission efficiency has a "neighborhood effect", that is, it has a spatial spillover effect on carbon emission efficiency in neighboring areas, and this effect only exists in a short time; Third, the impact of green finance on carbon emission efficiency is heterogeneous in different regions with different environmental regulations. This paper has reference significance for green finance development and the implementation of the goal of "carbon peaking and carbon neutrality" in China.

KEYWORDS

green finance, carbon emission efficiency, China, environmental regulation, sustainable development

1 Introduction

Climate warming caused by greenhouse gases, especially carbon dioxide emissions, has become one of the global environmental problems and has attracted much attention (Rezanezhad et al., 2020; Işık et al., 2021a, Işık et al., 2021b; Pan et al., 2022). Climate change has led to the frequent occurrence of extreme weather events around the world, further causing ecological imbalances, environmental damage (Işık et al., 2019), and affecting the normal production and living order (Wolff and Haase, 2019; Tuladhar et al., 2021). As the backbone of the global ecological civilization construction and green responsibility, China attaches great importance to climate governance (Meng et al., 2021). In September 2020, Chinese President Xi Jinping made it clear at the 75th United Nations General Assembly that China's carbon dioxide emissions should peak by 2030 and achieve carbon neutrality by 2060 (Huang et al., 2022). Achieving the goal of "carbon peaking and carbon neutrality" is a broad and profound systemic change related to energy,

environment, economy and society, and a historic turning point for China's carbon emission reduction (Rehman et al., 2021; Dong et al., 2022; Pata et al., 2022; Ullah et al., 2022). As the world's second largest economy and the largest developing country, China must focus on both economic development and environmental governance, and promote carbon emission reduction in the process of economic activities. Therefore, in addition to the rigid constraints of carbon emission quotas, China should pay more attention to carbon emission efficiency. Improving carbon emission efficiency is the key path to advance the "carbon peaking and carbon neutrality" goal, and it is an inherent requirement for the high-quality development of China's economy (Sun and Huang, 2020). Furthermore, according to China's Green Finance Development Report 2021, China needs to invest about 150–500 trillion yuan to realize the "carbon peaking and carbon neutrality" strategy, which cannot effectively meet such a huge capital demand only by fiscal strength. Therefore, financial support is an important part of improving carbon emission efficiency (Ali et al., 2022; Fareed et al., 2022; Rehman et al., 2022), and it is also an indispensable force for marketization to promote the realization of the "carbon peaking and carbon neutrality" goal (Zhang, 2011). In order to identify the flow of financial resources and ensure the accurate flow of supporting tools to the green development field, China actively explores green financial products and services and continuously improves the long-term development mechanism of green finance.

Green finance is a new financial development model that guides the transfer of financial resources to green and low-carbon industries and promotes the green transformation of industrial enterprises. Developing green finance to improve carbon emission efficiency is a requirement for China to achieve the carbon dioxide emission goal. In August 2016, seven ministries including the People's Bank of China jointly issued the "Guiding Opinions on Building a Green Financial System", which clearly proposed to establish a sound green financial system based on the overall situation of sustainable economic development. Since then, the top-level design of China's green financial system has been gradually clarified, and the market environment and institutional arrangements to support the development of green finance have been gradually improved. For example, in 2021, the central bank issued a carbon emission reduction support tool. As of the end of 2021, the balance of China's green loans is about 15 trillion yuan; as of the first half of 2021, the cumulative scale of green bond issuance in China and abroad has exceeded 1.73 trillion yuan. The scale of China's green finance market is developing rapidly. Has it played a role in promoting the efficiency of carbon emissions? Will this effect be heterogeneous with different environmental regulations? Will green finance have an impact on carbon efficiency in other regions through externalities (spillover effects)? This paper selects the macro panel data of 30 provinces in China from 2010 to 2019 as the research object, and explores the "local effect" and "neighborhood effect" of green finance in affecting carbon emission efficiency.

The possible marginal contributions of this paper are as follows: First, few studies currently focus on the impact of green finance development on carbon emission efficiency. This paper incorporates green finance and carbon emission efficiency into the same analytical framework, which broadens the research scope of green finance and carbon emission efficiency respectively, and provides evidence support for the government to continue to support the development of green finance in the future. Second, green finance has strong spatial spillover effects (Li and Gan, 2021). However, few literatures incorporate spatial factors into the research on the impact of green finance development on carbon emission efficiency. Therefore, this paper attempts to use the spatial Durbin model to analyze whether the carbon emission efficiency improvement effect of green finance has spatial spillover. Third, from the perspective of environmental regulation, this paper provides policy inspiration for promoting the realization of the goal of "carbon peaking and carbon neutrality" and establishing a sound green financial system. The conclusion shows that, with different environmental regulations, the impact of green finance on carbon emission efficiency is heterogeneous.

2 Literature review

At present, many scholars have conducted research on carbon emission, including the measurement and evaluation (Fang et al., 2022), dynamic change (Cheng et al., 2018b), influencing factors and effects analysis (Xu et al., 2021; Zhang H et al., 2021) of carbon emission efficiency. Scholars think that policy and supervision (Calvo et al., 2021; Yu and Zhang, 2021), technological innovation (Gouveia et al., 2021; He et al., 2021; Wu H et al., 2021; Wyse et al., 2021; Xie et al., 2021), human capital (Song et al., 2020), industrial structure (Cheng et al., 2018a; Wu L et al., 2021) and urbanization (Sun and Huang, 2020; Wang F et al., 2021) will affect carbon emission efficiency. Fang et al. (2022) and Meng et al. (2016) used DEA model to measure the carbon emission efficiency of 42 thermal power plants and 30 provinces in China from the micro and macro levels respectively, and found that there was regional imbalance in China's carbon emission efficiency. Cheng et al. (2018b) used NDDF function to calculate the total factor carbon emission efficiency (TCEI) of industrial sectors in various provinces in China. The results showed that TCEI showed an increasing trend from 2005 to 2015, but the growth rate decreased. Yu and Zhang (2021) evaluated the effect of the low-carbon city pilot policy, and found that the carbon emission efficiency of the pilot group (pilot city) increased by 1.7%, and the carbon emission was reduced by more than 8 million tons. He et al. (2021) constructed the

TABLE 1 Descriptive statistical analysis.

	N	Mean	S. D	Min	Max
CEE	300	0.560	0.170	0.110	1
CEE_SBM	300	0.600	0.270	0.120	1
GF	300	0.180	0.110	0.0600	0.790
Eco	300	1.500	0.470	0.250	2.800
Ind	300	0.440	0.0900	0.160	0.590
Hum	300	9.270	0.860	7.510	12.71
Urb	300	0.570	0.120	0.340	0.900
ER	210	0.100	0.200	0	1.710

Renewable Energy Technology Innovation Index (RETI) and Total Factor Carbon Emission Performance Index (TCPI). The research found that RETI can promote the growth of TCPI, but the relationship between them is affected by the market environment. The research of Xie et al. (2021) once again proves the importance of technological progress to carbon emission reduction.

Green finance has attracted more and more attention as a bright spot to support low-carbon transition and high-quality development (Tsoukala and Tsiotas, 2021; Yang et al., 2021). Green finance increases the social responsibility of financial institutions (Kurt and Peng, 2021), encourages banks to provide funds for enterprises' development (Liu et al., 2021), and then promotes technological innovation (Wang M et al., 2021). The impact of green finance can be divided into three levels: enterprise, industry and region. For the enterprise level, Zheng et al. (2021) uses data from Bangladesh to confirm that the development of green finance business has a positive impact on the medium and long-term development of financial enterprises themselves. But there are also different research conclusions. Umar et al. (2021) believe that some financial enterprises have increased external costs and decreased profits because they have assumed social and environmental responsibilities. Zhang et al. (2021) used the data of 945 A-share companies to find that green financial incentives and punishment effects coexist, affecting the investment and financing behavior of enterprises, which in turn affects the quality of the environment. For the industry level, Wang and Wang (2021) used the grey correlation method and the GMM model as tools to test and found that green finance has a greater role in promoting the tertiary industry. For the regional level, Lee and Lee (2022) constructed a multi-dimensional index of green finance and incorporated the index into the framework of the theoretical model of green productivity. The study found that green finance is one of the basic paths for improving green productivity. In addition, Wang et al. (2021), Wang et al. (2022) and Yin and Xu. (2022) examine the impact of green finance on China's high-quality development, ecological efficiency, and economic growth, respectively.

TABLE 2 Baseline result.

	(1)	(2)	(3)	(4)
	OLS		FE	
GF	1.061***	1.244***	0.492***	0.363***
	(14.526)	(9.842)	(4.800)	(2.841)
Eco		−0.109***		0.062
		(−3.036)		(1.205)
Ind		0.668***		0.242*
		(6.929)		(1.837)
Hum		0.018		0.039***
		(1.068)		(2.632)
Urb		0.424***		0.033
		(2.613)		(0.144)
Cons	0.372***	−0.203	0.759***	0.138
	(24.400)	(−1.585)	(12.970)	(0.473)
Fixed effect	No	No	Yes	Yes
N	300	300	300	300
R^2	0.415	0.525	0.581	0.608

t statistics in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

To sum up, some scholars have studied the relationship between finance and ecology (Işik et al., 2017; Su et al., 2021), environment and energy (Haas et al., 2021), there are still areas that need to be improved. Although the impact of green finance and the influencing factors of carbon emission efficiency have been discussed, few studies have put green finance and carbon emission efficiency into the same research framework. Second, for related research at the macro level, the existing literature mostly focuses on the impact of green finance on the development of the region, while ignoring the spatial spillover effects or externalities. Based on this, this paper integrates green finance and carbon emission efficiency into the same analytical framework, and explores the local effect and spatial spillover effect of the former on the latter, in order to provide guidance for financial model innovation, the realization of the "dual carbon" goal and sustainable development.

3 Empirical models and variables

3.1 Empirical model

3.1.1 Baseline model

To test the impact of green finance on regional carbon emission efficiency, this paper constructs a two-way fixed effect model of time and individual as follows:

$$CEE_{it} = \beta_0 + \beta_1 * GF_{it} + \beta_i * Controls_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (1)$$

TABLE 3 Global Moran'I of carbon emission efficiency of 30 provinces in China from 2010 to 2019.

Year	Moran'I	E(I)	sd(I)	z	*p*-value
2010	0.216	−0.034	0.095	2.645	0.004
2011	0.233	−0.034	0.093	2.863	0.002
2012	0.241	−0.034	0.095	2.907	0.002
2013	0.221	−0.034	0.094	2.719	0.003
2014	0.233	−0.034	0.095	2.828	0.002
2015	0.223	−0.034	0.095	2.715	0.003
2016	0.200	−0.034	0.095	2.476	0.007
2017	0.191	−0.034	0.095	2.378	0.009
2018	0.196	−0.034	0.095	2.429	0.008
2019	0.101	−0.034	0.095	1.431	0.076

Among them, CEE stands for carbon emission efficiency; i refers to the province; t represents the year; β_0 is the intercept term; GF is the key independent variable of this paper, that is, the development level of green finance; And β_1 and β_i are coefficients respectively; Other control variables that affect CEE; α_i is individual effect; γ_t is the fixed effect of the year; ε_{it} is the random error term.

3.1.2 Spatial durbin model

The impact of green financial development on carbon emission efficiency may not only be limited to this region, but also have a certain impact on neighboring regions. Ignoring spatial correlation may lead to the bias of estimation results. Therefore, this paper uses spatial Durbin model to test the spatial impact of green finance on carbon emission efficiency. The spatial Durbin model can simultaneously examine the influence of green financial development and carbon emission efficiency in neighboring regions on the carbon emission efficiency in this region. In this paper, the spatial Durbin model is established as follows:

$$CEE_{it} = \beta_0 + \beta_1 * GF_{it} + \rho\sum_{j=1}^{N} W_{ij} * CEE_{jt} + \sigma\sum_{j=1}^{N} W_{ij} * GF_{jt} + \beta_i * Controls_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \tag{2}$$

Where ρ is the spatial autocorrelation coefficient of the dependent variable; As the spatial weight matrix, according to the particularity of the research variables, this paper considers using economic weight matrix to set the spatial weight. In this paper, the economic weight matrix is constructed according to the average GDP of each region in the sample period.

3.2 Variable measurement

3.2.1 Carbon emission efficiency

CEE is the dependent variable of this paper. SBM model and NDDF model are constructed to calculate GEE of each province. The CEE calculated by the SBM model and the NDDF model are represented by *CEE_SBM* and *CEE*, respectively. The inputs indicators include the capital stock of each province (city, autonomous region), the total number of employees in urban units, and energy consumption. The expected output indicators are GDP and carbon emissions, and the unexpected output involves coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas. Based on this, CEE of 30 provinces (municipalities and autonomous regions) in China is calculated. Among them, the perpetual inventory method is adopted to calculate the capital stock of each province.

3.2.2 Green finance

GF is the independent variable of this paper. GF is the independent variable of this paper. GF consists of four indicators: green credit, green investment, green insurance and government support. The specific indicators are as follows:

3.2.3 Other variables

1) Control variables. *Eco* is the logarithm of real GDP per capita, which is used to indicate the economic growth level of provinces (autonomous regions or municipalities). Economic growth has driven the change of energy consumption structure and changed people's awareness of environmental protection. Thus, economic growth directly or indirectly affects carbon emission efficiency (Salahuddin et al., 2016; Wu et al., 2021). *Ind* is the ratio of the added value of the secondary industry to GDP, which is used to indicate the industrial structure of each region. The continuous increase of the proportion of tertiary industry and the continuous decrease of the proportion of secondary industry are the main reasons for the decrease of carbon emission intensity (Zhang et al., 2020). *Hum* means regional human capital. Human capital is an important support for the continuous optimization of energy structure and the continuous decline of carbon emission intensity (Cheng and Yao, 2021). *Urb* is the level of urbanization, represented by the ratio of urban population to total population in each region, and the unit is 1. Urbanization mainly affects carbon emission efficiency through population structure, economic structure and energy consumption structure (Wang et al., 2021). 2) Heterogeneous analysis variables. *ER* is a case of environmental punishment in various regions (unit: 10,000 pieces), indicating the level of environmental regulation. When there are many cases of environmental punishment in a region, we think that the level of environmental regulation in that region is higher. The impact of *ER* on energy conservation and emission reduction efficiency has been confirmed by scholars (Wu et al., 2020). Table 1 is descriptive statistical analysis.

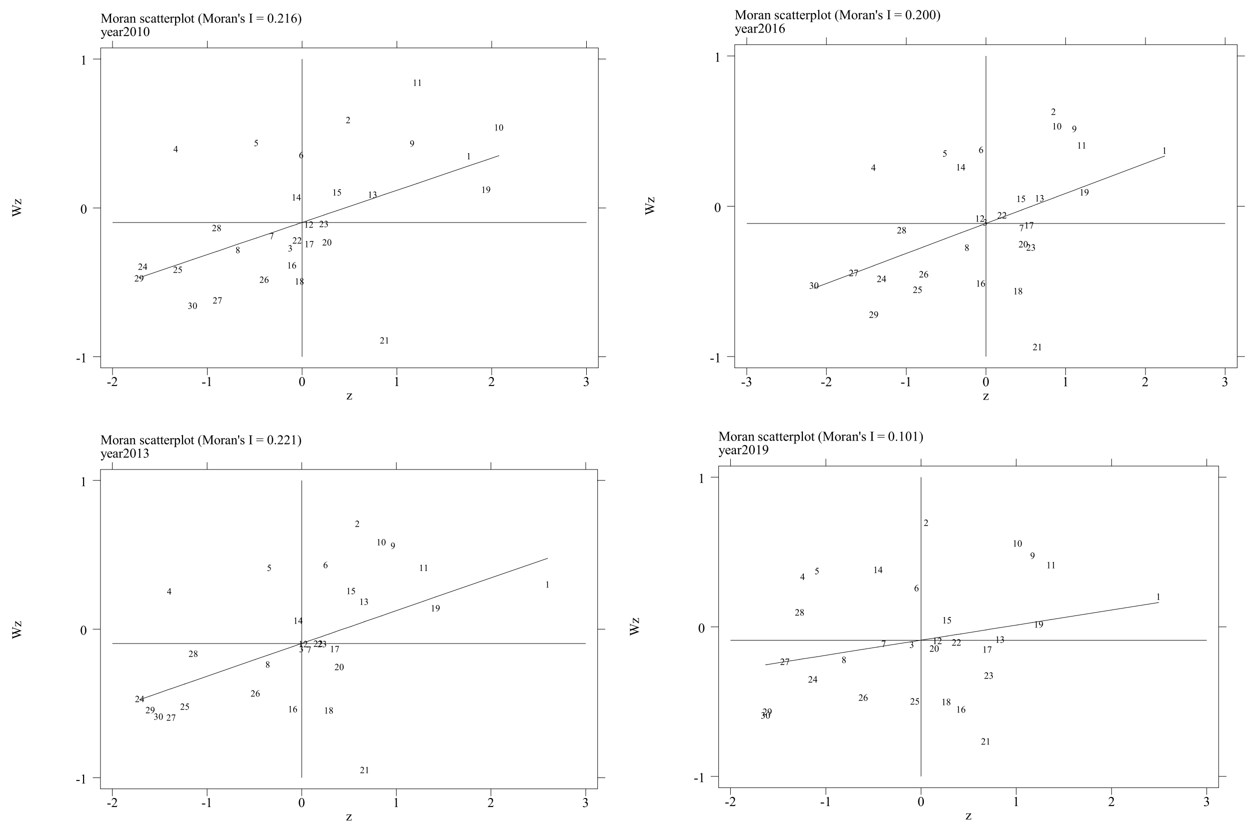

FIGURE 1
Local Moran'I scatter diagram of carbon emission efficiency of China's provinces in 2010, 2013, 2016, and 2019.

3.3 Data

Green finance data comes from *China Statistical Yearbook*, *Provincial Statistical Yearbook* and *China Insurance Yearbook*; carbon emission efficiency data comes from EPS (Express Professional Superior) database and the National Bureau of Statistics. The environmental regulation data comes from Chinalawinfo Pkulaw Database. Data for other control variables were obtained from the EPS database.

4 Empirical results and discussion

4.1 Baseline result

In Table 2, columns (1–2) and columns (3–4) are the analysis results using the OLS model and the FE (fixed effects) model, respectively. Among them, columns 1) and 3) do not add control variables, and columns 2) and 4) consider the influence of control variables. The fitting results show that no matter what model is used, and whether control variables are added or not, the coefficient of GF is always significantly positive at the level of 1%, which indicates that the development of green finance can promote the regional carbon emission efficiency and contribute to the realization of the "double carbon" goal. The overall regression results are in line with expectations. The reasons are as follows: First, green finance injects strong power into green technology innovation (Yu et al., 2021). Specifically, under the background of the development of green finance, the funds of financial institutions are inclined to green and high-tech industries, forcing the "two high and one surplus" industries to carry out green technological innovation under the constraint of funds (Wang et al., 2022). At the same time, the green finance policy can not only incite the resources of financial institutions, but also incite social capital to gather in green technology innovation of enterprises, and mobilize the vitality of green technology innovation and research and development of enterprises (Fang and Shao, 2022). Second, green finance contributes to the ecological transformation of industrial structure (Hu et al., 2020). Green finance can exert financing pressure on high-pollution industries, increase their capital cost, and force polluting industries to carry out ecological transformation (Cheng et al., 2022). To sum up, we believe that green finance can

TABLE 4 Spatial estimation result.

	Main spatial effect	Wx	Short run spatial effect			Long run spatial effect		
			Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.CEE	1.130***							
	(0.023)							
GF	0.091**	1.428***	1.230***	0.035	1.195***	12.739	0.810	11.929
	(0.042)	(0.128)	(0.109)	(0.043)	(0.103)	(110.550)	(99.406)	(146.453)
Eco	−0.035***	−0.272***	−0.249***	−0.024*	−0.225***	−2.486	0.006	-2.491
	(0.012)	(0.036)	(0.035)	(0.013)	(0.037)	(26.221)	(21.188)	(33.139)
Ind	0.306***	0.744***	0.846***	0.280***	0.566***	8.781	−0.830	9.611
	(0.039)	(0.102)	(0.104)	(0.036)	(0.095)	(82.005)	(78.750)	(112.134)
Hum	0.011**	0.009	0.017	0.011**	0.006	0.191	−0.028	0.220
	(0.005)	(0.012)	(0.010)	(0.004)	(0.011)	(1.883)	(1.751)	(2.530)
Spatial rho	0.237***							
	(0.059)							
Year Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	270	270	270	270	270	270	270	270

Standard deviation in parentheses.

TABLE 5 IV estimation result.

	(1)	(2)	(3)	(4)
	First-stage regressions		Second-stage regressions	
GF			1.266***	0.918***
			[19.835]	[7.968]
IV	1.069***	1.056***		
	(206.49)	(105.92)		
Eco		0.005		0.146***
		(1.42)		[3.565]
Ind		-0.006		0.057
		(-0.70)		[0.551]
Hum		0.001		-0.024
		(0.90)		[-1.525]
Urb		-0.012		0.106
		(-0.97)		[0.694]
Cons	-0.004***	-0.011	0.231***	0.179
	(-1.87)	(-1.07)	[9.357]	[1.481]
N			270	270
R^2	0.994	0.994	0.613	0.667

() is t value; [] is the z value.

TABLE 6 Replace variable result.

	(1)	(2)	(3)	(4)	(5)
GF	1.705***	0.747***	0.956***	0.921***	0.982***
	(14.813)	(4.566)	(5.028)	(4.697)	(4.931)
Eco		0.319***	0.290***	0.274***	0.193***
		(7.650)	(6.647)	(5.612)	(2.754)
Ind			0.353**	0.399**	0.428**
			(2.123)	(2.254)	(2.411)
Hum				0.016	-0.011
				(0.763)	(-0.400)
Urb					0.415
					(1.605)
Cons	0.407***	0.199***	0.028	-0.125	-0.024
	(10.214)	(4.371)	(0.302)	(-0.567)	(-0.102)
Fixed effect	Yes	Yes	Yes	Yes	Yes
N	300	300	300	300	300
Adj R^2	0.431	0.526	0.531	0.531	0.533

() is t value.

TABLE 7 Heterogeneity effect based on environmental regulation.

	(1)	(2)	(3)	(4)
	OLS	OLS	FE	FE
	Weak ER	Strong ER	Weak ER	Strong ER
GF	1.129***	1.080***	0.921***	0.534***
	(4.343)	(7.155)	(2.997)	(2.999)
lnpgdp	0.123*	-0.014	0.181**	0.097
	(1.668)	(-0.217)	(2.156)	(1.116)
strind	-0.073	0.209	0.181	0.661***
	(-0.429)	(1.020)	(0.955)	(3.828)
hum	0.029	-0.106***	0.010	-0.011
	(1.072)	(-3.981)	(0.489)	(-0.422)
urban	-0.129	0.949***	-0.095	0.611**
	(-0.498)	(3.382)	(-0.325)	(2.020)
Fixed effect	√	√	√	√
N	105	105	105	105
R^2	0.658	0.721	0.618	0.629

t statistics in parentheses.

improve carbon emission efficiency through green technology innovation and green transformation of industrial structure.

4.2 Spatial estimation result

In the market economy, regional economic activities do not occur independently, but are integrated and influence each other (Griffith, 2021; Feng et al., 2022). Regional linkage development has become the trend of geo-economy (Hao et al., 2021). Studies have also shown that there are obvious spatial correlations between GF (Huang and Chen, 2022) and CEE (Liu and Song, 2020) in different regions. Therefore, this paper uses spatial Durbin model to empirically test the "neighborhood effect" of GF on CEE. Firstly, Moran's I index is used to test the spatial autocorrelation of carbon emission efficiency. From the test results of Moran's I index in Table 3, the Moran index of CEE from 2010 to 2019 is significantly positive. In addition, the local scatter plots of 2010, 2013, 2016 and 2019 in Figure 1 once again prove the positive correlation between them. It shows that China's CEE presents a positive spatial agglomeration.

In order to accurately measure the dynamic change of spatial spillover effect in the model, increase the explanatory power of the model and reduce the errors of the model, this paper uses the dynamic spatial model to further test. The direct and indirect effects of the dynamic Durbin two-way fixed effect model include short-term and long-term effects. It can be seen from the estimated results in Table 4: First, the lag term of the dependent variable is obviously not zero, indicating that the CEE of the previous period will promote the development of the current CEE, and it has inertia. Secondly, the estimated coefficients of GF and W*GF in columns (1–2) are all positive, indicating that GF has a positive direct impact on CEE and spatial spillover effect. Third, compared with the short-term spatial effect, the long-term spatial effect is not significant. This shows that in the long run, the influence of green finance on CC in "neighboring" areas is not clear. To a certain extent, this shows that the road of China's green financial construction still needs to be explored. While pursuing short-term ecological benefits, we should also pay attention to the improvement of long-term green financial mechanism.

4.3 Robustness test

4.3.1 IV estimation result

There are missing variables, measurement errors and two-way causality in the empirical test, which will lead to endogenous problems, so that the regression results can't converge to the real overall parameters. In order to make the research conclusion credible, this paper uses instrumental variable method to deal with endogeneity. In this paper, the lag period of independent variable is IV, and IV-2SLS regression is carried out. Generally, the selection of instrumental variables needs to meet two conditions: first, correlation: namely, instrumental variables are related to endogenous independent variables; Second, it is exogenous: that is, tool variables are not related to disturbance terms. The IV selected in this paper satisfies these two conditions. And the F value of weak tool variables test is far more than 10. According to the regression results in Table 5, there is a strong correlation between instrumental variables and independent variables, which is significant at 1%. The regression results of the second stage show that the main conclusions of this paper are still valid after dealing with endogenous problems.

4.3.2 Replace the measurement method of dependent variable

In order to ensure the reliability of the research conclusion, this part replaces dependent variables for robustness test. Specifically, the benchmark regression part is measured by NDDF model and replaced by SBM model here. Table 6 shows the results of stepwise regression estimation. With the gradual addition of control variables, the positive effect of GF on CEE still exists, and it is statistically significant. The positive effect of GF on CEE is steady.

5 Heterogeneity analysis of environmental regulation

Regional heterogeneity exists in regions with different economic development and carbon emission efficiency (Ahmad et al., 2021). Green finance expands more

financing channels for green enterprises, on the contrary, it restricts the financing of polluting enterprises (Zhang and Wang, 2021). Therefore, it essentially belongs to the market incentive environmental regulation policy. Compared with the "soft constraint" of green finance, the mandatory environmental regulation belongs to the "hard constraint". Has China's green financial sector and environmental regulatory authorities achieved synergy, that is, in areas with strong environmental regulation, does GF play a greater role in promoting CEE? In the other case, there is substitution effect between "soft constraint" and "hard constraint". Therefore, this paper takes the case of regional environmental punishment as the proxy variable of mandatory environmental regulation, and investigates what heterogeneous influence GF has on CEE. See Table 7 for the results: columns (1–2) and (3–4) are OLS and FE estimation results, and columns 1), 3) and 2) and 4) are the results of weak and strong environmental regulation. We found that, no matter the estimation results of OLS or FE, when the environmental regulation is strong, the promotion effect of GF on CEE in this area is weak. It shows that the linkage and coordination mechanism between China's financial and environmental supervision departments is not perfect, and the two departments should establish a joint law enforcement mechanism to jointly contribute to the "double carbon" goal.

6 Conclusions and policy implications

Promoting the improvement of carbon emission efficiency is the basic requirement to achieve the "double carbon" goal, and it is also the proper path of China's realization of high-quality and sustainable economic development. Based on the data of 30 provinces in China, this paper makes an empirical analysis, and finds that green finance can significantly promote the carbon emission efficiency in this region; This promotion utility has spatial spillover effect, but this effect is significant in the short term and not significant in the long term; The influence of green finance on carbon emission efficiency is obviously heterogeneous based on environmental regulation.

First, the government is required to establish and improve the green financial development system, and innovate and enrich green financial products. The conclusion of this article shows that green finance can improve the efficiency of carbon emission, so the Chinese government should speed up the innovation of green financial instruments and promote the diversified and sustainable development of green financial market. Specific measures include encouraging banking institutions to develop financing products and services based on the pledge of ecological resources rights and interests, and piloting other innovative green bond products such as green collective bonds, water-saving loans and climate bonds for small and medium-sized enterprises. In addition, China should continue to expand the scope of the green financial reform and innovation pilot zone and promote the business model of the pilot zone.

Second, the government is required to encourage green finance, environmental protection supervision departments, enterprises and other forces to link up, coordinate and extensively carry out cooperation in the field of green finance. Doing a good job in green finance is not something that one department or one region can accomplish alone, and it needs to gather all forces. Specific measures include: increasing financial incentives to guide carbon reduction, increasing the support of financial departments and institutions, and improving the carbon supervision and statistical system. In addition, market-driven environmental regulation policies (such as green finance) and mandatory environmental regulation tools (such as environmental protection law) should coordinate with each other, establish various environmental regulation systems, and work together to promote the realization of China's "3,060″ dual-carbon goal officially promised to the international community.

Third, the government is required to build a cross-regional cooperation platform for green finance and carry out regional cooperation projects to realize communication and cooperation with surrounding areas. In view of the conclusion that green finance has a positive impact on the carbon emission efficiency of surrounding areas, we think that government departments should encourage green financial institutions to innovate financial products, disclose environmental information and exchange and cooperate with professional and technical personnel, so as to avoid resource waste caused by information asymmetry, redundant construction and disorderly competition, and promote the efficiency of financial resource allocation and use.

This article empirically analyzes the impact of green finance on carbon emission efficiency from the perspectives of "local effect" and "neighboring effect". Although this article has expanded the research scope of green finance and carbon emission efficiency, there are still some shortcomings, which can also be considered as the future research prospect: First, due to the limitation of data volume, this article only selects provincial data as the research sample, but the data of prefecture-level cities or microcosmic data may be more representative and research-oriented. Second, this article does not deeply study the dynamic impact of green finance on carbon emission efficiency. With the sustainable development of China's green finance, we will pay attention to it dynamically and strive to make the research conclusion more accurate and perfect.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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BRIEF RESEARCH REPORT
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Organizational Agrarian Protection: A Roadmap to Sustainable Green Rural Development

Yunpeng Sun, Weimin Guan*, Ying Li* and Tingting Qu**

School of Economics, Tianjin University of Commerce, Tianjin, China

To achieve its extraordinary goal of attaining the top carbon level in 2025 and eliminating carbon bias by 2045, Pakistan needs to focus on reducing carbon emissions in rural areas. Insurance for farmers is seen as a viable risk management and insurance strategy that might help spread the risk of agricultural activities and promote green rural development. In the present study, a multistage dynamic verified model was conducted from 2000 to 2019 in Pakistan, to assess the influence of a strategy of planned rural protection on green horticulture outcomes, fundamentally to characterize the unique impact system. The results indicate that rural fossil fuel byproducts are rising steadily, and implementing an agricultural protection plan significantly reduce these byproducts. In addition, this research provides practical ideas for a low-carbon rural turn of events and the formulation of vital macroeconomic horticulture techniques. It confirms the positive outcomes for strategically located agricultural insurance, and provides critical contract suggestions for reducing rural fossil fuel byproducts, and controlling initiatives in Pakistan and other countries.

Keywords: environment disaster, ecological agrarian growth, multistage active DID model, strategy suggestions, instruments

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Edited by:
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****Correspondence:***
Yunpeng Sun
tjwade3@126.com
Weimin Guan
weibe89@163.com
Ying Li
yingzijj2006@126.com
Tingting Qu
nktingting@tjcu.edu.cn

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1 INTRODUCTION

There is a consensus that the accumulation of ozone-depleting substance (GHG) releases is the primary cause of the environmental changes that are taking place (Sun et al., 2022a; Sun et al., 2022b). Pesticides and economic growth substantially impact carbon emissions in Pakistan, but short-term data show that economic expansion has a beneficial impact on carbon emissions. Pakistan significantly impacts, and is affected by, global environmental change since it is a growing, developing economy, with an enormous population of 22 billion and the lowest score (33.1/100) in the overall environmental performance index, standing at 142 ranks globally. In response to the current ecological crisis, low-carbon horticulture management can be used as an optimal tool. A low-carbon development strategy is required for emerging nations to retain their overall economic production, while emitting less carbon dioxide (Duan et al., 2020). State-run governments worldwide spend billions of dollars on farm subsidies, and international efforts have invested vital resources in horticulture protection. Agricultural carbon emissions are an essential metric for assessing the ecological impact of agriculture. As a result of numerous catastrophes, POAI was instituted. POAI refers to the direct physical and compound expenditure insurance provided by the public authority as a form of contract support (Sun and Razzaq, 2022). For soil erosion and water quality, as well as broader soil health, cover crops and decreased tillage (referred to as conservation tillage) are suggested (Gardezi and Arbuckle, 2019). Protecting horticulture is expected to have a positive effect on agricultural productivity in both rural and low-carbon contexts. Ranchers' interest in new

ventures, compound speculation, and the farming climate are all affected by mortal danger and antagonistic choice within the agricultural protection framework. The execution of a strategy is evaluated by comparing the differences in independent variables between the trial group and the benchmark group when such arrangements are put into practice . In line with the multistage dynamic difference-in-difference (DIDs) model, the present study explores the influence of a strategy of planned rural protection on outcomes in green horticulture in Pakistan.

The remainder of this article is structured as follows: Section 2 presents relevant literature and hypotheses, Section 3 outlines study data and methdology, while results and discussion are presented in Sections 4 and 5. Finally, Section 6details conclusions and recommendations.

2 LITERATURE REVIEW

When it comes to agricultural media coverage of crop insurance and cover crop use, many stories focus on farmers who could not meet crop insurance criteria while growing cover crops, and so decided to quit using crop insurance altogether (Sun et al., 2022b). The dual hazards of agriculture can be alleviated by agricultural insurance, which can help farmers better withstand risks by using green technology and reducing agricultural carbon emissions. Pesticide usage in Pakistan increased from 14,848 metric tons per year in 1987 to 78,132 metric tons per year in 2003, according to Syed and Malik (2011). According to the statistics, about 206,730 metric tons of pesticides were used in Pakistan in 2017 as a result of this rise in consumption (GOP 2017). Crop insurance might help reduce agricultural carbon emissions, but chemical inputs are a significant source of those emissions. According to the latest statistics, pesticides are used in Punjab Province, Sindh Province, Khyber Pakhtunkhwa Province, and Baluchistan Province. Even though Pakistan's Agricultural Pesticide Ordinance of 1971 provides clear guidelines for the prudent use of pesticides, many farmers still fail to follow them (PARC 2018). Generally, Pakistani farmers do not follow the required chemical measures for managing dangerous pests and weeds in their crops (Tariq et al., 2007). Agricultural non-point source pollution prevention strategies include source reduction, transmission process blocking and interception, nutrient recycling and water body ecological restoration, all of which fall into four broad categories. Green agriculture and the shift from high-carbon, widespread agriculture development to green, intensive agricultural development are both effective ways to increase agriculture's long-term sustainability. There are several advantages to exchanging point sources for non-point sources to regulate agricultural non-point sources and gain additional emissions permits (Sun et al., 2022c). However, according to Leblois et al. (2014), agricultural weather index-based insurance can help alleviate some of the problems of traditional insurance, such as asymmetric information and high transaction costs, and transfer the risk of weather disasters to insurance companies, which is essential for the promotion of index-based insurance. Insuring farmers' income, enhancing farmers' ability to withstand risk through agricultural protection facilities, and encouraging farmers to use environmental protection equipment all contribute to reducing agricultural carbon emissions (Gunnsteinsson 2020; Sun et al., 2022c). Only three nations—Pakistan, India, and the United States—collectively pay about $18 billion each year on government insurance subsidies. It may encourage farmers to take on too much risk, such as planting inappropriate crops in unsafe areas or growing more of them, which may increase future costs of insurance to the government, and may harm the environment as a result. Traditional crop insurance policies can benefit from the findings of this study, as can innovative solutions that reduce base risk while addressing the issues associated with asymmetrical knowledge. As a second objective, this article connects the research on insurance in developing countries with the more general literature on trust in organizations. Asymmetric information has been studied in recent years using a dynamic data, (DID) approach, direct data on subjective beliefs, and structural estimates (Finkelstein et al., 2005). By controlling excess field moisture and preserving organic matter, conservation methods can help reduce some of the harmful effects of climate change (Gardezi and Arbuckle, 2019). When it comes to agricultural media coverage of crop insurance and cover crop use, many stories focus on farmers who could not meet crop insurance criteria while growing cover crops and decided to quit using crop insurance altogether. The farmers' primary goal is to minimize risks and maximize income. Producers may lose coverage if they implement a conservation strategy that reduces the insured crop's production. Producers need to ensure, in any way possible, that their methods do not hinder the maturity of the insured crop. Most of the agricultural carbon emissions arise from the excessive use of agricultural chemicals, which are directly linked to the farming environment.

3 RESEARCH METHODOLOGY

3.1 Difference-In-Differences Model

Pakistan's POAI plan begins with an experimental run program, and the pilot time varies in different areas of Pakistan. With these goals in mind, the study used the DID method to examine the effects of horticulture insurance contracts on farmed fossil fuel byproduct levels in a semi-regular experiment. The following models can be used to evaluate the POAI strategy's impact:

$$\mathbf{X}_{it} = \boldsymbol{\alpha} + \boldsymbol{\beta Treat}_{it} + \varnothing \sum \mathbf{Y}_{it} + \boldsymbol{\sigma}_i + \vartheta_t + \epsilon_{it} \tag{1}$$

X_{it} refers to the reliant variable, which is the agricultural fossil fuel byproduct level of area i in t, where i refers to the territory and t refers to the year. To determine the quantity of farm-produced fossil fuel byproducts, our study examined per-capita fossil fuel byproducts (Decline). X_{it}, on the other hand, addresses several control factors at the common level(discussed further below), while $Treat_{it}$ addresses the study's central free factor (the POAI strategy). For the year, $Treat_{it}$ has a value of 1 and a value of 0 in all other circumstances. The use of an arbitrary pejorative is

TABLE 1 | Shows the sources, coefficients, and benchmarks for agricultural CO_2 emissions.

CO_2 sources	CO_2 emissions coefficient	Mentions
Fertilizer	0.5673 kg kg^{-1}	ORNL
Pesticide	2.0987 kg kg^{-1}	NIAB
Agricultural film	3.098 kg kg^{-1}	AUFP
Diesel	0.3422 kg kg^{-1}	PSO
Plowing	154.87 kg km^{-2}	AAUR
Irrigation	13.76 kg hm^{-2}	NIAB

An average thermal power coefficient of 0.819 is added to the 25 kg base to arrive at a final carbon emission coefficient of agricultural irrigation of 20.476 kg/hm^2.

regrettable σ_i and t are introduced to the scenario structure to manage the region-fixed impact and time-fixed impact, respectively, in the DID approach. When it comes to the feasibility of a strategy's implementation, the coefficient in Condition 1 is of particular interest to us. POAI techniques can alleviate rural fossil fuel byproducts if the value is significant and negative at a given factual level.

3.2 Selection of Variables

The study draws on the after-effects of IPCC and the exploration consequences of ancestors to compute horticultural fossil fuel byproduct levels, and uses per-capita fossil fuel byproducts as a reliable variable to gauge natural contamination from rural creation and cultivation. The computation strategy is displayed in Conditions 2–4, and the carbon source coefficient is expressed in **Table 1**.

$$Emission_i = \sum F_{si} = \sum R_{si} \cdot \tau_s \tag{2}$$

$$Remission_i = F_i / TRP_i \tag{3}$$

$$\text{Intensity}_i = F_i / AAV_i \tag{4}$$

For Condition 2, $Emission_i$ refers to the entire farmed fossil fuel byproduct in area I whereas F_{si} refers to different carbon sources' absolute fossil fuel byproduct in area i. Use of fossil fuel byproduct sources in region i is the carbon emission source's fossil fuel byproduct coefficient. Per-capita farming fossil fuel byproduct of area i is addressed by (Remissioni) in Condition 3, where TRP_i refers to the whole provincial population of territory i. Strength analysis below picks agricultural fossil fuel byproduct power as an example of a heavily dependent variable. As shown in Condition 4, the horticulture carbon emission power (total agricultural fossil fuel byproducts divided by agrarian added value) of area I is represented by $CIOA_i$ while the additional agricultural worth of region (agrarian) is represented as AAV_i. Uses rural financial use and all-out spending to determine how neighboring states support agriculture. Local green space creation will see positive outcomes and progress if neighboring states give greater thought to horticulture. Due to the fact that horticulture innovation and rural hardware creation levels are linked to the refreshing speed of modern development and determine the progress of green agrarian creation afterward, this study also controls the added value of an industry.

3.3 Data Collection

This study used panel data from 415 perspectives in 24 locations from 2000 to 2019 to investigate rural protection's real influence and internal component on horticulture fossil fuel byproducts. The data on farming insurance payments and agricultural subsidies were obtained from the Pakistan Bureau of Statistics, the Government of Pakistan and the Pakistan Agriculture and Dairy Farmers Associations, while control variables were gathered from the World Bank database. A detailed definition and description of variables are presented in **Table 2**.

We used Stata (Version 15.0) in this study to conduct analyses. The measurable tests are two-sided, and the p-esteem indicates if the outcome is genuinely critical. p upsides of <0.1 (*), <0.05 (**) and <0.01 (***) are thought of as genuinely critical.

4 RESULTS

4.1 Examination of POAI on Agrarian Fossil Fuel by Product Power

In this study, a multistage dynamic model was used to analyze the impact of provincial insurance pilot policies on agrarian non-renewable energy sources. Without controlling variables, Section 1 of **Table 3** presents the veritable effect of agrarian assurance on the per-capita rustic non-renewable energy source.

Further, after the circumstance controls the disaster area, guidance level, provincial assistance level, cultivating status, and various components, the coefficient sign of the Treat variable (twofold phony variable of agrarian insurance pilot) in Model 2 of **Table 3** is still significantly negative, confirming that the policy intervention has moderate decreases per-capita agricultural petroleum derivative. According to the outcome of the Treat coefficient, when various variables stay unaltered, the per-capita rural non-renewable energy source side-effects of pilot domains are decreased and center on typical differentiated and non-pilot locations, which is colossal at the level of 1%. Along these lines, the specific results attest that Pakistan's continuous plant insurance policy plays a role in mitigating non-renewable energy source side-effects. With the coefficients of the control factors, it is observed that the coefficient of farmers' run-of-the-mill extensive stretches of preparation (Tutoring) is negative and substantial at the 5% level, showing that the higher the tutoring level of farmers, the more significant effect of mitigating agricultural petroleum derivative. Meanwhile, the coefficients of agricultural disaster degree, provincial outcome regarding extent (Status), and present-day added regard (Industry) are negative, showing that the more certified the cultivating disaster degree, the higher the circumstance with agribusiness or the higher the level of current development, the lower the level of agricultural petroleum product. Besides, the coefficient of farmers' per-capita optional income (Pay) and financial assistance to agribusiness (Cash) are positively associated, certifying that the development in farmers' compensation and cultivating assistance will increase the levels of agricultural petroleum derivative.

TABLE 2 | Definitions of variables and statistics.

Variables	Definitions	Mean	SD	Min	Max
Dependent variable					
Remission	Per-capita agricultural CO_2 emissions	1.143	0.426	0.126	1.643
Intensity	Agricultural CO_2 concentration	2.243	1.426	1.344	10.321
Independent Variable					
	Treat Province i is an agricultural insurance pilot area in year t and takes the value 1; otherwise, it is 0				
Other variables					
Damage	The actual area of crops impacted	1.143	1.026	0	1.643
Education	In rural regions, the average number of years of schooling is lower	3.434	0.244	3.043	4.461
Status	The percentage of GDP added by primary industry	17.243	3.143	0.31	26.4
Income	Calculation of the natural logarithm of rural disposable income per capita	4.434	0.243	1.603	10.326
Finance	Proportion of fiscal support to agriculture in fiscal expenditure	0.426	0.263	0.043	1.443
LnIndustry	Normal logarithm of modern added esteem	4.124	1.124	1.614	10.226
Compensation	Real pay measure of horticultural protection	0.313	0.432	0	1.612
Technician	Number of rural experts	1.263	1.13	0.264	2.344
Fertilizer	Fertilizer feasting	0.134	0.13	0.002	0.426
Pesticide	Pesticide ingesting	0.231	0.26	0.054	1.262

TABLE 3 | Benchmark relapse consequences of POAI on rural fossil fuel byproducts.

Independent variable	Dependent variable	Regression
	−1	−2
Treat	−1.01** + 01	−0.105***
	(0.002)	(0.034)
Damage		−0.003
		(0.013)
Education		−0.202**
		(0.053)
Status		−0.005
		(0.007)
LnIncome		1.373***
		(0.202)
Finance		0.370***
		(0.023)
LnIndustry		−0.041
		(0.071)
Constant	1.323***	−10.045***
	(0.017)	(0.404)
Province FE	YES	YES
Year FE	YES	YES
Observations	415	415
R-squared	0.237	0.751

*The standard errors adjusted by province-year clustering are in brackets; ***, ** and * indicate significance at 1, 5, and 10%, respectively.*

4.2 Robustness Analysis: Parallel Trend and Placebo Test

4.2.1 Parallel Trend Test

The parallel trend test effectively analyzes the real effects of strategy-based rural protection experimental run programs on agricultural fossil fuel byproducts. This technique is significant in analyzing whether there is a significant difference in agrarian fossil fuel by-product levels between the pilot and non-pilot groups, and without a trace of the rural protection pilot's external influence. In line with equal pattern test approach, the present study adopts the following bidirectional fixed impact model:

$$\mathbf{X_{it}} = \boldsymbol{\alpha} + \boldsymbol{\beta}_1 \mathbf{Treat}^{-8} + \boldsymbol{\beta}_2 \mathbf{Treat}^{-7} + \ldots + \boldsymbol{\beta}_{16} \mathbf{Treat}^{8} + \sigma_\mathbf{i} + \vartheta_t + \boldsymbol{\varepsilon}_{it} \tag{4a}$$

In Condition 4, $Treat^{-7}$ is the twofold false factor taking into account the pilot time of typical techniques. At the point when the locale is in the i^{th} the year before the pilot, $Treat^{-8}$ has designated a value of 1; regardless, the value is 0. At the point when it is in the i^{th} year after the pilot, $Trearj$ is given the value of 1; for various cases, the value is 0. Likewise, to fully use the model uncertainty, data of $i \leq -8$ were associated with −8, data of $i \geq 8$ were associated with 8, and the ramifications of various elements remained unaltered. β_1 to β_8 insinuates the effects inside 1–8 years before the cultivating assurance pilot, and β_9 to β_{16} suggests the effects inside 1–8 years after the agricultural security pilot.

4.2.2 Placebo Treatment Test

This research uses Cai et al.'s (2016) approach for fake treatment testing to construct "pseudo-arrangement faker variables" by hastily designating preliminary time to ensure that the above exact ends are not influenced by ordinary elements. From 2007 to 2012, the pilot season of agricultural insurance in 30 territories was randomly picked to manufacture "pseudo contract fake factors" and 1,000 irregular examples and rehashed relapse several times as suggested by Condition 1. The x-hub alludes to the amount of the "pseudo-approach fake variable" coefficient gauge, the y-hub is the part thickness esteem, and the p-esteem is the blue speck.

4.2.3 Robustness Tests

This section includes a variety of tests designed to ensure that the observational endpoints are also credible. Most fundamentally, agricultural fossil fuel byproduct force is used as an intermediary variable of rural fossil fuel byproduct level rather than per-capita fossil fuel byproduct in Segment 1 of **Table 4**. Despite removing the autonomous center variable, the result indicated that the Treat gauge remained entirely negative, confirming the carbon reduction benefit of agricultural protection. Furthermore, in Qain

TABLE 4 | Additional robustness tests of POAI on agricultural carbon emissions.

Independent variable	Dependent variable: Intensity0		Remission	
	1	2	3	4
Treat	−0.022* (0.012)			−0.009 (0.015)
Treat*Compensation		−0.215*** (0.002)		
$Treat_1$			−0.202*** (0.015)	
Compensation		0.545* (0.245)		
Constant	12.266** (5.219)	−9.122*** (0.565)	−0.447 (0.512)	−5.555*** (0.222)
Control variable	YES	YES	YES	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observations	415	415	415	415
R-squared	0.645	0.903	0.902	0.696

*The standard errors adjusted by province-year clustering are in brackets; ***, ** and * indicate significance at the levels of 1, 5, and 10%, respectively.*

and Nunn (2011) "semi multiplier technique," the genuine horticultural protection remuneration measure is replaced by the pilot faker variable to quantify the execution power of protection sponsorships and the collaboration between the real agrarian protection pay measure and the virtual variable is added to the relapse.

As shown in **Section 2** of **Table 4**, the communication coefficient is significant, indicating that fossil fuel byproducts per capita are dropping while protection benefits continue to rise. Finally, Segment 3 of **Table 4** outlines a counterfactual experiment shifting the location of the approach. After randomly implementing the POAI strategy a year ahead of schedule, it was discovered that the assessment aftereffect of the center autonomous variable coefficient was not critical, indicating that the horticultural protection pilot's development did not have a fossil fuel byproduct reduction impact. Finally, due to the issue of missing components, all control factors were one period behind. Rural protection continues to cripple agricultural fossil fuel byproducts, as seen in Segment 4 of **Table 4**. In contrast to Segment 2 of **Table 1**, the Treat and endorsed at the 1% level, confirming the pattern's power. In summary, the power tests provide sufficient observational support for Hypothesis 1.

4.3 POAI Instrument Testing for Reducing Horticulture Carbon Emissions

Ranchers' reactions to new agrarian innovations are heavily influenced by their wealth and risk aversion. In contrast, agricultural protection plays a significant role in dispersing risks and balancing out the supply of assets. Protected farmers are more likely to update agricultural innovations and embrace environmentally friendly and skilled equipment, thereby increasing interest in rural specialized abilities. As mentors in rural development, farming professionals advise safe farmers to embrace cooperative improvements that might help reduce rural fossil fuel byproducts. This section uses cross-econometric models to investigate the beneficial effect of horticulture protection on agrarian carbon discharges due to agricultural exports.

TABLE 5 | Mechanism analysis of POAI on agricultural carbon emission.

Independent variable	Dependent variable: Remission1			
	−1	−2	−3	−4
Treat	−0.107*** (0.073)	−0.101*** (0.053)	−0.170*** (0.037)	−0.140*** (0.012)
Treat*Technician	−0.057** (0.017)	−0.042** (0.031)		
Technician	−0.035 (0.051)	−0.073 (0.034)		
Treat*FP			−0.012*** (0.007)	−0.077** (0.031)
FP			1.017*** (0.115)	0.543*** (0.067)
Constant	1.343*** (0.113)	−4.754*** (1.421)	0.701*** (0.074)	−7.042*** (1.712)
Control variable	NO	YES	NO	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Observations	510	510	510	510
R-squared	0.471	0.477	0.447	0.707

*In brackets are the standard errors corrected for province-year clustering; ***, **, and * indicate significance at 1,5, and 10%, respectively.*

The assessed coefficient of the number of farming professionals (Professional) is negative and significant, regardless of whether other factors are controlled, and the coefficient of Treat*Technician is also negative, demonstrating that POAI can reduce per-capita farming fossil fuel byproducts by increasing the number of horticultural professionals, explaining the mechanism's viability1. Second, in **Table 5**, Sections 3 and 4 show the relapse implications of Component 2. We discovered that whether or not different factors were controlled, the assessed coefficient of FP was fundamentally positive, and the Treat *FP coefficient was fundamentally negative, demonstrating that POAI

TABLE 6 | Heterogeneity analysis results: Differentiation in Eastern, Central and Western Regions.

Independent variable	Dependent variable: Remission1		
	East	West	Middle
Treat	−0.042	−1.11E + 01	−0.118**
	(0.037)	(0.022)	(0.051)
Damage	−0.016	0.045**	0.003
	(0.018)	(0.016)	(0.010)
Education	−0.142***	−0.001	−0.313***
	(0.071)	(0.053)	(0.085)
Status	−0.051***	−0.017	−0.001
	(0.01)	(0.011)	(0.011)
LnIncome	1.037***	1.035	1.307***
	(0.317)	(0.542)	(0.301)
Finance	0.170*	0.580***	0.342***
	(0.042)	(0.086)	(0.130)
LnIndustry	0.168**	0.033	-0.064
	(0.131)	(0.153)	(0.116)
Constant	−8.117**	−7.811	−5.705**
	(3.145)	(5.45)	(1.422)
Province FE	YES	YES	YES
Year FE	YES	YES	YES
Observations	177	177	64
R-squared	0.777	0.805	0.87

*The standard errors adjusted by province-year clustering are in brackets; ***, **, and * indicate significance at the levels of 1, 5, and 10%, respectively.*

reduced farming fossil fuel byproducts by reducing pesticide and manure utilization and endorsing preposition 2.

4.3.1 Heterogeneity Investigation: Contrasts in the Eastern, Focal and Western Areas

The moderation impact of rural protection on agricultural fossil fuel byproducts has been exhibited previously. Because of diverse contrasts in institutional circumstances and protection execution among regions, we theorized that this impact might be spatially heterogeneous. The fundamental assessments are displayed in **Table 6**, where the Treat gauge for the eastern and western areas are insignificant, while the carbon decrease impact of the relating horticultural protection in Central locations is substantially negative at the 5% level.

Simultaneously, the negative coefficients in Sections 2 and 3 of **Table 6** show that the rural insurance contract decreases the per-capita rural fossil fuel byproducts focal Pakistan individually, and the impact is for sure more clear than that in the eastern location. Through the above bunch test, it is affirmed that there is a heterogeneous spatial impact of the horticultural insurance contract.

5 DISCUSSION

Pakistan has had the most consecutive horticultural disasters and misfortunes. Notably during the 1990s, the frequency of disasters and the magnitude of casualties increased. Unfortunately, due to credit restrictions (Mehmood et al., 2018) and knowledge asymmetry concerning health insurance, health insurance in Pakistan is not widely available. The accelerated implementation of POAI in Pakistan has significantly improved Pakistani farming's risk mitigation capabilities, widening horticulture threats, stabilizing the horticultural market, and speeding up present farming growth. As noted in the 2019 IPCC Extraordinary Report on Environmental Change and Land, ozone-depleting substance outflows from horticultural exercises totaled 10.8 to 19.1 billion tons of emissions between 2007 and 2016, comprising 21–37% of worldwide ozone-depleting substance emanations. Therefore, green agricultural transformation is the only solution to minimize the ecological footprints of the agriculture sector. This study applied multistage dynamic DID to investigate the environmental impacts of horticultural protection. This uniqueness might be brought about by moral peril and unfavorable choice, reinforcing the replacement connection between protection and component input, empowering farmers to utilize input the increment risk and diminish inputs/risks to exert a specific influence on the farmland climate. Although POAI strategies can be compelling in reducing carbon power, the primary systems should be explained. Khan and Khan et al. (2021) confirmed with study information from eight areas in Pakistan that rural protection essentially debilitates pesticide use force, which is consistent with our findings. Second, the increment of specialized horticultural faculty can more readily direct farmers to use proficient and safe manures, low-harmfulness and low-buildup pesticides, green creation advancements, and successfully reduce farming fossil fuel byproducts. In contrast, In contrast, uninsured farmers and protected farmers are more disposed to change their horticultural creation conduct, which is from the agrarian protection. Maguire-Rajpaul et al. (2016) affirmed that agricultural protection can improve the capacity of farmers who took on natural security innovation and advance green horticultural creation. Likewise, considering the attributes of protection plans and the extraordinary contrasts in rural gamble levels in various areas, the widespread impacts of yield protection will normally fluctuate enormously. The present study confirmed speculation 3 through heterogeneity investigation and power examination. Results of the spatial heterogeneity investigation show that the impact of the carbon decrease of agricultural protection in eastern Pakistan is not on par with that in central and western Pakistan. The reason for this outcome might be that the western and central locations are overwhelmed by substantial horticultural territories. Furthermore, the advancement of rural protection in these locales has essentially advanced horticultural gamble obstruction, subsequently speeding the rate of rural natural assurance innovation, and significantly decreasing in substance utilization. Overall, results affirmed that the relief impact of horticultural protection on fossil fuel byproducts expanded step by step, justifying the need for extensive execution of the approach.

6 CONCLUSION

Changing the conventional horticultural creation method of independence and expanding activity to the green and serious current agrarian creation mode is an inescapable pattern of

farming activity. It is also unavoidable in order to develop further rural creation effectiveness and the intensity of rural item advertisements. Using adjusted board information from 24 areas in Pakistan from 2000 to 2019, this study utilized a multistage dynamic verified to investigate the "net impact" of POAI on rural fossil fuel byproducts. The study, most importantly, found that rural protection can successfully check horticultural fossil fuel byproducts, and fossil fuel byproduct force of the execution areas diminished, which has incredible importance for guaranteeing ranchers' pay, making farming more efficient, acknowledging supportable agrarian outcomes, and enhancing green rural economy. Furthermore, the restraining impact of farming protection on horticultural fossil fuel byproducts occurs because of the significant decrease of pesticide and compost inputs and the increment of agrarian specialized staff. The results confirmed that farming insurance contracts lead to carbon decreases in central and western territories, demonstrating the need to develop individualized horticultural protection contracts. This article presents the results of strategy-situated horticultural insurance, offering a reference for the public authority to advance the current farming protection sponsorship framework through developing a contract direction component for national ecological security. Accordingly, we propose best practice rules for enhancing the plan and execution of horticultural protection, adding a green sponsorship component to help the advancement of low-carbon farming and improvement of agribusiness. Thus, public authorities would allow the execution of horticultural insurance, continually work on supporting contracts and measures for rural protection, speed up the extension of farming protection inclusion, and give full play to the job of agricultural protection as a stabilizer and supporter in current green agrarian creation. Second, policymakers should upgrade the current rural insurance sponsorship framework, focus on building a low-carbon green appropriation instrument and supporting measures, and execute individual endowment contracts for various harvests and/or creation modes. For instance, more appropriations should be given to low-carbon and harmless ecosystem creation techniques, which will assist with increasing food security and improving horticultural climate. Third, the public authority should execute a province-specific farming sponsorship framework, increment strategy inclination for the central and western districts, and change the emphasis of horticultural protection from "safeguarding creation costs" to "safeguarding grain yield" and "safeguarding neighborhood attributes". Fourth, the public authority needs to normalize horticultural protection regulation, set flexible farming protection appropriation proportions as circumstances dictate, explain the fiasco distinguishing proof pay instrument, and direction the utilization of protection charge. To summarize, rural protection is an irreplaceable and powerful device to enable modern green farming. This study detailed the effect of farming protection on horticultural fossil fuel byproducts and its inner components, which supports recent evidence of green rural creation and gives a dependable reference to the incorporated advancement of money and agribusiness and policymaking.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YS: conceptualizing, writing, drafting-original draft; WG: data and methodology; YL: conceptualizing, writing, drafting-original draft; TQ: conceptualizing, writing, drafting.

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Industry 4.0 Powered Process Technology Innovation, Firm's Leanness, and Eco-Environmental Performance During the COVID-19 Phase

*Han Sun and Xiao Chu**

School of Business and Management, Jilin University, Changchun, China

Amid rising market competitiveness, Industry Revolution (IR) 4.0 oriented technological integration is considered an imperative driver of sustainable organizational performances and green supply chain management. This study explores the role of IR 4.0 powered process technology innovation in enhancing Leanness, Green Supply Chain Management, and Organizational Performance (including operational, economic, and environmental) during COVID-19. For this purpose, a novel conceptual framework was developed, and Partial Least Square-Structural Equation Modelling (PLSM) was employed on primary data of 314 respondents collected from Chinese manufacturing industries. Moreover, Multi-Group Analysis was also implemented to compare firms' willingness to implement IR 4.0 technologies powered process innovation. The results exhibit that Green IR 4.0 powered process technology innovation improves firm's leanness and stimulates environmental, optional, and economic performances. Similar findings are endorsed through the green supply chain management channel. Manifestly, COVID-19 instigated firms to adopt IR 4.0-based technological processes for efficient supply chain management. Based on these results, organizations are recommended to integrate IR 4.0 induced technology innovation to spur manufacturing firms' eco-economic and operational performance.

Keywords: industry revolution 4.0, COVID-19, technology innovation, green supply chain, environmental performance

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Iqra University, Pakistan

****Correspondence:***
Xiao Chu
chuxiao9999@sina.com

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1 INTRODUCTION

In recent times, firms have been facing immense pressure to have a higher level of technology and, accordingly, transform their supply chain to maintain their relevance in the market (Giovanni and Cariola, 2021). In addition to this, with the ongoing debate related to the relevancy and scalability of the Industry Revolution (IR) 4.0, several technological solutions are available. These include the internet of things, big data, Cyber-physical systems, Augmented Reality (AR) and simulation, 3D printing, Automated Guided Vehicles, and so on (Ivanov et al., 2019; Kanapathy et al., 2022). These solutions are designed to bring operational excellence in organizations by deploying green investments and offering a solution through technology innovation (Preeker and De Giovanni, 2018).

Conventionally, specific solutions related to manufacturing have been reported as consistent, reliable, and robust for operational excellence. Among them, the philosophy of lean is the most

utilized and followed (Jasti and Kodali, 2015; Buer et al., 2018). Lean manufacturing philosophy has been explained as a combination of multiple operations and practices deployed to eliminate non-value-added activities and all kinds of wastes, including human motion, inventory, process duplication, and so on (Womack et al., 1990). In lean philosophy, the organization aims to enhance their productivity and efficiency, performance, sales, customer value, and satisfaction (Yang et al., 2011) through implementing best practices of lean; organizations tend to attain the leanness at a certain level (Genc and De Giovanni 2018).

In terms of environmental friendliness, lean practices should positively affect environmental quality; however, scholars have a certain level of disagreement regarding this relationship (Giovanni and Cariola, 2021). Researchers in favor of positive relationships highlight that implementing lean practices reduces wastage and excessive operations that negatively affect the environment (Genc and De Giovanni, 2017). However, researchers also argue that both phenomena can have negative relationships. This is because a lean organization which is principally operated as customer-focused and incorporates customization by customers will have production batches that are relatively larger with small sizes, leading to additional startup and processing costs, and in turn to the destruction of the environment (Venkat and Wakeland, 2006). And this situation does not just reside with the manufacturing firm itself; it follows along the whole supply chain (Giovanni and Cariola, 2021). Therefore, there is a need to explore these relationships better.

In addition, the regular worsening and destruction of ecology and human health is motivating individuals to consume responsibly (Najmi et al., 2021a) and demanding organizations fulfil their extended responsibilities (Najmi et al., 2022). Moreover, not just customers but also government institutions are forcing organizations to increase compliance with the rules and directives governing environmental safeguarding (Ahmed et al., 2021). Therefore, organizations are transforming their supply chain towards more environmentally friendly decisions and moving towards having practices oriented to Green Supply Chain Management (GSCM) (Ahmed et al., 2018). It does not just include the incorporation of environment orientation in the forward supply chain, sourcing, manufacturing, and selling, but also includes the disposition of product when it is consumed (Najmi et al., 2021b), calling back products (Najmi et al., 2019), and recycling (Razzaq et al., 2021). Nevertheless, implementation of GSCM is not easy, and requires sound financial investment and participation of all related stakeholders (Ahmed et al., 2020a).

Innovation is a term that reflects novelty, recency, advancement, and high efficiency, and is considered an important determinant of organizational performance and competitiveness (Ahmed et al., 2020a). Therefore, despite the association of lean GSCM with organizational performances, there will still be a need for innovation to assist in achieving operational, economic, and environmental excellence (Ahmed et al., 2020a; Giovanni and Cariola, 2021). Especially in recent times, when the technological solution of IR 4.0 powers involve innovation, there is the highest probability that organizational performance excellence will be easily achieved. However, these require empirical investigation to back the arguments with practical justification and reasoning. Hence, this study seeks the answers to the following research questions:

RQ1: To what extent do lean and GSCM contribute to excelling organizational performances (including operational, economic, and environmental)?

RQ2: How does IR 4.0 powered process innovation enhance the relationships of lean and GSCM with organizational performances (including operational, economic, and environmental)?

2 LITERATURE REVIEW

2.1 Leanness and Green Supply Chain Management

The operationalization of lean practices to acquire a competitive advantage is integral, especially in current manufacturing in challenging business environments (Giovanni and Cariola, 2021). Moreover, it has been reported in a study that more than 80% of the studied sample agree to adopt the lean strategy in their manufacturing operations for the attainment of a competitive advantage (Dombrowski and Mielke, 2012). Whenever there is a discussion of lean philosophy, there are some crucial elements that form its foundations. These include: reduction in the generation of waste and non-value added activities, reduction in excess inventory and lead times, and the transformation of the overall organizational culture where continuous improvement and innovation are encouraged (Martínez-Jurado and Moyano-Fuentes, 2013; Giovanni and Cariola, 2021). Similarly, lean manufacturing has been explained as a value addition process in which there is a transformation of raw material into a value-added product after following the principles of lean as discussed earlier (Jasti and Kodali, 2015; Buer et al., 2018; Genc and De Giovanni, 2018). In addition to this, when a firm follows the lean philosophy and reduces the generation of waste by improving resource optimization, it eventually contributes to the greenness of the environment, and such practices and operations are considered environment-friendly operations (Giovanni and Cariola, 2021).

According to Dües et al. (2013), there is a high correlation between lean and green when operationalizing and integrating them at different levels, including fulfilling customer demands, reducing lead times, and improving product design. On the other hand, companies that implement lean practices move towards green philosophy (Franchetti et al., 2009; Inman and Green, 2018). The concept of Green Supply Chain Management (GSCM) revolves around the ideology of collaboration and coordination among the supply chain partners for environmental betterment and well-being (Wong et al., 2015; Ahmed et al., 2018). Hence, for the coordination, there is a need to have synergy among the partners and a common understanding of environmental protection. GSCM has pushed the philosophies beyond the boundaries of a single organization (Vachon and Klassen 2006). Researchers agree that for an environment-friendly operation that follows the GSCM principles, the manufacturing concerns need to be efficient

(De Giovanni, 2016; Colicchia et al., 2017). Hence it is proposed that:

H1a: Leanness of the organization directly enhances the level of organizational GSCM.

2.2 Leanness and Organizational Performances

In the current study, there are three kinds of organizational performances studied. These are environmental, operational, and economic performances. Considering the relationship between leanness and ecological performance, despite the positive attributes that leanness contributes to environment and ecology, there is a disagreement in terms of the nature of the relationships (Giovanni and Cariola, 2021). For instance, Dhingra et al. (2014) reported that firms could easily improve their corporate reputation and profile in terms of greenness through leanness. However, not all leanness necessarily contributes to the environment. For instance, removing excessive inventory is one of the principles of leanness, and by doing that, there will be the production of small batches; however, due to such small batches, there will be more frequent transportation expenses across the supply chain, thus leading to environmental pollution through carbon emissions (Venkat and Wakeland, 2006; Ramani and De Giovanni, 2017). Hence, there will be a tradeoff on whether the organization should opt for leanness or greenness as products and resources optimization are often done at the cost of the environment (Inman and Green, 2018). Despite this, leanness foundations are built on the principles of waste elimination; thus, it will also be beneficial for the environment. Hence it is proposed that:

H2a: Leanness of the organization directly enhances organizational environmental performance.
H2b: Leanness of the organization indirectly enhances organizational environmental performance.

There should not be any doubt that whichever firms opt to have leanness in their operations is doing it to improve their operational and financial performance (Martínez-Jurado and Moyano-Fuentes, 2013). For instance, when the firm is willing to reduce the lead time without impairing any other efficiencies and eventually do it successfully, it will improve both operational and economic performances (De Giovanni, 2017). However, this is not the case in every situation. For example, for customer service, if a firm offers customized products, it is challenging to handle operationally. In contrast, when the firms implement a continuous improvement philosophy, frequent changes adversely affect economic and operational performances (Giovanni and Cariola, 2021). Additionally, during these changes, there will be an additional expenditure of training, monitoring, sacrifice of product quality, and so on (Duhaylongsod and De Giovanni, 2019). However, leanness is expected to enhance the organizational operational and economic performance in the long-term. Hence it is proposed that:

H3a: Leanness of the organization directly enhances the level of organizational operational performance.
H3b: Leanness of the organization indirectly enhances the level of organizational operational performance.
H4a: Leanness of the organization directly enhances the level of organizational economic performance.
H4b: Leanness of the organization indirectly enhances the level of organizational economic performance.

2.3 Green Supply Chain Management and Organizational Performances

As already discussed, the concept of GSCM encompasses all of the aspects of the typical supply chain (Ahmed et al., 2018) and enhances the level of collaboration between the supply chain partners (Ahmed et al., 2021) for environmental betterment and well-being (Ahmed et al., 2020b). In addition to this, for successful implementation of GSCM, firms need to have suppliers on board (Najmi et al., 2020), transformation of internal operations towards green (Ahmed et al., 2019), and the concerns of the relevant stakeholders (Ahmed et al., 2021). Through the implementation of GSCM, there are several benefits that a firm can extract. These include improvement in profits because of resources' optimization (Ahmed et al., 2021), an increase in sales due to improved corporate image and reputation (Giovanni and Cariola, 2021), and extending competitive advantage (Rao and Holt 2005). In addition to this, researchers have documented the positive association between GSCM and competitiveness and environmental excellence (Chen et al., 2015), economic performance (Bowen et al., 2003), and operational performance (De Giovanni and Ramani, 2017). However, certain researchers are against these findings (see De Giovanni and Vinzi, 2014; De Giovanni (2017); Rao 2002). Hence, despite the contrasting evidence, it has been assumed that:

H5a. GSCM directly enhances the level of organizational Environmental Performance
H6a. GSCM directly enhances the level of organizational Operational Performance
H6b. GSCM indirectly enhances the level of organizational Operational Performance
H7a. GSCM directly enhances the level of organizational Economic Performance
H7b. GSCM indirectly enhances the level of organizational Economic Performance

2.4 Environmental Performance, Operational Performance, and Economic Performance

The different aspects of organizational performances have interesting relationships within themselves. For instance, for environmental performance, firms opt for consuming green inputs that normally are not up to the mark in terms of quality, which adversely affect operational performance and economic performance (Kirchoff et al., 2016). On the other

hand, implementing green initiatives for environmental performance, which are comparatively dearer than conventional investments, leads to adverse effects financially, but the benefits are reaped over a longer period of time (Ahmed et al., 2018). Thus, despite the contrasting evidence, it has been assumed that:

H8a. Environmental performance directly enhances the level of organizational Economic Performance
H9a. Environmental performance directly enhances the level of organizational Operational Performance
H9b. Environmental performance indirectly enhances the level of organizational Operational Performance

In addition to this, theoretically, operational performance directly correlates with the firms' economic performance. This is because, for improving operational performance, an organization takes certain initiatives, like improving productivity, optimizing resources, eliminating non-value-added activities, improving sales, enhancing market share, attaining competitive advantage, and so on (De Giovanni and Zaccour 2019; Ahmed et al., 2021). And by doing that, it is more likely that this will improve the organization's financial position, profits, and economic performance.

H10a. Organizational Operational Performance enhances the level of organizational Economic Performance.

2.5 Interaction of Process Innovation Through Industry 4.0 Technologies

Another objective of the current study was to explore the role of Industry revolution (IR) 4.0 powered process innovation in better organizational outcomes. Though the organizations are quite aware of their environmental responsibilities and are taking necessary initiatives to meet their environmental targets, they are either reluctant or not sure about the benefits and scalability of innovation through IR 4.0 powered technologies (Chiarini et al., 2020). On the other hand, Liu and De Giovanni (2019) confirms the association between GSCM, leanness, and organizational performance. Furthermore, Buer et al. (2018) highlighted that IR-based innovation is being made to improve productivity and efficiency, which aligns with the principles and foundations of lean. With the help of investing in IR 4.0, firms will be in a position to incorporate smart technologies like the internet of things, robotics, big data, cyber-physical systems, and so on (Kanapathy et al., 2022), which improves the operational, economic, and environmental outcome of the organization. However, due to the stakeholders' reluctance, rigidness, and non-cooperation, firms resist taking such initiatives. Hence, the present study intends to compare whether that companies are willing to implement process innovation powered by IR 4.0 technologies are better in their operations than those companies that resist. Therefore, it is proposed that:

H1–H10c: IR 4.0 powered process innovation enhances the earlier proposed hypotheses (H1–10).

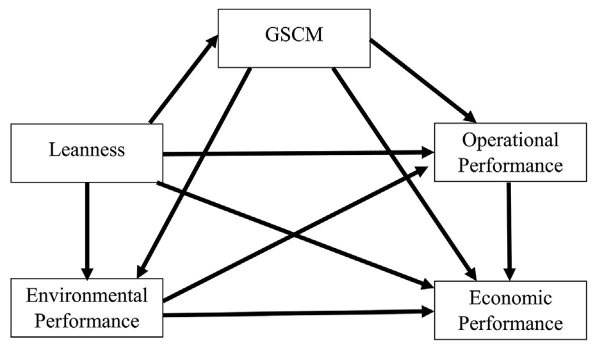

FIGURE 1 | Framework of the study.

The conceptual framework is presented in **Figure 1**, following the above discussion.

3 METHODOLOGY

3.1 Research Approach and Design

To empirically investigate the proposed hypotheses (discussed in the previous section), the current study utilizes the Quantitative research approach. It involves the numeric data drawn by the outcome, logic, and results. After incorporating specific statistical analysis, it should also be noted that because of this kind of research approach, the logical conclusions and outcome can be drawn by utilizing the primary data collected from the potential samples and that such findings are treated as generalizable for the whole population, of which such a sample is representative of (Cooper et al., 2006). Moreover, within the quantitative research approach, there are various research methodologies that can be selected depend upon the objectives and nature of the study. Likewise, following the current study's objectives, the survey research design was chosen. In such a research design, a survey questionnaire is developed that reflects the studied phenomena and upon which the potential respondents' responses are sought. However, this methodology needs to be followed by addressing certain precautions as, otherwise, the collected data and the generated outcome could be biased and inferior. Therefore, following the guidelines of Hulland et al. (2018), there was a development of a survey questionnaire that intends to ask the questions measuring the studied phenomena and the queries catering for the demographic information of the respondents discussed in the following section.

3.2 Questionnaire Development

As mentioned earlier, for the purpose of collecting the data, a survey questionnaire was designed, which was self-administered and intended to measure the studied phenomena, along with the queries catering for the demographic information of the respondents. The researchers relied on the existing developed scales for measuring the studied phenomena as they have already been tested and validated in other studies. Therefore, the researchers adapted the measuring questions from the sources

TABLE 1 | Source of measures.

Constructs	Number of items	Sources
Leanness	4	Giovanni and Cariola, (2021)
Green Supply Chain Management	4	Giovanni and Cariola, (2021)
Environmental Performance	4	Giovanni and Cariola, (2021)
Operational Performance	4	Giovanni and Cariola, (2021)
Economic Performance	2	Giovanni and Cariola, (2021)
Innovation	1	Giovanni and Cariola, (2021)

listed in **Table 1**. Moreover, on all of these questions, the respondents were asked about their level of agreement on the 5-point Likert Scale, which stated that "1 represents Strongly Disagree," "2 represents Disagree," "3 represents neither Disagree nor Agree," "4 represents agree," and "5 represents Strongly Agree." Furthermore, for the demographic questions, respondents were asked about their gender, age, size, and nature of the organization they belonged to. In addition to this, following the objective of understanding the potential role of process innovation through IR 4.0 technologies in improving the overall supply chain performances, an additional question was added to the questionnaire seeking the respondent's willingness to implement such technologies for process innovation. Such a question is intended to act as the moderator and hence requires additional application of Multi-Group Analysis (discussed in **Section 4.3.3**).

3.3 Face and Content Validity

Apart from relying on the same statements, the researchers also validate the understanding of the questions through the experts about the face and the content. The purpose behind this is to remove confusion and ambiguity that may arise in the respondents' minds when responding to the survey questions. Since the current study is based on the data collected from the Chinese respondents, and as the respondents' first language is not supposed to be English, therefore the comprehension of the statements of the measurement scale needs to be easy to comprehend and understand. Therefore, a panel of five experts comprising of two languages and three subject-related individuals was consulted. The comments and improvements suggested by the individuals were incorporated, and then the questionnaire was made available for the data collection.

3.4 Sample and Data Collection

Since the geographical context of the current study resides in China and the study's objectives are focused on resource optimization and environmental well-being, only the supply chain professionals from those companies were approached for data collection through the questionnaire that is, ISO14001 certified. Initially, 1,000 questionnaires were circulated, and 390 respondents responded, leading to a response rate of 39%. Among those 390, the responses having missing values and identified as univariate and multivariate outliers were eliminated following the discussions by Hair et al. (2010), leading to the useable sample of 314 respondents upon which the statistical analysis was applied.

TABLE 2 | Descriptive statistics.

		Frequency	Percent (%)
Gender	Female	132	42
	Male	182	58
	Total	314	100
Age	30 or less years	74	24
	31–40 years	141	45
	41–50 years	91	29
	51 and above	8	3
	Total	314	100
Size (Number of Employees)	Less than 100	90	29
	101–250	102	32
	251–450	79	25
	More than 450	43	14
	Total	314	100
Industry	Automobile	74	24
	Electronics	119	38
	Chemical	49	16
	Pharmaceutical	45	14
	Others	27	9
	Total	314	100

Source: Authors Estimation

3.5 Ascertaining Common Method Variance

In the research involving survey design, there is a significant likelihood of having methodological and operational biases, which accordingly need to be controlled; otherwise, they lead to distorted and inaccurate outcomes (Podsakoff et al., 2012). Such kinds of unexpected and unwanted variance, which have the potential to inflate the outcome, are termed as "Common Method Variance" (CMV) (Podsakoff et al., 2003). Hence, for the exploration, the study employs Harman's (1967) single factor test also applied in other related studies (see Najmi and Ahmed, 2018). In addition to this, another test was applied to gauge the level of CMV proposed by Kock (2015) and is named Full Collinearity Assessment. Both of the tests nullify the presence of CMV.

3.6 Demographic Profile of Sample

The final data sample for the current study comprised 314 respondents that belong to the ISO 14001 certified companies from China. The majority of the respondents were male, accounting for 58%, and were aged between 31 and 40 years, accounting for 45% of the data. In terms of the size of the companies the respondents belong to, 90 (29%) were from

TABLE 3 | Measurement model results.

Variables	Items	Factor loadings	Cronbach's alpha	Composite reliability	AVE
Leanness	LEAN1	0.799	0.786	0.829	0.695
	LEAN2	0.756			
	LEAN3	0.746			
	LEAN4	0.876			
Green Supply Chain Management	GSCM1	0.768	0.784	0.775	0.515
	GSCM2	0.718			
	GSCM3	0.715			
	GSCM4	0.906			
Environmental Performance	ENP1	0.762	0.803	0.800	0.545
	ENP2	0.833			
	ENP3	0.763			
	ENP4	0.847			
Operational Performance	OPR1	0.890	0.776	0.713	0.540
	OPR2	0.760			
	OPR3	0.899			
	OPR4	0.767			
Economic Performance	ECP1	0.819	0.754	0.711	0.703
	ECP2	0.827			

Source: Authors Estimation

companies with less than 100 employees, 102 (32%) were from companies with employees between 101–250, 79 (25%) were from companies with employees between 251–450, and 43 (14%) were from companies with greater than 450 employees. In terms of the nature of the business, 74 (24%) were from the automobile industry, 119 (38%) were from the electronics industry, 49 (16%) were from the chemical industry, 45 (14%) were from the Pharmaceutical industry, and 27 (9%) were from industries other than those mentioned earlier. The demographic profile of the respondents are listed in **Table 2**.

4 ESTIMATIONS AND RESULTS

Based on the objective and the conceptual framework proposed in **Figure 1** and exploring the direct relationships of predictors with the criterion variables, the current study also explained the indirect and the exploration of the role of technological innovation as moderator. Therefore, because of the complexity of the research framework, the current study employs the application of Partial Least Square-Structural Equation Modelling (PLS-SEM) as its technique belongs to the second generation and is known for explaining greater variance from the data when the models are complex (Hair et al., 2019). However, the application of PLS-SEM was made through SmartPLS, which was designed by Ringle et al. (2015). Additionally, the guidelines discussed by Hair et al. (2016) were followed, which suggested applying PLS-SEM in two stages. The first stage involves assessing the outer model, and the later stage consists in evaluating the inner model.

TABLE 4 | Results of loadings and cross loadings.

Variable	Lean	GSCM	ENP	OPR	ECP
Leanness	0.371	0.373	0.388	0.306	0.294
	0.373	0.390	0.388	0.346	0.336
	0.287	0.290	0.368	0.386	0.280
	0.291	0.349	0.342	0.341	0.284
Green Supply Chain Management	0.347	0.322	0.349	0.343	0.365
	0.294	0.285	0.360	0.364	0.365
	0.377	0.378	0.292	0.279	0.350
	0.336	0.388	0.315	0.319	0.274
Environmental Performance	0.387	0.339	0.325	0.289	0.293
	0.366	0.372	0.381	0.283	0.331
	0.338	0.314	0.285	0.276	0.296
	0.321	0.319	0.295	0.358	0.308
Operational Performance	0.322	0.314	0.379	0.333	0.348
	0.288	0.336	0.373	0.368	0.383
	0.345	0.317	0.286	0.292	0.361
	0.299	0.273	0.365	0.380	0.357
Economic Performance	0.373	0.282	0.359	0.350	0.380
	0.385	0.306	0.313	0.288	0.340

Source: Authors Estimation

4.1 Assessment of Outer Model

As per Hair et al. (2016) guidelines, the outer model is also referred to as the measurement model. It involves examining the relatedness of the measuring items with their respective construct, referred to as convergent validity. The level of un-relatedness that the measuring items of a construct possess with the measuring

TABLE 5 | Discriminant validity Fornell-Larcker criterion.

	Lean	GSCM	ENP	OPR	ECP
Lean	0.833				
GSCM	0.474	**0.718**			
ENP	0.451	0.445	**0.738**		
OPR	0.414	0.485	0.462	**0.735**	
ECP	0.395	0.452	0.392	0.479	**0.838**

Source: Authors Estimation

Bold values indicates that the Cross Loadings.

TABLE 6 | Results of HTMT ratio of correlations.

	Lean	GSCM	ENP	OPR	ECP
Lean					
GSCM	0.516				
ENP	0.516	0.675			
OPR	0.644	0.601	0.606		
ECP	0.639	0.588	0.584		
				0.686	

Source: Authors Estimation

items of another construct is denoted as discriminant validity (Mehmood and Najmi, 2017).

Firstly, the assessment of convergent validity is done using three criteria. The first is that factor loading must be larger than 0.7 (Hair et al. (2016); the second is that internal consistency, which is assessed by Cronbach's Alpha and Composite Reliability, should also be larger than 0.7; and Average Variance Extracted (AVE) which according to Hair et al. (2016) must be larger than 0.5. **Table 3** summarizes the assessment of convergent validity.

For the discriminant validity, three criteria have been utilized in the current study. Firstly, according to Gefen and Straub (2005), the loading of a factor into its respective construct must be higher, and the difference between the higher respective loadings and the loadings into other constructs, referred to as cross-loadings, must be greater than 0.1. **Table 4** summarizes the assessment of discriminant validity through the criteria of cross-loadings.

The second criterion for assessing discriminant validity is Fornell and Larcker (1981) criterion. According to this measure, the square root of AVE of a particular construct should be higher than all of the values representing correlations of a construct with all of the other constructs. Referring to **Table 5**, the value which is highlighted and placed at the diagonal line is the square root of AVE, whereas the values other than the diagonal values are the correlations among the constructs. It is evident that based on the criteria proposed by Fornell and Larcker (1981), the outcome listed in **Table 5** reflects the meeting of the discriminant validity.

The third criteria utilized for the assessment of discriminant validity is "Heterotrait-Monotrait ratio of correlations" (HTMT). The criteria is the latest one that Henseler proposes, and, since its proposition, has been used in many studies. Henseler et al. (2015) proposed that the threshold for HTMT is 0.85. The outcome listed in **Table 6** summarizes the HTMT correlations and confirms the accomplishment of the said criteria.

TABLE 7 | Predictive power of construct.

	R-Square	Q-square
GSCM	0.121	0.137
ENP	0.157	0.121
OPR	0.226	0.127
ECP	0.262	0.137

Source: Authors Estimation

TABLE 8 | Results of path coefficients (direct effects).

Hypothesized path	Path coefficient	C.R	*p*-value	Remarks
LEAN → GSCM	0.192	8.605	0.000	Supported
LEAN → ENP	0.270	7.659	0.000	Supported
LEAN → OPR	0.253	6.772	0.000	Supported
LEAN → ECP	0.135	7.512	0.000	Supported
GSCM → ENP	0.174	6.888	0.000	Supported
GSCM → OPR	0.154	7.036	0.000	Supported
GSCM → ECP	0.261	8.329	0.000	Supported
ENP → OPR	0.225	7.524	0.000	Supported
ENP → ECP	0.267	7.938	0.000	Supported
OPR → ECP	0.162	8.930	0.000	Supported

Note: Level of Significance (5% i.e., 0.050)
Source: Authors' Estimation

TABLE 9 | Results of path coefficients (indirect effects).

Hypothesized path	Path coefficient	C.R	*p*-value	Remarks
LEAN → ENP	0.152	6.677	0.000	Supported
LEAN → OPR	0.171	5.422	0.000	Supported
LEAN → ECP	0.123	5.823	0.000	Supported
GSCM → OPR	0.114	6.777	0.000	Supported
GSCM → ECP	0.120	6.438	0.000	Supported
ENP → ECP	0.104	5.848	0.000	Supported

Note: Level of Significance (5% i.e., 0.050)
Source: Authors' Estimation

4.2 Assessment of Inner Model

In the inner model, the predictability, relevancy, and accuracy of the predictor variables while linking them with the criterion variables is assessed, which is necessary in accordance with the guidelines proposed by Hair et al. (2016). Though for this assessment, the nature and operationalization of the predictor variables are extremely important, as their nature, number, and theoretical connectivity with the criterion variables decide the level of explanation that is, made of criterion variable. Still, there are certain thresholds that provide an interpretation to the generated outcome. For instance, Cohen (1988) suggested that with R-Square, which is the measure of "coefficient of determination", any value which is greater than 0.25 is substantial. In contrast, values found between 0.02 and 0.25 are said to be between weak and moderate. On the other hand, Hair et al. (2016), suggested that with the Q-Square, which is the measure of Stone Geisser's Cross-Validated Redundancy, that a value is acceptable if found to be more than 0. The generated outcome for these measures is listed in **Table 7**.

4.3 Hypothesis Testing

After assessing both the inner and outer models, the hypotheses testing was proposed in **Section 2** of the current study. Another advantage of using PLS-SEM is that it computes the significance by following bootstrapping, which involves generating multiple subsets from the data. According to Hair et al. (2016), the recommended number of sub-samples should be 5000. This led to the generation of robust and reliable significance.

4.3.1 Direct Effects

Firstly, the effects of leanness were studied with the rest of the variables, as shown in **Figure 1**. The impact of Leanness on GSCM is found to be positive and significant ($\beta = 0.192, p < 0.01$), which is also significant at a 1% level of significance. It reflects that an improvement in leanness by 1% will improve the GSCM by 19.2% (**Table 8**). This means that when the organization opts for maximum utilization of resources and follows the methodology of improving productivity through continuous improvement and gradual elimination of non-value-added activities, it also contributes to the philosophy of the GSCM, which shares the values with the leanness when it comes to environmental well-being, resource optimization, and elimination of waste and non-value-added activities. In addition to this, the impact of Leanness on Environmental Performance is also found to be positive and significant ($\beta = 0.270, p < 0.01$), which is also significant at 1% level of significance. It shows that an improvement in leanness by 1% will improve the ENP by 27%. This means that when the organization follows the philosophy of leanness and strives to improve productivity and continuous improvement, it will also improve environmental performance as there will be a smaller consumption of resources and operations. Similarly, leanness is also found to be positive and significant in operational performance ($\beta = 0.253, p < 0.01$), and economic performance ($\beta = 0.135, p < 0.01$) which is also significant at 1% level of significance. It is a reflection that improving leanness by 1% will improve the OPR by 25.3% and ECP by 13.5%. This is because leanness, where there is a regular elimination of non-value-added activities and an improvement in consumption of resources for optimization, will not just improve the operational performance, but also expand the economic benefits through reduction in consumption of resources and its respective optimization.

Secondly, the role of GSCM in improving organizational performances was evaluated against three aspects: environmental, operational, and economic. All of these relationships were found to be significant and positive at 1% level of significance, which means that enhancing the level of GSCM will improve all of these performances. An improvement in GSCM by 1% will improve the ENP by 17.4%, upgrading in GSCM by 1% will improve the OPR by 15.4%, and improving GSCM by 1% will improve the ECP by 26.1%. These relationships are justified when the organization strives for greenness in its operations and performance. There will be an improvement in the quality of environment as there will be a lesser level of pollution and carbon emissions, thus improving environmental performance. Similarly, due to greenness, there will be less consumption of resources due to its optimization, leading to improved operational performance. Since there will be a reduction in the consumption of resources, it will lead to improved financial performance, which is the organization's economic performance.

TABLE 10 | Results of multi group analysis (direct effects).

Hypothesized path	|Difference|in path coefficient	*p*-value	Remarks
LEAN → GSCM	0.134	0.000	Supported
LEAN → ENP	0.092	0.136	Not Supported
LEAN → OPR	0.340	0.000	Supported
LEAN → ECP	0.404	0.242	Not Supported
GSCM → ENP	0.299	0.180	Not Supported
GSCM → OPR	0.262	0.460	Not Supported
GSCM → ECP	0.229	0.196	Not Supported
ENP → OPR	0.292	0.387	Not Supported
ENP → ECP	0.337	0.302	Not Supported
OPR → ECP	0.099	0.000	Supported

Note: Level of Significance (5% i.e., 0.050)
Source: Authors' Estimation

Thirdly, the relationships among the three kinds of performances were evaluated and environmental performance was found to improve operational performance through less pollution and carbon emissions. This is because of the improved environmental performance because of the efficient utilization of resources, which leads to improved operational efficiency performance. Similarly, environmental performance is also found to improve the economic performance, as less pollution and carbon emissions will reap more financial benefits, thus increasing economic performance. Likewise, such operational performance will also lead to improved economic performance because when there is comparatively a lesser investment in resources, there will be an improvement in economic performance. The outcome of the direct relationships is listed in **Table 8**.

4.3.2 Indirect Effects

Similar to the outcome of the direct effects listed in **Table 8**, the indirect effects were also statistically significant for all of the studied relationships (**Table 9**). According to Giovanni and Cariola (2021), this kind of relationship is evidence of the presence of a long-term effects. This is because regular operations within the organization will continue improvement, elimination of waste, and reduction in non-value-added activities. These improvements in an organization's environment, operational, and economic performances are already discussed in the direct relationships. The same is seen for the association of GSCM with operational and economic performance and environment with economic performance. Thus, for organizations, the investments made in the lean and GSCM will continue to have benefits over a long period.

4.3.3 Multi-Group Analysis

In the current study, one of the objectives was to evaluate the role of process innovation through investing in IR 4.0 technologies. Moreover, since that question is categorical, a Multi-Group Analysis was performed. The group is divided into two based

TABLE 11 | Results of multi-group analysis (indirect effects).

Hypothesized path	|Difference|in path coefficient	*p*-value	Remarks
LEAN → ENP	0.114	0.364	Not Supported
LEAN → OPR	0.288	0.000	Supported
LEAN → ECP	0.163	0.202	Not Supported
GSCM → OPR	0.499	0.199	Not Supported
GSCM → ECP	0.236	0.460	Not Supported
ENP → ECP	0.251	0.000	Supported

Note: Level of Significance (5% i.e., 0.050)
Source: Authors' Estimation

on the categories and their path coefficients, and the explanation of variation is compared. If there is a significant difference between the groups, then the role of process innovation is said to be integral; otherwise, its implementation is not recommended.

The outcome generated revealed the role of process innovation in improving GSCM through Lean and improving operational performance through lean. This reflects that through lean, when non-value-added activities are eliminated, standardization in the operations is being done, and delivery time is optimized; it will improve the greenness of the supply chain, whereas these improvements in operations also lead to improving the operational performance. Additionally, the role of process innovation in operational and economic performance is also significant. This reflects that technology innovation in the process also enhances economic performance as it will optimize the consumption of resources and reap enhanced financial and economic benefits. The generated outcome of multi-group analysis for direct effects is listed in **Table 10**.

The long-term benefits of lean toward improving the operational performance are also reported through the outcome listed in **Table 11**, which remains legitimate when process innovation through technology is implemented. This suggested that organizations need to invest in the IR 4.0 technologies as it continues to reap benefits over a more extended period. Similarly, this also assists in transforming environmental performance into economic performance. Hence, improving environmental performance for a long time through process innovation powered by IR technologies will enhance financial performance. The generated outcome of multi-group analysis for indirect effects is listed in **Table 11**.

5 CONCLUSION AND RECOMMENDATIONS

The surge in competition urges market organizations to instigate innovation and remain relevant and competitive. For that, it is of the utmost importance that organizations have increased productivity and efficiency, which eventually will assist them in attaining and sustaining competitive advantage. Following the restrictions by government agencies and pressure from customers and other related stakeholders, a firm needs to think beyond its own financial gains and benefits. Moreover, the gradual destruction to the quality of the environment and ecology demands firms to have environmental excellence in addition to economic and operational well-being.

The conventional solution to address the operational, economic, and environmental problems is implementing lean and green practices within the supply chains. For operational and economic excellence, firms heavily rely on implementing lean practices. In contrast, to mitigate the adverse repercussions to the environment, the implementation of GSCM practices is beneficial. However, both lean and GSCM share a significant portion of similarity as both philosophies urge to mitigate wastages and elimination of non-value-added activities. However, having the right fit between the two needs to be attained by firms. This is because if a firm opts for improving operational performance and targets the elimination of excessive stock, it will, through reducing the amount of inventory and production, but it increases the startup of the machinery and the level of pollution due to such a rapid startup. On the other hand, when firms opt to consume green inputs, they are likely to increase their financial expenditure as such green products are relatively more expensive than conventional products. Hence, the right strategic fit between leanness and GSCM must be maintained.

To attain the strategic fit, firms need to have technological innovation that are deployed to improve the supply chain processes. Additionally, in the era of IR 4.0 there are several potential solutions available to firms through which organizational excellence in terms of performance can be achieved. However, firms still seem resistant when they are told about innovation, technological advancements, and business operation changes. Therefore, the present study is conducted to explore the role of Industry Revolution 4.0 powered process innovation in enhancing the Leanness, Green Supply Chain Management, and Performance of the Organization (including operational, economic, and environmental). Through the employment of a survey research design, a self-administered questionnaire was formulated, through which 314 responses from supply chain professionals working in ISO 14001 certified Chinese manufacturing companies were received. With the collected data, the application of PLS-SEM is made to assess the nature and significance of direct and indirect relationships, whereas Multi-group Analysis was applied to assess the presence of difference of variances between the relationships of firms willing to implement the process innovation powered by IR 4.0 and the firms not willing to implement. The generated outcome reported significant and positive relationships among the studied hypotheses, whereas, while assessing the interaction effect of technological process innovation, a few of the relationships were found to be significant and supported, which are thoroughly discussed in **Section 4**.

Based on the findings, the current study offers multiple policy implications. Firstly, the empirical evidence suggests that there is no one-size-fits-all solution regarding the generic level of strategic fit. Firms need to obtain an equilibrium point according to the nature of their business and respective operations. Secondly, both leanness and GSCM enhance the performance; therefore, firms need to promote a culture of innovation, advancements, and

continuous improvements through which any sort of structural and/or operational changes are welcomed by the internal and external stakeholders of the supply chain. Thirdly, since the cost of technology and advancements is expensive and firms used to have a low return of investments in the short run, any decision regarding technology implementation should not be backed by short-sightedness and must be given enough time to reap the expected financial, operational, and environmental benefits. Lastly, firms need to encourage the other supply chain partners in terms of their support, acceptance, and transformation towards more environment-friendly initiatives.

Based on the limitations, there are also various future research recommendations. Firstly, firms need to explore the determinants and success factors that can assist in implementing lean and green initiatives. Relevant literature has urged the exploration of the role of top management support, employee commitment, collaboration and integration among the partners, etc. Secondly, the current study is based on data from multiple companies, which may have a certain level of heterogeneity that is, quite obvious because of the change in the nature of the business. Therefore, there is a need to have industry-specific studies to draw precise conclusions and recommendations. The current study explains only linear relationships among the variables in terms of methodology. Thus, exploration through machine learning-based techniques can assist in exploring non-linear variance among the studied phenomena. Lastly, the current study is based on the operationalization of lean and GSCM as generic constructs. Hence, it is recommended to explore the relationships of the practices precisely and separately like eco-design, elimination of waste, reverse logistics, and integrated environmental management.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The data used in this study is a part of funded project and not allowed to share. However, required information can be obtained from Corresponding author. Requests to access these datasets should be directed to the data can be obtained from Corresponding author.

AUTHOR CONTRIBUTIONS

HS and XC equally contributed and completed all thesis together.

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EDITED BY
Cem Işık,
Anadolu University, Turkey

REVIEWED BY
Hayot Berk Saydaliev,
Institute of Forecasting and Macroeconomic Research, Uzbekistan
Md Shabbir Alam,
University of Bahrain, Bahrain

*CORRESPONDENCE
Md. Qamruzzaman,
zaman_wut16@yahoo.com

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Nexus between uncertainty, remittances, and households consumption: Evidence from dynamic SUR application

Ying Yin[1], Md. Qamruzzaman [2]*, He Xiao[3], Ahmed Muneeb Mehta [4], Farah Naz Naqvi[5] and Imran Ali Baig [6]

[1]Agricultural Bank of China LTD Nanjing Chengbei Sub-branch, Nanjing, Jiangsu, China, [2]School of Business and Economics, United International University, Dhaka, Bangladesh, [3]School of Political Science and Economics, Waseda University, Tokyo, Japan, [4]Hailey College of Banking and Finance, University of the Punjab, Lahore, Pakistan, [5]Hailey College of Banking and Finance, University of the Punjab, Lahore, Pakistan, [6]Department of Economics, Aligarh Muslim University, Aligarh, India

Household consumption induces aggregated economic activities by pushing market demand, capital accumulation and financial growth in the economy; on the other hand, instability in household consumption adversely affects the overall economic progress. Thus, exploring the key determinants responsible for household consumption instability is essential. The motivation of the study is to gauge the role of pandemic uncertainties and remittance inflow on household consumption in lower, Lower-middle, and Upper-Middle-income Countries for the period 1996 to 2020. The study employed several econometrical tools, including a panel cointegration test with the error correction term, dynamic SUR. The panel unit root test following CADF and CIPS documented variables are stationary after the first difference, and long-run associations are confirmed with the panel cointegration test. The coefficient of Dynamic Seemingly Unrelated Regression exposed pandemic uncertainties and has a negative impact on household consumption in all three-panel estimations; however, the coefficient of PUI is more prominent with COVID-19 effects. Remittances' role in household consumption was positive and statistically significant, suggesting migrant remittances encourage additional consumption among households. On the policy aspect, the study proposed that the government should undertake macro policies to manage policy uncertainties so that the normal course of consumption level should not be interrupted because household consumption volatility creates discomfort in aggregated development. Moreover, efficient reallocation and remittance channels should be ensured in the economy; therefore, efficient institutional development has to be confirmed.

KEYWORDS

households consumption, remittances, pandemic uncertainties, dynamic SUR, COVID-19

Introduction

Household consumption, according to the Keynesian macro-economic model, plays a critical and deterministic role in ensuring economic growth with the extension of capital formulation, aggregated output escalation and elevation of aggregated expenditure in the economy. The impact of household consumption can also be discovered in financial development, poverty reduction, trade liberalization, and foreign capital flows. Thus, policymakers always seek an appropriate policy (monetary and fiscal policy) to encourage household expenditures. Furthermore, a growing number of researchers in literature have investigated the key determinants and revealed several macro and micro fundamentals. According to the existing literature, household consumption is influenced by several variables. Among those remittances, inflows have been placed on the apex. Literature suggested that remittance inflows contribute to household consumption levels by lessening income variability, security, and liquidity. The study by Adams, Lopez-Feldman (Adams, 2008) documented that households' spending behavior differs among households who received remittances and who did not.

With this study, we considered pandemic uncertainties, remittances and household nexus in the panel data estimation for lower, lower-middle and Upper-Middle-Income Countries with and without potential effects from COVID-19. In December 2019, the coronavirus (COVID-19) outbreak gained extensive media attention (Qamruzzaman, 2018; Qamruzzaman et al., 2019a; Qamruzzaman et al., 2019b; Haroon and Rizvi, 2020) and prompted widespread anxiety (Ali et al., 2020), virtually closing down most of the economy. When a virus spreads, several elements determine its economic impact, including the immediate impacts of containment attempts to control it; the duration of these containment efforts; and the amount to which direct economic implications endure, amplify, and spread across regions. Since the direct impacts of solitary confinement have been thoroughly explored elsewhere, our model does not mention them. It is worthwhile to utilize when it is more accurate than projections based on mechanically adding up the expenses of shutting down various sectors of the economy. Furthermore, as seen by widespread lockdowns and restrictions to prevent new infections, the outbreak has had a significant effect on the economic slowdown, unemployment (Uddin and Alam, 2021; Azam et al., 2022), The motivation of this study is to seek the impact of uncertainties and emittances on household consumption with the inclusion and exclusion of covid effects in empirical estimation. The study has taken into account three panels of data which are sub-grouped according to income level that is lower-income countries (LIC), Lower-middle income countries (LMIC) and Upper-Middle-Income Countries (UMIC), respectively, for the period 1996–2020. The empirical estimation has been executed by implementing several econometrical tools, including the homogeneity test, cross-sectional dependency and panel unit root test. The magnfititutes of pandemic uncertainties and remittances on household consumption has detected by performing dynamic SUR. The elasticity of pandemic uncertain tie has documented a negative and statistically significant connection to household consumption, whereas remittances support increasing household consumption by ensuring income stability and preferred liquidity.

The present study contributes to the existing literature in two folds. First, the nexus between pandemic uncertainties and household consumption with the inclusion of COVID-19 effects, for the first-ever empirical assessment as far as the existing literature is concerned. According to existing literature, a negligible number of researcher has investigated the impact of uncertainties on household consumption, while referring to pandemic uncertainties' effects on household consumption has yet to be extensively investigated. The present study intends to explore the existing literature by exploring fresh insights and establishing a bridge to mitigate the research gap. Furthermore, assessing the impact of pandemic uncertainties study has implemented an empirical model assessment to include and exclude the COVID-19 economic phenomenon. Second, the impact of uncertainties on macro fundamentals has been investigated. However, the effects of pandemic uncertainties on household consumption have yet to assess extensively. This study tried to explore fresh insight relating to the nexus between pandemic uncertainties and household consumption. Third, it is well established that remittances significantly impact a household's consumption and support stability. However, the role of remittance on household consumption with pandemic uncertainties has yet to investigate extensively. The present study has contributed to mitigating the research gap.

The remaining structure of the paper is as follows: *Introduction* deals with the relevant literature survey pertinent to the present study. The variables definition and methodology of the study are reported in *Introduction*. Data analysis and interpretation are exhibited in *Introduction*. Finally, the conclusion of the study is reported in *Introduction*.

Theoretical model

The motivation of the study is to explore the household's consumption trend due to economic policy uncertainty and pandemic-related uncertainty for the period 1996–2020. The following theoretical model has been established by following the income-expenditure relationship in an open economy (see, for instance, Wu (Wu, 2020), (Coddington, 1976; Karim and Qamruzzaman, 2020; Qamruzzaman, 2020; Qamruzzaman and JIANGUO, 2020; Jia et al., 2021; Lingyan et al., 2021;

QAMRUZZAMAN et al., 2021)). The generalized I-E economic relationship cab is reported as follows:

$$Y_t = C_t + I_t + G_t + (X - M) \quad (1)$$

Household consumption (C) can be derived by subsuming the trade balance in Eq 1 with (X-M). Therefore,

$$C_t = Y_t - I_t - G_t + TB \quad (2)$$

Furthermore, it is believed that during uncertainties, the aggregated output in the economy is adversely affected, the money flows from foreign remittances positively increase in securing households' financial security, and pandemic uncertainties have adverse effects on domestic trade expansion, that is, the trade balance will be experienced negative trend which eventually decreases overall consumption in the economy. By subsuming the focused variables in Eq 2, the empirical model can be rewritten in the following manner.

$$C_t = RE_t - I_t - FD_t + PUI \quad (3)$$

Noted that FD stands for financial development role in the theoretical model.

Literature survey

Uncertainty and household consumption

Economic uncertainty in the global economy during the COVID-19 Pandemic, according to Altig, Baker (Altig et al., 2020), is greater than before the COVID-19 Pandemic. According to Baker, Bloom (Baker et al., 2020a), COVID-19 Pandemic-related economic uncertainty has a considerable impact on macroeconomic variables (consumption, employment, and investments) and is adversely associated with stock market returns. According to Leduc and Liu (Leduc and Liu, 2020), COVID-19-related uncertainty is a substantial driver of macroeconomic indices. Following these articles, we concentrate on Ahir, Bloom (Ahir et al., 2750) Pandemic Uncertainty Index for measuring pandemic-related. Wu and Zhao (Wu and Zhao, 2021) have investigated household consumption behavior during economic uncertainty using Chinese household consumption data. The study documented that EPU has negative effects on liquidity position that household prefers to hold more liquid assets such as cash or cash equivalent by subsidizing their present level of consumption.

The COVID-19 Pandemic has had a detrimental impact on many aspects of the global economy. Governments have enacted several policy consequences to restrict the spread of the new coronavirus, which is more lethal than the virus that causes normal flu. During the COVID-19 Pandemic, governments have locked down public locations such as schools, restaurants, and shopping malls, or individuals willingly remain at home. (Fetzer et al., 2020; Ganlin et al., 2021; Pu et al., 2021; QAMRUZZAMAN et al., 2021; Xu et al., 2021; Yang et al., 2021). In the study, Guo, Liao (Guo et al., 2021) documented with survey data in China that the outbreak of COVID-19 produces tremendous concern among households in making consumption decisions, especially in managing their liquidity position. Laborde, Martin (Laborde et al., 2020) revealed that the COVID pandemic had challenged food security by raising concerns about global agricultural production disruption. Food prices rose almost immediately, and as a result, there has been substantial concern that poverty and food insecurity will rise, and the nutritional status of vulnerable groups will fall, as the pandemic continues.

Wu (Wu, 2020) has gauged the nexus between pandemic-related uncertainties and household consumption from 1996-to 2017 with a panel of 138 countries employing feasible generalized least squares (FGLS). Household consumption is adversely affected by gross fixed capital creation, government spending, balance of trade, and the Pandemic Uncertainty Index, according to the theoretical model and empirical data from the Feasible Generalized Least Squares (FGLS) estimates. The findings are also true in the panel dataset, including 42 high-income nations and 96 developing economies. Liu, Pan (Liu et al., 2020) investigated the nexus between mobile banking, pandemic uncertainties and household consumption in China by capitalizing on the micro-level data extracted from china household finance survey data (CHFS). Study findings documented that during the COVID outbreak, the household consumption level declined in rural and urban areas. Mobile banking facilitates augmented household consumption in urban areas but remains unaffected in rural areas. The study further postulated that mobile payment systems, in particular, may help consumers and organizations migrate from offline to online consumption, overcoming space and time constraints, avoiding wasteful staff mobility, and addressing consumer and corporate demands throughout the epidemic. Mobile payment is important in increasing consumption; nevertheless, it is only seen in metropolitan households. Li, Song (Li et al., 2020) revealed that pandemic uncertainties significantly impact household consumption and liquidity constraints. The study also documented that the propensity of savings willingness has increased with limiting liquidity constraints due to COVID-19 outbreaks. For tourism development, Işık, Sirakaya-Turk (Işık et al., 2020) has evaluate the effects of EPU on tourism development, study revealed that adverse association between EPU and tourism development, implying that increase of uncertainties in the economy decrease the arrival of international tourist in the economy.

Remittance and household consumption

The current economic crisis has prompted policymakers and economists to reconsider economic stabilization mechanisms. One of the most severe effects of production shocks is household consumption unpredictability, which harms the welfare of risk-averse agents. Household consumption uncertainty, according to Athanasoulis and Van Wincoop (Athanasoulis and Van Wincoop, 2000) and Pallage and Robe (Pallage and Robe, 2003), might have negative effects on the buildup of human and physical capital. The determinants of household consumption instability include financial security, financial development, economic progress, and macro diversification. In contrast, many researchers have investigated the key determinants in stabilizing household consumption and established that excess money and financial security could mitigate the adversity of household consumption (Hossain and Gani, 2022; JinRu and Qamruzzaman, 2022; Karim et al., 2022; Zhao and Qamruzzaman, 2022). Remittance inflows have emerged and placed in a position to ensure stability in income elasticity, especially in the volatile macroeconomic state.

Moreover, migration is predicted to improve household income and consumption via remittances, including cash and products sent by migrants to family members remaining in the place of origin. The study of Debnath and Nayak (Debnath and Nayak, 2022) addressed the impact of remittances on household consumption by taking a sample of 785 migrants remittances recipients located in a frequently drought-affected Bankura district in the *Rarh* region of West Bengal State of India. Logistic regression model estimation documented that households preferred remittance to maintain food costs and repay their debt obligation. Moreover, the study established remittances' role in eradicating chronic poverty and relieving the rural population from the vicious cycle of poverty by offering income liquidity and financial security. In Adams and Cuecuecha (Adams and Cuecuecha, 2010), a two-stage multinomial selection model was used to analyze household survey data collected in Guatemala in 2002. The study discovered that households receiving international remittances spend less on food expenses, and those receiving either internal or international remittances spend more on education and housing than they would have otherwise. A similar vine of evidence is available in the study of Adams, Lopez-Feldman (Adams, 2008) and Wouterse (Wouterse, 2008).

Remittance's role in reducing household consumption instability has investigated and documented the critical role that the inflows of remittances bring households consumption stability by ensuring financial security and liquidity (Combes and Ebeke, 2011; Mehta et al., 2022; Serfraz et al., 2022). This effect may be examined via changes in household migration status and consumer purchasing patterns (To et al., 2017), which is critical for determining whether migrant remittances contribute to household welfare enhancement. Additionally, if remittances are utilized to cover health and education costs, they help ensure the long-term development of human capital (Nguyen et al., 2017; Alam et al., 2020).

Limitations in the existing literature

After careful assessment of the existing literature, we have found the following limitations.

1. The impact of uncertainties on macro fundamentals has been investigated; however, the effects of pandemic uncertainties on household consumption have yet to assess extensively. This study tried to explore fresh insight relating to the nexus between pandemic uncertainties and household consumption.
2. It is well established that remittances significantly impact households' consumption and support stability. However, the role of remittance on household consumption with pandemic uncertainties has yet to investigate extensively. The present study has contributed to mitigating the research gap.

Data and empirical estimation procedure

Model specification

By taking into account the motivation of the study, the generalized empirical equation can be displayed in the following manner;

$$C_{it} = \alpha_0 + \beta_1 RE_{it} - \beta_2 I_t - \beta_3 FD_t - \beta_4 PUI + \epsilon_t \tag{4}$$

Where C_{it} stands for household consumption, RE_{it} for remittances inflows, I_t denotes gross capital formation, FD_t for financial development, and PUI for pandemic uncertainty index. The magnitudes of independent variables on household consumption established with $\beta_1 \ldots . \beta_4$ I and t represent cross-section and time, respectively.

As a dependent variable, household consumption is measured by final household consumption (constant 2015 US$) and remittances inflows are measured by Personal remittances received (current US$). Ahir, Bloom (Ahir et al., 2750) first proposed the Pandemic Uncertainty Index (PUI). This new dataset tracks national-level conversations regarding pandemics. The PUI is computed by measuring the number of words in Economist Intelligence Unit (EIU) national reports that refer to pandemic uncertainty (and its variations). Note that

TABLE 1 Results of descriptive and pairwise correlation (full sample).

	REM	*C*	*FD*	*G*	*PUI*
Panel –A: Descriptive Statistics					
Mean	18.40622	22.48694	2.238706	26.74617	19.85807
Standard Deviation	1.741595	1.099748	0.762877	2.363313	7.64975
Kurtosis	3.044949	-0.47868	1.854194	1.228285	18.42863
Skewness	-1.13121	0.091912	-1.08585	-0.91341	4.291967
Minimum	9.347575	20.16861	-0.90986	18.67719	0
Maximum	21.45386	25.24185	3.692947	31.10306	483.4768
Panel –B: pair-wise correlation					
	REM	*C*	*FD*	*G*	*PUI*
REM	1				
C	0.1123	1			
FD	0.207159	0.152923	1		
G	−0.56619	0.096122	0.539383	1	
PUI	0.548866	−0.199112	-0.17014	-0.15407	1

Estimation strategies.

TABLE 2 Cross-sectional dependency test.

	LM_{BP}	LM_{PS}	LM_{adj}	CD_{PS}	Δ	Adj.Δ
Panel –A: Lower-income countries						
HC	150.636***	39.892***	155.11***	46.422***	35.994***	82.622***
PUI	433.423***	44.034***	176.181***	14.08***	62.571***	89.099***
REM	244.745***	39.975***	104.31***	37.516***	32.622***	144.081***
FD	244.357***	35.782***	189.89***	34.332***	51.842***	97.02***
G	188.651***	39.34***	203.56***	16.437***	57.789***	104.879***
Panel –B: Lower-Middle income countries						
HC	294.172***	21.065***	194.262***	35.498***	82.515***	84.097***
PUI	274.312***	41.819***	123.25***	8.826***	53.125***	84.685***
REM	328.376***	42.868***	236.728***	11.195***	27.049***	146.317***
FD	185.497***	30.698***	175.091***	39.957***	25.356***	96.289***
G	187.431***	38.422***	147.957***	15.363***	67.887***	121.204***
Panel –C: Upper Middle-Income Countries						
HC	173.477***	34.713***	105.014***	18.424***	83.611***	62.344***
PUI	178.765***	22.864***	191.495***	55.585***	85.029***	56.051***
REM	174.937***	29.458***	187.476***	52.488***	83.68***	149.683***
FD	204.769***	21.904***	109.338***	12.626***	55.839***	137.95***
G	434.976***	25.167***	102.226***	17.775***	51.538***	130.818***

Note: the superscript of *** exhibits a significant level at a 10%.

a higher index value suggests higher uncertainty about pandemics. Apart from target variables, two additional variables are considered in empirical estimation: financial development and government expenditure. According to existing literature, financial benefits availability and investment opportunity in the financial system allows households financial mobility and liquidity, which eventually encourages consumer spending behavior. On the other hand, government spending injects money into the economy, allowing households greater scope for income accumulation. Therefore, the inclusion of financial development and government spending might have the capacity to produce diverse outcomes from empirical assessment.

The descriptive statistics of research variables display in Table 1 include panel A for descriptive statistics and the pairwise correlation matrix in Panel–B. The mean value of REM is 18.406 with a standard deviation of 1.741, indicating the range of remittances inflows of 15.671–20.014. Moreover, the minimum level of remittances is 9.347, and the maximum level of remittances is 21.453. The average household's consumption level is 22.4869, and the standard deviation is 1.099, implying the household consumption level ranges from 19.994 to 23.512. The minimum value of C is20.168, and the maximum is 25.24. The mean value of the pandemic uncertainties index is 19.85807, and the standard deviation is 7.64975, indicating the PUI range of 12.214–27.457.

According to pairwise correlation output, a positive correlation between remittances inflows and pandemic uncertainties is apparent, suggesting the migrant population has sent more money to their home country to ensure their financing security. Household consumption and PUI revealed a negative association which is expected. It implies that uncertainties discourage households from spending money on second-category demand. Furthermore, remittance inflows cause household consumption on a positive note. Excess capital flows to households allow them to maintain their present level of consumption even in a state of uncertainty.

The motivation of the study is to investigate the nexus between pandemic uncertainties, remittances and household consumption from 1996 to 2020. The study implemented Dynamic Seemingly Unrelated Regression (DSUR), which was proposed by Mark, Ogaki (Mark et al., 2005), for detecting the impact of pandemic uncertainties, remittances, financial development and gross capital formation on households consumption in LIC, LMIC, and UMIC countries. The DSUR method is practicable for panels where the number of cointegrating regression equations N is much less than the number of time-series data T. furthermore, heterogeneous sets of regressors are included in the regressions, as well as when equilibrium errors are linked via cointegration regressions, the DSUR outperforms non-system techniques such as dynamic ordinary least square (DOLS) and provides efficiency gains over these methods. Another benefit of the DSUR is that it may be used when the panel is heterogeneous or homogenous, as previously stated (Hongxing et al., 2021). The DSUR is as follows:

$$y_{it} = \gamma_{it} x_{it} + \delta_{it}^{\tau} \quad (5)$$

$$\delta_{it}^{\tau} = \alpha_i \delta_{it-1}^{\tau} + \sum_{j=1}^{n-1} \delta_{ij} \Delta x_{it-1} + \varnothing_{it} \quad (6)$$

$$\Delta x_{it} = \theta_i \Delta x_{it-1} + \partial_{it} \quad (7)$$

$$\varnothing_{it} = \rho_i \vartheta_{it-1} + \aleph_{it} \quad (8)$$

Where x_{it} is the i*k dimensional vector for explaining the explanatory variables. Where xit is the $k \times 1$-dimensional vector for the exploratory variables, the cross-sectional endogeneity and cross-sectional dependency are inflected by varying ρ_i and α_i. $xit-1$ was included to control the problem endogeneity. $\delta_{it}^{\tau} = (\delta_{1t}^{\tau} \ldots\ldots\ldots\ldots \delta_{iN}^{\tau})$. $\varnothing_{it} = \delta_{it}^{\tau'}$ It is a dimensional vector $N(K = 1)$ with a moving average representation.

Apart from the key target model, the study has implemented several data properties assessment tests by employing widely applied panel data tests, including research units heterogeneity tests by following the framework offered by Pesaran and Yamagata (Pesaran and

TABLE 3 CIPS and CADF unit root test.

	CIPS		CADF	
	At Level	Δ		
Panel –A: Lower-Income countries				
HC	−1.112	−3.643***	−1.95	−4.122***
PUI	−1.876	−5.902***	−1.086	−2.085***
REM	−1.339	−4.795***	−2.361	−4.881***
FD	−1.531	−5.577***	−2.76	−3.678***
G	−1.838	−5.751***	−2.064	−2.22***
Panel B: Lower-Middle income countries				
HC	−1.055	−7.485***	−1.858	−2.137***
PUI	−1.398	−2.407***	−1.532	−6.227***
REM	−2.67	−4.669***	−2.928	−6.913***
FD	−1.07	−4.52***	−2.149	−2.091***
G	−1.792	−2.968***	−1.967	−2.774***
Panel –C: Upper Middle-Income Countries				
HC	−1.569	−7.553***	−2.027	−4.357***
PUI	−1.171	−4.634***	−2.009	−4.485***
REM	−2.034	−6.275***	−2.583	−7.588***
FD	−1.512	−6.678***	−2.717	−5.845***
G	−2.688	−7.881***	−2.878	−7.105***

TABLE 4 Panel cointegration test.

	LIC	LMIC	UMIC
Panel v-Statistic	1.261	2.84	2.041
Panel rho-Statistic	-4.071***	-6.005***	-4.819***
Panel PP-Statistic	-10.021***	-10.026***	-9.505***
Panel ADF-Statistic	-5.84**	-2.984	-3.575*
Panel v-Statistic	-1.665	-1.074	-1.203
Panel rho-Statistic	-7.476***	-6.913***	-9.756***
Panel PP-Statistic	-7.891***	-6.089***	-8.066***
Panel ADF-Statistic	-7.653***	-11.181***	-9.879***
Group rho-Statistic	-11.574***	-10.243***	-7.831***
Group PP-Statistic	-10.289***	-10.682***	-10.449***
Group ADF-Statistic	-2.736	-4.453***	-4.978**

Note: the superscripts ***/**/* indicates the level of significant at a 1, 5, and 10%, respectively.

TABLE 5 Cointegration with an error correction term.

Model	Gt	Ga	Pt	Pa
LIC	-15.817***	-13.885***	-10.879***	-10.588***
LMIC	-6.465***	-8.994***	-7.081***	-6.459***
UMIC	-6.24***	-5.239***	-13.229***	-10.323***

Note: the superscripts ***/**/* indicates the level of significant at a 1, 5, and 10%, respectively.

Yamagata, 2008). The internal interdependency among research variables has been assessed by employing the test of cross-sectional dependency following Pesaran, Ullah (Pesaran et al., 2008), Pesaran (Pesaran, 2004). Panel stationary tests have been implemented for diagnosing the variables stationarity test following Pesaran (Pesaran, 2007), which can handle the cross-sectional dependency among research units.

Empirical results and discussion

Before implementing the target model, the study possessed several elementary assessments such as cross-sectionally dependent tests, tests of heterogeneity, unit root test, and cointegration test. Table 2 exhibits the cross-sectional dependency test results with the cross-sectionally independent null hypothesis. Regarding the test statistics and associated *p*-value from the CSD test, study findings suggest rejecting the null hypothesis, alternatively confirming the common dynamics among research units. Furthermore, the homogeneity test results documented heterogeneous proprieties in the research unit in all three data panels.

Following, Study deals with panel unit root tests by employing cross-sectionally dependent test of stationary, offered by Pesaran (Pesaran, 2007), commonly known as CIPS and CADF. The panel unit root test results in Table 3 include panel-A for LIC, Panel-B for LIMC and Panel–C for UMIC. According to the test statistics of panel unit root tests, it is apparent that all the variables are stationary after the first difference.

The long-run association study has implemented the panel cointegration test by following Pedroni (Pedroni, 2004), Pedroni (Pedroni, 2001), and Table 4 exhibits the cointegration test results. Refers to test statistics, it is apparent that most test statistics are statistically significant at a 1% level of significance, suggesting the rejection of the null hypothesis that on-cointegration. Alternatively, the study established a long-run association between pandemic uncertainties, household consumption, remittances inflows, and financial inclusion in all three panels.

Nest's study further implemented with advanced panel cointegration test by following Westerlund (Westerlund, 2007) with the null hypothesis of no-cointegration. Gt, Ga, Pt, and Pa test statistics were statistically significant at a 1% significance level, suggesting the long-run association in the empirical equation (see Table 5).

Dynamic Seemingly uncorrelated Regression

The following study performed dynamic SUR in exploring the coefficients of independent variables that are Pandemic Uncertainty Index (PUI), remittance (REM), gross capital formation (GCF), and financial development (FD) household consumption in LIC, LMIC, and UMIC. The results of the empirical estimation are displayed in Table 6.

Refers to the impact of pandemic uncertainties on household consumption, the study documented negative and statistically significant linkage in LIC (a coefficient of -0.0655), LMIC (a coefficient of -0.01362), and UMIC (a coefficient of -0.06779). In particular, a 10% increase in pandemic uncertainties can decrease household consumption by 0.655% in LIC, 0.1362% in LMIC, and 0.677% in UMIC, respectively. Our study findings are in line with existing literature see Chen, Qian (Chen et al., 2021), Wu (Wu, 2020), ACMA (ACMA, 2014), Li and Qamruzzaman (Li and Qamruzzaman, 2022), Baker, Farrokhnia (Baker et al., 2020b). The possible explanation regarding household consumption variability is the fare of unavoidable consequences due to economic uncertainties. To maintain the normal course of life, households should have to maintain financial and food security with sufficient money flows; therefore, during the pandemic, they become more

TABLE 6 Result of SUR estimation.

	With Covid-19 Uncertainties				Without Covid-19 Uncertainties			
	Coefficient	Std. Error	t-Statistic	Prob	Coefficient	Std. Error	t-Statistic	Prob
Panel –A: Lower-income Countries								
PUI	-0.0655	0.00718	-9.11160	0.0000	-0.01103	0.01328	-0.830295	0.4071
REM	0.287870	0.031698	9.081751	0.0000	0.269298	0.033980	7.925127	0.0000
FD	-0.24486	0.076311	-3.20865	0.0005	-0.19805	0.081734	-2.42312	0.0187
GCF	0.092616	0.021481	4.311613	0.0000	0.096927	0.024820	3.905194	0.0001
C	14.72003	0.791240	18.60375	0.0000	14.85685	0.894794	16.60365	0.0000
Panel –B: Lower-Middle Income Countries								
PUI	-0.013629	0.009356	-1.456747	0.1456	-0.014813	0.012775	-1.159534	0.2466
REM	0.447699	0.016984	26.36056	0.0000	0.445000	0.017317	25.69671	0.0000
FD	-0.146859	0.043706	-3.072125	0.0040	-0.131731	0.044486	-3.713277	0.0009
GCF	0.240712	0.009268	25.97173	0.0000	0.241318	0.009395	25.68699	0.0000
C	8.333755	0.346097	24.07922	0.0000	8.323032	0.351592	23.67243	0.0000
Panel –C: Upper- Middle-Income Countries								
PUI	-0.06779	0.015132	-4.47967	0.0001	0.01896	0.032006	0.592374	0.5539
REM	0.448783	0.034279	13.09198	0.0000	0.446341	0.035044	12.73673	0.0000
FD	0.188436	0.080666	2.335997	0.0199	0.178505	0.082351	2.167621	0.0306
GCF	0.193245	0.019197	10.06646	0.0000	0.191338	0.019697	9.713992	0.0000
C	9.643090	0.755830	12.75828	0.0000	9.780974	0.772910	12.65475	0.0000

cautious in their present consumption trend. In the study of Coibion, Gorodnichenko (Coibion et al., 2020), the authors postulated that pandemic uncertainties discourage households' spending behavior and increase negative perception in recovering the economic adversity due to unforeseen causes. Furthermore, refers to output derived in Model-2 (without covid-19 uncertainties). The study documented a negative and statistically significant connection between pandemic uncertainties and household consumption in all three panel estimates. More specifically, a 10% increase of uncertainties due to non-human causing events in the economy can result in an adverse impact on household consumption that is level of consumption to be decreased by 0.1103% in LIC, 0.148% in LMIC, and 0.189% in UMIC, respectively. With a comparison note, it is obvious from the magnitude of PUI on HC that in both cases household consumption has adversely affected by the empirical model estimation with COViD-19 has produced more prominent scratch on households mind in compare to the past events.

The study documented a positive and statistically significant linkage between remittances inflows and household consumption in LIC (a coefficient of 0.2878), LMIC (a coefficient of 0.4476) and UMIC (a coefficient of 0.4487). The existing literature supports our study findings see Combes and Ebeke (Combes and Ebeke, 2011), Mondal and Khanam (Mondal and Khanam, 2018). In particular, a 10% development in remittance inflows can positively affect household consumption by 2.876% in LIC, 4.476% in LMIC, and 4.487% in UMIC. The possible reasons that induce household consumption with excess liquidity are migrant's injection of money inflows into the economy. Additional money inflows into the economy, especially in the hands of households, increase their purchasing capacity and allow them to think about additional consumption over certain levels of savings (Adams, 2006; Faruqui et al., 2015; Jianguo and Qamruzzaman, 2017; Jia et al., 2020; Ganlin et al., 2021; Andriamahery and Qamruzzaman, 2022a; Andriamahery and Qamruzzaman, 2022b). Therefore additional expenditure for consumption is an inhabitable outcome with money availability.

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TABLE 7 Robustness test: GMM and System -GMM.

	Generalized method of Moments			System - GMM		
Panel –A: Lower-Income Countries						
HCD(-1)				-0.0668	0.01992	-3.3536
PUI	-0.0922	0.01369	-6.7348	-0.0481	0.0039	-1.2301
REM	0.13818	0.03672	3.76351	0.1331	0.10376	1.28283
FD	0.0241	0.08367	0.28802	0.13092	0.07271	1.80054
GCF	0.1046	0.02249	4.65036	-0.4432	0.10592	-4.1845
C	13.3664	0.93289	14.3278	94.7784	13.2267	7.16571
AR(-1)				0.000		
AR (2)				0.161		
Sargan test				0.811		
Panel B: Lower-Middle Income Countries						
HCD(-1)				0.0169	0.00293	5.77349
PUI	-0.0163	0.00939	-1.735	-0.0041	0.00072	-5.6328
REM	0.0477	0.01704	2.79874	0.01666	0.00188	8.8617
FD	–0.0469	0.04386	-1.0684	-0.0039	0.00341	-1.1432
GCF	0.0712	0.0093	7.65509	0.00214	0.001	2.13559
C	8.33376	0.34731	23.9949	0.03564	0.01644	2.16737
AR(-1)				0.000		
AR (2)				0.511		
Sargan test				0.815		
Panel C: *Upper-Middle Income Countries*						
HCD(-1)				0.02162	0.00169	12.7702
PUI	–0.0678	0.0152	–4.459	–0.0041	0.00058	-7.0069
REM	0.14878	0.03444	4.32019	0.0289	0.01571	1.8396
FD	0.18844	0.08104	2.32516	0.01676	0.00318	5.27874
GCF	0.19325	0.01929	10.02	0.00218	0.00082	2.6683
C	9.64309	0.759347	12.69919	-0.0207	0.033722	-0.61375
AR(-1)				0.000		
AR (2)				0.116		
Sargan test				0.855		

Country-wise assessment.

The study documented a negative and statistically significant linkage between financial development and household consumption in LIC (a coefficient of 0.2445) and LMIC (a coefficient of -0.1468). The study suggests that access to formal financial services and benefits increases savings propensity among households, and thus by subsidizing extravagant consumption, households prefer to save for future consumption. However, household consumption level in Upper-Income Countries has increased with the development of the financial sector (a coefficient of 0.1884), suggesting that opportunities for generating a higher income level with financing and investing opportunities in the economy induce households to expand their present consumption level. The possible motivation behind this rational behavior is that earning opportunities establish financial securities and liquidity; therefore, extra consumption can be managed; a study by Song, Li (Song et al., 2020) established that access to formal financial services and financial services digitalization promotes households consumption levels and the impacts are more prominent in an urban area than a rural area.

TABLE 8 Country-wise estimation.

	PUI	REM	GCF	FD	C
Algeria	−0.0014	−0.0024	0.0112	0.0227	−2.444
Angola	−0.0137	−0.0024	0.01	0.0093	0.28
Bangladesh	0.0047	−0.002	0.0099	0.0402	−2.684
Belize	−0.0099	−0.0037	0.0102	−0.0015	−2.715
Benin	−0.0223	−0.0085	0.0103	0.0045	4.617
Bolivia	−0.0254	−0.004	0.0108	0.0182	-2.836
Cambodia	−0.0159	0.0038	0.0104	0.0191	0.139
Cameroon	−0.0006	0.0087	0.0109	0.0106	1.182
Congo, Rep	−0.0109	−0.0089	0.0109	0.0082	-0.894
Cote d'Ivoire	0.0038	-0.003	0.0097	0.0193	4.884
Egypt, Arab Rep	0.007	0.0001	0.011	0.0364	1.362
El Salvador	−0.0173	−0.0077	0.01	0.0502	4.881
Ghana	−0.0118	−0.0078	0.0111	0.0288	-0.804
Haiti	-0.0048	-0.0067	0.0103	0.0373	4.979
Honduras	-0.0232	-0.0008	0.0099	0.0488	4.918
India	-0.0246	0.0109	0.0097	0.0344	-2.214
Indonesia	-0.005	-0.0062	0.0111	0.0386	1.008
Iran, Islamic Rep	-0.0039	0.0074	0.0101	0.0365	1.501
Kenya	0.0065	-0.0024	0.0113	0.0064	0.983
Kyrgyz Republic	-0.0043	0.0059	0.0113	0.0132	4.533
Lao PDR	-0.0246	0.008	0.0106	0.0014	3.421
Lesotho	-0.0023	-0.0013	0.0096	0.0434	1.234
Mauritania	-0.0238	-0.0031	0.0098	0.0164	-0.218
Morocco	-0.0246	-0.0059	0.0106	0.003	1.947
Nepal	-0.0253	-0.0062	0.0108	0.0394	-1.785
Nicaragua	-0.0022	-0.0013	0.0105	0.037	-3.024
Nigeria	-0.0215	-0.0024	0.0107	0.0317	0.014
Pakistan	0.0025	-0.0067	0.0106	0.0076	-2.017
Philippines	-0.0218	0.0067	0.0102	0.033	-2.949
Senegal	-0.0153	-0.0001	0.0097	0.0426	-2.327
Sri Lanka	-0.0109	0.0078	0.0099	0.0091	-1.435
Tanzania	-0.0222	0.0087	0.0099	0.0081	-0.698
Tunisia	-0.0246	-0.0043	0.0106	0.0257	2.637
Ukraine	-0.0101	0.0111	0.0096	0.0345	-1.504
Vietnam	-0.0217	0.0016	0.0102	0.0359	0.411
Zimbabwe	0.0063	-0.0053	0.0097	0.0146	-2.444
Burkina Faso	0.0073	0.0038	0.0095	0.0078	4.337
Burundi	0.0059	-0.0076	0.0109	0.0175	5.071
Congo, Dem. Rep	0.0017	0.0112	0.0109	0.0024	1.182
Ethiopia	-0.0223	0.011	0.0096	-0.0025	-0.691
Gambia, The	-0.0266	0.0009	0.0106	0.0418	-0.648
Guinea	-0.0039	0.0069	0.01	0.039	1.406
Guinea-Bissau	0.0103	0.0066	0.01	0.0182	0.311
Madagascar	0.0097	−0.0001	0.0103	-0.0005	0.52
Mali	−0.0018	0.0015	0.011	0.0446	−1.273
Mozambique	−0.0038	−0.0087	0.0097	0.0462	0.714
Niger	0.0093	0.0099	0.0102	0.037	-2.022
Rwanda	0.0081	-0.0034	0.0104	0.0254	4.048
Sierra Leone	−0.0192	0.0015	0.0106	0.0244	−2.224
Sudan	-0.0184	0.0098	0.01	0.0108	1.265
Togo	0.0092	0.0019	0.0109	0.0037	3.426
Uganda	0.0073	0.0005	0.0112	0.0201	0.786
Albania	0.0061	-0.0055	0.0107	0.0066	4.345
Argentina	-0.0003	0.0041	0.0108	0.0288	-0.057
Armenia	-0.0056	0.0027	0.0109	0.027	-0.724
Belarus	0.0074	-0.0062	0.0096	0.035	0.209
Bosnia and Herzegovina	-0.0246	0.01	0.0101	0.0419	-2.981
Botswana	-0.0284	0.0032	0.0107	0.0378	0.239
Brazil	−0.0016	−0.0019	0.0107	0.0508	−2.144
Bulgaria	−0.0107	−0.007	0.0101	0.0144	2.699
China	−0.0107	−0.0058	0.0108	0.0429	−0.713
Colombia	-0.0226	-0.0083	0.0101	0.0132	−2.715
Costa Rica	-0.0187	-0.0042	0.0101	0.0399	3.918
Dominican Republic	−0.0255	0.0107	0.0104	0.0252	2.958
Ecuador	−0.0186	−0.0013	0.0111	0.0401	3.608
Gabon	−0.0033	0.0071	0.0096	0.0044	4.468
Georgia	0.0067	−0.0068	0.0111	0.0083	4.143
Guatemala	−0.0262	−0.0041	0.0107	0.0275	0.693
Iraq	-0.0169	0.0075	0.0103	0.039	4.822
Jamaica	−0.0027	0.0044	0.01	0.0313	−0.683
Jordan	−0.0017	−0.0022	0.0097	0.0121	−2.625
Lebanon	−0.0197	0.0059	0.0108	0.0345	1.359
Malaysia	−0.0216	0.0101	0.011	0.0167	3.602
Mexico	−0.0198	0.0063	0.0111	0.0118	2.775
Paraguay	0.0075	0.0101	0.0101	0.0202	-1.13
Peru	−0.0099	0.0075	0.0107	0.0448	4.332
Romania	0.0081	0.0095	0.0112	0.0337	-2.806
Russian Federation	−0.0103	−0.0003	0.01	0.0255	3.328
South Africa	0.003	0.0064	0.0095	0.0455	3.802

(Continued in next column)

TABLE 8 (*Continued*) Country-wise estimation.

Next, the study moved to robustness assessment in empirical estimation by employing GMM and system GMM. The results of GMM and system-GMM are displayed in Table 7. For lower-income counties (see panel–A), the study reviled that policy uncertainty has an adverse impact on households consumption a coefficient of -0.0922 (-0.0481) in LIC, a coefficient of -0.0163 (-0.0041) in LMIC, and a coefficient of -0.0678 (-0.0041), respectively. Study findings suggest that the fear of uncertainties has adversely influenced the lower-income groups, thus reducing consumption.

While the impact of remittances revealed positive and statistically significant, suggesting that migrants' money inflows in the economy have accelerated households consumption in LIC (a coefficient of 0.1381), LMIC (a coefficient of 0.0477), and UMIC (a coefficient of 0.1488), moreover the elasticity with system-GMM revealed the similar

line of association in LIC (a coefficient of 0.1331), in LMIC (a coefficient of 0.0167), and UMIC (a coefficient of 0.0289), respectively. The notable fact has revealed that even though the role of remittances is positively connected with household consumption, the intensity is more prominent in lower-income countries in comparison with high-income countries.

Next, the study implemented Ordinary Least Square to investigate the potential impact of pandemic uncertainties on household consumption considering country-level information. The results of the country-level estimation are displayed in Table 8. The study documented three association lines that refer to pandemic uncertainties on household consumption. First, the negative linkage, that is, uncertainties, discourages household normal consumption level and induces maintaining the financial security and stability in Botswana, Gambia, Dominican Republic, Bolivia, Nepal, India, Lao PDR, Morocco, Tunisia, Bosnia and Herzegovina, Mauritania, Honduras, Colombia, Benin, Ethiopia, Tanzania, Philippines, Vietnam, Malaysia, Nigeria, Mexico, Lebanon, Sierra Leone, Costa Rica, Ecuador, Sudan, El Salvador, Iraq, Cambodia, Senegal, Angola, Ghana, Congo, Rep, Sri Lanka, Bulgaria, China, Russian Federation, Ukraine, Belize, Peru, Armenia, Indonesia, Haiti, Kyrgyz Republic, Iran, Islamic Rep, Guinea, Mozambique, Gabon, Jamaica, Lesotho, Nicaragua, Mali, Jordan, Brazil, Algeria, Cameroon, Argentina. A study suggests that uncertainties discourage household consumption by considering financial security and liquidity. The second line of evidence revealed positive effects run from pandemic uncertainties on household consumption in Pakistan, South Africa, Cote d'Ivoire, Bangladesh, Burundi, Albania, Zimbabwe, Kenya, Georgia, Egypt, Arab Rep., Burkina Faso, Uganda, Belarus, Paraguay, Rwanda, Romania, Togo, and Niger. The third line of evidence is no effects of pandemic uncertainties on household consumption in Burundi, Albania, Zimbabwe, Kenya, Georgia, Egypt, Arab Rep., Burkina Faso, Uganda, Belarus, Paraguay, Rwanda, Romania, Togo, Niger, Madagascar, Guinea-Bissau.

Refers to remittances' impact on households consumption, study findings revealed remittances disarrange households consumption in Congo, Rep, Mozambique, Benin, Colombia, Ghana, El Salvador, Burundi, Bulgaria, Georgia, Haiti, Pakistan, Nepal, Indonesia, Belarus, Morocco, China, Albania, Zimbabwe, Tunisia, Costa Rica, Guatemala, Bolivia, Belize, Rwanda, Mauritania, Cote d'Ivoire, Nigeria, Angola, Algeria, Kenya, Jordan, Bangladesh, Brazil, Ecuador, Lesotho, Nicaragua, Honduras, Russian Federation, Senegal, Madagascar. Study findings advocated that households tend to accumulate money flows for future investment capital accumulation after a certain standard of living. Our finding is in line with Ang, Jha (Ang et al., 2009). The second line of findings revealed positive nexus between remittances and households consumption in Egypt, Arab Rep., Uganda, Gambia, Sierra Leone, Mali, Vietnam, Togo, Armenia, Botswana, Cambodia, Burkina Faso, Argentina, Mexico, South Africa, Guinea-Bissau, Philippines, Guinea, Gabon, Iran, Islamic Rep. Iraq, Peru, Sri Lanka, Lao PDR, Tanzania, Cameroon, Romania, Sudan, Niger, India, Ethiopia, Ukraine, Congo, Dem. Rep. study postulated that excess money flows induce household spending, which is in line with Kakhkharov and Rohde (Kakhkharov and Rohde, 2020). Neutral effects are available in Bosnia and Herzegovina, Malaysia, Paraguay, Dominican Republic, Jamaica, Lebanon, Kyrgyz Republic. Study findings advocated that the recipients of migrants' remittances do not affect household consumption, which is in line with Castaldo and Reilly (Castaldo and Reilly, 2015).

Discussion

Household consumption variability relies on macro-economic shocks such as piece hikes of necessity goods, political instability, and economic uncertainty. The impact of unforeseen and uncontrolled economic events adversely affected household consumption due to liquidity constraints, income instability and future insecurity. In line with the existing literature, study findings have extended the prevailing belief that uncertainties discourage households from spending additional consumption expenditures rather than a conservative approach. The magnitudes of PUI on household consumption revealed negative and statistically significant, suggesting household consumption tends to decline in the pandemic state, especially when the situation appears unpredicted. Adams Jr and Cuecuecha (Adams and Cuecuecha, 2013) found that households' economic expectations deteriorated regarding these expectations and the uncertainty around these levels. According to theory, Uncertainty impacts the economic behavior of families; moreover, Uncertainty influences future consumption and should prompt conservative conduct, such as higher precautionary savings and liquidity, lower levels of consumption, and reduced consumption exposure to hazardous financial investments, among other things. Furthermore, household saving increases dramatically when the level of uncertainty regarding the future direction of income rises, A family may raise its savings by either consuming less or working more; however, most prior research on precautionary savings.

By understanding remittances as a source of income for the homes that receive them, it is possible to logically explain the link between remittance and household consumption in the United States. Traditional consumption models, such as the lifecycle and perpetual income theories of consumption, assert that the source of income has little impact on consumption behavior since families seek to smooth expenditure over a long period. Consequently, we should assume that families receiving

remittances would act the same way any other home would under the same circumstances. Refers to remittances' impact on household consumption, the study documented an U–invert association between remittances inflows and household consumption, implying that excess money inflows increase consumption propensity up to a certain level; after that, households tend to move savings for future consumption. Furthermore, the consumption level with migrant's remittances has exhibited different magnfititutes with income group and economic status of the home economy. Migrant transfers are generally acknowledged as a substantial source of income for households and a significant source of foreign currency for the country (Zwager, 2005). According to a growing body of studies, remittances seem to have a favorable influence on development. Consequently, the government, international organizations, and non-governmental organizations (NGOs) collaborate to establish rules for improved remittance management to benefit families and the country.

Findings and conclusion

Household consumption patterns in society vary based on the macroeconomic state; macro volatility, inequality, poverty level, income constraints, and others have played a detrimental role. Furthermore, unforeseen economic uncertainties due to non-human events have a critical role in managing society's consumption pattern. The motivation of the study is to investigate the impact of pandemic uncertainties on household consumption levels in Lower-income countries (LIC), Lower-Middle Income countries (LMIC) and Upper-Middle Income Countries (UMIC) for the period 1996-to 2020. The key findings of the study are as follows:

First, the cross-sectional dependency test revealed that research units share some common dynamics that variables exhibited cross-sectionally dependent. Moreover, the heterogeneous properties in research variables have been established by rejecting the null hypothesis of homogeneity. Second, panel data stationary tests have documented that all the variables have become stationary after the first difference I(1), and neither has been exposed to stationary after second difference I(2). Second, the study has implemented a panel cointegration test to document a long-run association between PUI REM, FD, G, and HC. Referring to Pedroni (Pedroni, 2004), Pedroni (Pedroni, 2001) cointegration test, the study found that most test statistics have established statistically significant confirmation of long-run cointegration. Furthermore, the panel contention test following Westerlund (Westerlund, 2007) established a similar line of conclusion that is a long-run association in empirical estimation.

Third, study findings with SUR revealed the negative nexus between pandemic uncertainties and household consumption, suggesting a state of uncertainties adversely influenced household consumption and motivated control consumption for liquidity. Our study findings are in line with existing literature see Chen, Qian (Chen et al., 2021), Wu (Wu, 2020), Baker, Farrokhnia (Baker et al., 2020b). The possible explanation regarding household consumption variability is the fare of unavoidable consequences due to economic uncertainties. Maintaining the normal course of life, households should maintain financial and food security with sufficient money flows. Therefore during pandemics, households become more cautious in their present consumption trend. In the study of Coibion, Gorodnichenko (Coibion et al., 2020), the authors postulated that pandemic uncertainties discourage households' spending behavior and increase negative perception in recovering the economic adversity due to unforeseen causes.

On policy note, the study has come up with the following suggestion.

1. Household consumption stability has immensely relied on the availability of money in households and has promoted economic development by ensuring economic optimization. The study suggested that to ensure the continual flow of remittances in the economy, and the promotional offerings must be disclosed and implemented effectively.
2. Financial efficiency and intermediation have induced the migrant population to send foreign remittances to their relatives through formal financial channels, which accelerates economic activities and ensures household consumption stability, especially in the long run. Therefore, an efficient financial system has to be offered with operational and distributional efficiency.
3. Monetary and fiscal stability accelerated economic well-being and long-run growth with equitable development. Good governance and institutional quality in the economy are the prerequisites for establishing stability and reducing uncertainties, leading to long-term consumption stability. The study postulated that effective policy formulation and implementation would offer institutional effectiveness and stability in the economy.

The present study does not have certain limitations; first, it is suggested to consider the asymmetric framework for getting fresh evidence and explaining the nexus between uncertainties, remittances and household consumption for future studies. Second, further study might be initiated by including the most adversely affected economy with COVID-19 in one panel and the top 50 remittances receiving economy in another panel. The data homogeneity might reveal diverse results for further insight development. In addition, the

outcomes of this research indicate that the EPU index should be incorporated in Households demand assessment models as an independent variable in addition to the conventional variables connected to economic considerations. Today's complicated and unstable global economy makes this concern more important than ever. There may be a need for further empirical investigations using other methodology and data sets including various nations.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: WDI.

Author contributions

YY: data curating; empirical estimation; Final Preparation. MQ: introduction; data curation; empirical estimation, First Draft; Final Preparation. HX: literature survey; methodology; first draft; AM: literature survey; methodology; first draft; final preparation. FN: Literature survey, Discussion, Conclusion, Final Preparation. IB: literature survey; methodology.

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Conflict of interest

Author YY was employed by the company Agricultural Bank of China LTD Nanjing Chengbei Sub-branch.

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Faik Bilgili,
Erciyes University, Turkey

REVIEWED BY
Muhammad Kamran Khan,
Bahria University, Pakistan
Muhammad Imran Khan,
University of Agriculture, Pakistan
Sevda Kuşkaya,
Erciyes University, Turkey
Nudrat Fatima,
Beijing Technology and Business University, China

*CORRESPONDENCE
Lu Zhang,
zhanglu.edu@outlook.com

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Technological innovation evolution and industrial modernization driven by green factors: Case of combined heat and power (CHP) industry in Yangtze River Delta, China

Chenqing Su[1], Chengsi Wang[2], Zhanao Wang[1], Lu Zhang[3]* and Yaqi Tian[4]

[1]School of Finance and Trade, Wenzhou Business College, Wenzhou, China, [2]School of Continuing Education, Wenzhou Business College, Wenzhou, China, [3]School of Management, Wuhan University of Technology, Wuhan, China, [4]Department of Diplomacy and Foreign Affairs Management, China Foreign Affairs University, Beijing, China

China's Yangtze River Delta region has banned the approval of new thermal power projects except for combined heat and power (CHP) generation and is promoting technological innovation in CHP. However, technological innovation of energy technology has been evidenced to be often affected by spatial elements. The role of spatial agglomeration in the energy industry on technological innovation has not been discussed in the context of CHP. Therefore, this article studied the spatial agglomeration and evolution characteristics of CHP technological innovation point elements through the Global Moran's index, kernel density analysis, and thermal map analysis and analyzed the influencing factors and changes by the spatial regression model. The results show that environmental regulation and high-tech park agglomeration are the key factors influencing CHP technological innovation. This indicates that future policy making needs to consider the economic factors of green development and the role of high-tech parks in innovation.

KEYWORDS

combined heat and power, innovation, Moran's I, high-tech parks, China, economics, green total factors

1 Introduction

With the increasing global energy demand, it is urgent to find new alternative energy or adjust the existing energy structure Chou et al. (2020); Lan et al. (2021). Combined heat and power generation (CHP), a mode of combined production of heat and electricity, is a technology for comprehensive energy utilization (Jimenez-Navarro et al., 2020). CHP is a new mode of production derived from the traditional thermal power industry. After the oil crisis in the 1970s, CHP received great attention from Western countries. With the

global energy crisis and environmental deterioration, the research and development (R&D) in sustainable energy technologies has been gradually popularized around the world (He et al., 2020a, 2020b; Qian et al., 2021; Wei et al., 2021; Pu et al., 2022; Su et al., 2022). After steam is generated by a boiler of a traditional thermal power plant that drives the steam turbine generator set to generate electricity, the steam which has been discharged still contains most of the heat taken away by cooling water, so the thermal efficiency of the thermal power plant is only 30–40% (Vishwanathan et al., 2018). If the heat energy of the steam-driven steam turbine process or subsequent steam pumping or discharge can be used, it can generate both electricity and heat. This process has both electrical and thermal energy production. It is an efficient form of energy utilization at the same time as heat and electricity production. CHP has many advantages such as high efficiency of energy utilization and environmental protection and is regarded as the best centralized heating source (Zheng et al., 2021). In addition, due to the large capacity, high chimney, and high dust removal efficiency of the boilers that generate steam, the CHP unit is beneficial to the realization of desulfurization and denitrification in the furnace (Pu et al., 2019). Compared with traditional thermal power plants, their social and environmental benefits are significant. Although innovation discussion on energy technologies has spread to economic, behavioral, and policy areas (Bai et al., 2021; Zhang et al., 2022; Li et al., 2018), regional policy significantly has a huge impact on CHP technology. When compared with a single conventional power supply and heating system, the CHP projects have many advantages such as high energy utilization efficiency and environmental protection and are considered to be the best central heating source. After being aware of this, the National Development and Reform Commission of China officially issued a notice in 2016, which is on the development plan of urban agglomerations in the Yangtze River Delta. This plan aims to improve the coordination mechanism of air pollution prevention and control in the Yangtze River Delta region and solve air environmental problems in an integrated and coordinated manner. Among them, it is worth noting that the plan requires new projects in Shanghai, Jiangsu, and Zhejiang to prohibit the construction of self-provided coal-fired power stations, prohibit coal consumption projects to implement the replacement by coal reduction, and prohibit approval of new coal-fired power generation projects except the CHP (Zhang and Zheng, 2020). According to statistics, the CHP of the current heat source in China's heating industry accounts for 62.9%, while the rest accounts for 37.1%.

Although the significant increase in the proportion of CHP is a good signal to achieve environmental protection requirements under climate change, further technological innovation in CHP technology is an important way to further achieve low-carbon development. At present, the categories of CHP unit mainly include the type of back-pressure, the type of steam pumping condensing, and the type of pumping back-pressure. But scholars do not limit their attention to traditional technological means or transformations. At present, more expectations are to integrate new and clean energy into CHP systems. For example, Suman (2018) believes that the study of new energy systems in which renewable energy and fossil fuels are complementary is extremely important for building efficient and safe modern energy systems. On the one hand, it is necessary to establish an overall performance model of the solar combined cycle unit to realize the online performance monitoring of ISCC units and master the operation characteristics of the unit. On the other hand, it is also necessary to study the variation of the peaks regulating the capacity of the ISCC system under CHP conditions, so as to provide a theoretical and design basis for operation optimization and application of ISCC units in CHP (Wang et al., 2021). Similarly, Zhou et al. (2019) have reviewed the types and research prospects of energy storage technology in the CCHP system and believe that the application methods of the power storage and thermal energy storage technology in the CCHP system are pluralistic. It has been pointed out that under the combination of traditional energy and renewable energy and the increasingly complex energy development trend of energy supply systems, system characteristics, optimization technology, and the formulation of operation plans for different scenarios are the future innovative directions of energy storage technology and CCHP integrated systems. It can be seen that CHP has great potential for technological innovation, and its innovation has multiple potential directions in technologies.

But how did the technological innovation of CHP happen? Bai et al. (2021) take the smart grid as an example and point out that there are obvious technological differences between the smart grid in China and the United States in terms of technology. China pays more attention to the innovation of hardware, while the United States pays more attention to intelligent scheduling. But more importantly, based on the analysis of China's technology innovation patent data, they have found that the innovation of China's smart grid technology has obvious spatial differentiation, which is related to regional characteristics. This study inspires this article to take CHP technology as an example to further verify the spatial differentiation of technological innovation and its motivations. Different from the study of the smart grid by Bai et al. (2021), the innovation of thermal technology in China is often significantly related to requirements of environmental protection and industrial policies, which has been mentioned by several scholars (Ouyang et al., 2020). This is mainly because thermal power, as a high-pollution industry, is often the most regulated industry and its production often needs to be carried out in specific industrial parks, which lead to the research purpose of this article, namely, the correlations among CHP technological innovations, green total elements, and industrial policies. In terms of industrial policies, taking the Yangtze River Delta as an example, China is presently promoting innovations such as the CHP technology by establishing high-tech industrial parks, the hope of which is mainly to gather innovation elements such

as scientific research resources and achieve them. In recent years, more and more studies have used spatial detection methods. Spatial analysis is a process of cognition, interpretation, prediction, and regulation of spatial information. The results of spatial analysis depend on the distribution of events. The relationship between things with spatial attributes is detected according to the theory of spatial data analysis and spatial connection processes—both location information and attribute data (Ying ad Ning, 2005). Spatial analysis works well in describing and showing the unique spatial information, relationships, patterns, and processes contained in these data, exploring what's behind the phenomenon taking spatial patterns as its occurrence mechanism. At the same time, space is the interface between the existence of things and interaction between humanity and nature, so geographical space is also the index of multisource information and the interface of man–land relationship. Taking the above situation into consideration, this article takes the Yangtze River Delta, an area that pays the most attention to CHP technology, as an example, discusses the spatial differentiation of CHP innovation by referring to the method of space detection proposed by Bai et al. (2021), and explores the impact of green total factors and high-tech industrial agglomeration on CHP innovation.

2 Methodology

2.1 Data sources

This article takes the Yangtze River Delta urban agglomeration as the research object, which includes 25 cities in the Shanghai, Jiangsu, Zhejiang, and Anhui provinces. The data of green total factor eco-efficiency used in this article are mainly from the China Statistical Yearbook and the Wind-Economic Database from 2015 to 2019. The data of the 25 cities in the Yangtze River Delta are selected, and the corresponding indicators are selected by referring to Chen et al. (2018). The patent data used in this study are from the patent database of PatSnap. This article searched the keyword "combined heat and power generation" in October 2021, and a total of 5,068 technological innovation patents from the Yangtze River Delta region in related fields were obtained before 31 December 2020. The point data of the industrial park was obtained from the Gaode geographic data platform by Python technology.

2.2 Global spatial autocorrelation analysis

The Moran's I index is often used to describe the spatial clustering characteristics of an attribute in the whole region and reflect the spatial correlation of the observed values in the spatial neighborhood. It also summarizes the number of enterprises in each unit of space to determine the degree of their spatial agglomeration. In this article, the Moran's I index is used to test whether there is spatial dependence or spatial heterogeneity among the 25 cities selected in this study, so as to analyze the characteristics of spatial correlation among technological innovation efficiency of the 25 cities in the Yangtze River Delta. The formula is as follows:

$$I = \frac{1}{e^2} \cdot \frac{\sum_{a=1}^{m}\sum_{b=1}^{m} w_{ab}(x_a - \bar{x})(x_b - \bar{x})}{\sum_{a=1}^{m}\sum_{b=1}^{m} w_{ab}}. \quad (1)$$

In formula (1), $e^2 = \frac{1}{m}\sum^{m}(x_a - \bar{x})^2$; n represents the study of enterprises' number; x_a, x_b are the number of enterprises in positions a and b, respectively; $\bar{x}$ is the mean value of x_a; and w_{ab} is the spatial relationship between the research units a and b. At a given level of significance, the Moran's I value range [−1,1] is positive to indicate the relative agglomeration distribution of innovation points, equating to zero indicates that there is no spatial correlation, and the distribution of innovation points is relatively random.

2.3 Kernel density estimation

Kernel density estimation is a nonparametric method of estimation, which studies the distribution characteristics of data from the data sample itself and has strong adaptability. Combined with the spatial smoothing technology, kernel density estimation is widely used in the visualization and detection of spatial point patterns. Based on data samples, the density of point events within a certain radius of each sample is calculated to calculate the intensity of events. The output grid pixel is the smooth surface of the sum of all the core surface values superimposed on the center of the grid pixel, which can intuitively identify the differences in the spatial density distribution of the data. This article explores the spatial heterogeneity of the CHP energy industry in the Yangtze River Delta. The formula of the kernel density estimation method is as follows:

$$\hat{\lambda}_h(p) = \sum_{i=1}^{n} \frac{1}{\pi t^2} k \frac{(p - p_i)}{t}. \quad (2)$$

In the formula, $\hat{\lambda}_h(p)$ is the kernel density estimate; n is the number of enterprises; and k is the distance weight between p and p_i. Taking p as the center and t as the search radius of the circle, the longer the radius is, the more innovation points the range contains.

2.4 Getis-ord Gi*

In this article, the method of analyzing hot spots is used to distinguish the local spatial clustering types of CHP enterprises in the Yangtze River Delta: Gi* statistical value of each grid unit in the statistical data set can be used to judge the spatial clustering of high and low values in the region, and low-value clusters and

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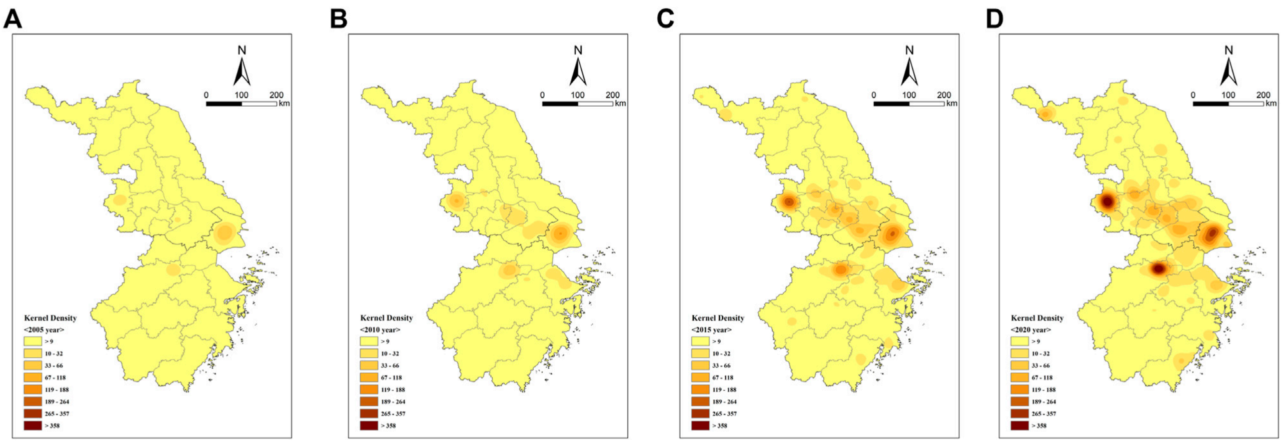

FIGURE 1
Kernel density of CHP technological innovation in 2005 **(A)**, 2010 **(B)**, 2015 **(C)** and 2020 **(D)**.

high-value clusters are the spatial distribution of cold spots and hot spots. The analysis of hot spots is more accurate in detecting local spatial autocorrelation, especially high-value agglomeration, and the calculation formula is as follows:

$$G_i^* = \sum_j w_{ij} x_j \Big/ \sum_j x_j, \quad (3)$$

$$Z(G_i^*) = \frac{G_i - E(G_i)}{\sqrt{\mathrm{VAR}(G_i)}}. \quad (4)$$

In the equation, x_j is the observation value of the space unit j and w_{ij} is the relationship between the spatial weight matrix i unit and j unit. The G_i* value of each unit, that is, the Z score, is of great statistical significance ($p < 0.05$), and the higher the Z score is, the closer the aggregation of the high value (hot spot) is, otherwise the low value (cold spot) is closely aggregated.

3 Results and discussions

3.1 Global spatial dependence pattern

For the Moran' index of CHP technology innovation in the Yangtze River Delta, the values of I were, respectively, 0.027304, 0.001518, 0.063144, and 0.023341 in 2005, 2010, 2015, and 2020, while the values of Z were, respectively, 0.507122, 0.342052, 0.758221, and 0.469879. Judging from these results of global autocorrelation measurements, the four-year Global Moran's I index has been between 0.0015 and 0.0631, has been positive, and has passed the significant test at the level of 1%, which indicates that the CHP technology innovation industry in the Yangtze River Delta, on the whole, has significant spatial agglomeration and dependence, that is, the level of CHP technology innovation industry in each city is positively affected by its neighboring districts and counties. In terms of temporal evolution, since 2005, the Global Moran's I index has shown a trend of decreasing first, then increasing and again decreasing, with large decreasing amplitudes in 2010 and 2020, indicating that the degree of spatial agglomeration and dependence of industries on CHP technology innovation in the Yangtze River Delta has weakened, and the industrial layout has presented a trend of diffusion.

3.2 Spatial heterogeneity pattern

With the help of ArcGIS, the spatial kernel density of the point distribution of CHP technology innovation enterprises in the urban agglomeration of the Yangtze River Delta from 2005 to 2020 was estimated and visualized according to the natural fracture method classification in four selected years: 2005 (Figure 1A), 2010 (Figure 1B), 2015 (Figure 1C), and 2020 (Figure 1D). It can be seen from the figures that the spatial patterns of the CHP technology innovation industry in the urban agglomeration of the Yangtze River Delta presents the following characteristics: Shanghai's core position has always been stable, the sub-centered position of Nanjing and Hangzhou has been increasingly prominent, the intensity of agglomeration continues to improve, and the radiation range has expanded significantly, which presents the evolution pattern of "One Core of Shanghai"–"Dual Cores of Shanghai and Nanjing"–"Three cores of Shanghai, Nanjing, and Hangzhou." It has been indicated that the developmental gradient of the Jiangsu Province is increasingly obvious which is from the initial sprouting and unfinished climate to the emergence of small agglomerations in the main urban areas of the cities, and then to the scale and intensity of agglomerations in various cities,

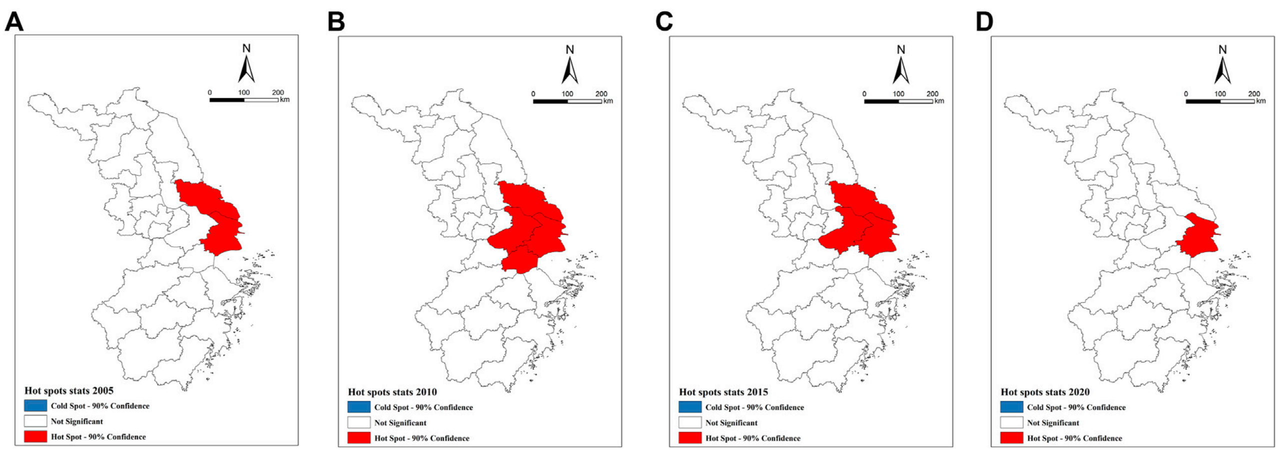

FIGURE 2
Distribution of CHP technology innovation hotspots in the Yangtze River Delta in 2005 **(A)**, 2010 **(B)**, 2015 **(C)** and 2020 **(D)**.

showing that the spatial heterogeneity distribution is strong in the south and weak in the north. Among them, Nanjing plays a prominent role as the core of the province and has become an important radiating point in the Yangtze River Delta. With Shanghai and Hangzhou in series to form the northwest–southeast axis belt, the Yangtze River Delta industrial belt begins to take shape. Generally speaking, from the presentation of the four selected years, the number of CHP technology innovation enterprises in the Yangtze River Delta urban agglomeration has surged, the distribution density has increased as a whole, and the spatial agglomeration scope has continued to expand. This has indicated that the cliff-like gap between Shanghai and its surrounding cities is gradually shrinking, and the pattern of "three cores and two axes" has gradually been formed and the regional development equilibrium has been improved, initially showing a trend of coordinated development.

The hot spot results of the four selected years of 2005 (Figure 2A), 2010 (Figure 2B), 2015 (Figure 2C), and 2020 (Figure 2D) can effectively identify characteristics of the specific distribution and local variation of CHP technology innovation industry agglomeration in the Yangtze River Delta. From 2005 to 2020, the number of significant local cities in the CHP technology innovation industry layout in the Yangtze River Delta has shown an upward trend first and then a decline, which is in line with the previous changes' trend of the Moran's I index. The hot spots are concentrated in the northeast of the Yangtze River Delta, and significant types have gradually increased, indicating that the spatial dependence on local areas is becoming stronger and stronger. The specific performances are as follows: in 2005 (Figure 2A), the H-H cluster mainly spread around Shanghai and its surrounding cities, became concentrated in the downtown of Shanghai and Nantong city, and gradually extended to the surrounding areas, highlighting the vigorous development of the CHP technology innovation industry in Shanghai. In 2010 (Figure 2B), Hangzhou and Suzhou, which are located around Shanghai, also showed the H-H cluster, reflecting the enhancement of the radiation power of the Shanghai CHP technology innovation industry. From 2010 to 2020 (Figure 2C and Figure 2D), the H-H cluster shrank and was confined to Shanghai, indicating that its CHP technology innovation industry had relatively good development but limited radiation power, which is presented as an "isolated island" form.

Considering the availability and operability of data, this article refers to the research related to energy industry agglomeration, and based on the comprehensive consideration of the principles such as being available, quantifiable, comparable, and so on, eight factor indicators were selected according to the original data of green all-factor TFP in 285 prefecture-level cities from 2003 to 2018 for specific construction to test the impact of the relevant factors on the CHP technology innovation industry, and further to clarify the effective intensity of different factors and analyze the influencing mechanism of the spatial pattern of the CHP technology innovation industry. We named the industrial soot emission (ton), discharge amount of wastewater, sulfur dioxide emissions (ton), PM2.5, quantity of employment, stocks of capital, total electricity consumption, constant-price GDP as E_{soot}, E_{was}, E_{sul}, E_{pm}, Q_e, S_c, T_e, and C, respectively. At the same time, the hierarchical visualization was carried out according to the numerical values to obtain the characteristics of spatial differentiation of the eight indicators at four time nodes. Firstly, the visualized results of spatial differentiation of each index were compared with the results of kernel density analysis of the creative industry for visual translation, and the influencing factors were preliminarily determined. Then, the indicator graphs of the same time nodes in

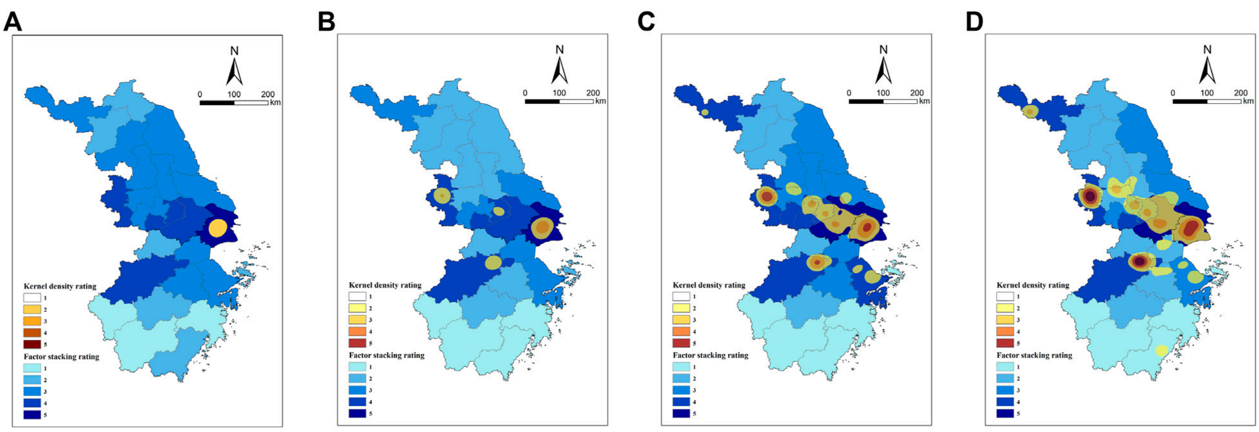

FIGURE 3
Spatial differentiation of influencing factors in 2003–2005 **(A)**, 2005–2010 **(B)**, 2010–2015 **(C)** and 2015–2018 **(D)**.

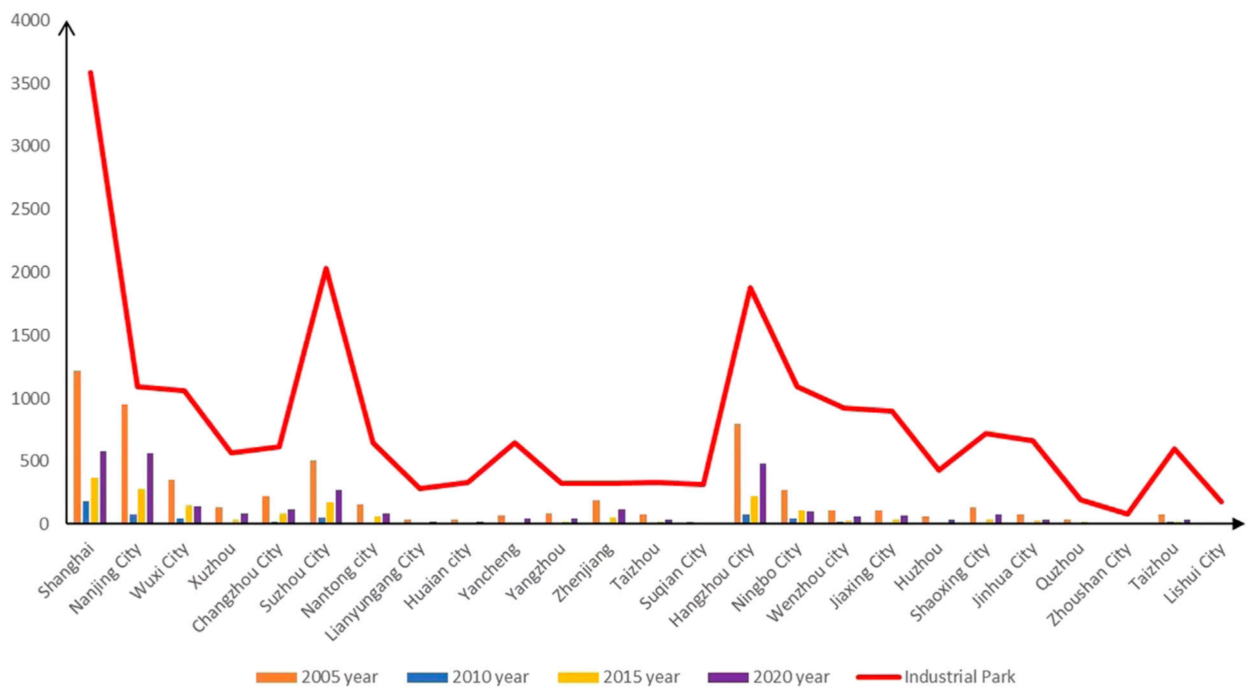

FIGURE 4
Relationship between CHP technology innovation and agglomeration of high-tech industrial parks.

the visual translation results were superimposed with hierarchical assignment, and the result was the spatial differentiation pattern under the comprehensive action of each indicator, which has spatial coupling with the kernel density analysis results. For 2003–2005 (Figure 3A), the influencing factors included E_{soot} Q_e; for 2005–2010 (Figure 3B), the influencing factors included E_{sul} Q_e C; for 2010–2015 (Figure 3C), the influencing factors included E_{soot} E_{sul} Q_e T_e C; and for 2015–2018 (Figure 3D), the influencing factors included E_{soot} E_{sul} E_{pm} Q_e T_e C.

The results show that the driving effect of energy technology innovation on total factor ecological efficiency is not monotonous (decreasing) but a nonlinear impact under the

regulation of the economic development level, energy policy planning, and market level. Generally speaking, the results of the factors affecting the CHP technology innovation pattern of the four-time nodes in Figure 3 show that the region with the high economic development level, area with the high environmental protection management level, area with the high energy policy planning level, and area with the high market level effectively promote the optimal range of regional ecological efficiency of the total factors to stimulate energy technology innovation.

The development of the CHP technology innovation industry in the Yangtze River Delta has spatial heterogeneity. Based on the above global–local perspective on the detection results of the influencing factors, this article attempts to build the relationship between CHP technology innovation and agglomeration of high-tech industrial parks (Figure 4). It demonstrates that the influencing mechanism of the development of the CHP technology innovation industry in the Yangtze River Delta mainly includes three factors: aggregation of resources, social environment, and policy environment. Each factor contains many elements and has self-contained integration. The factors are interrelated and interact with each other, and jointly play a role in the development and evolution of the CHP technology innovation industry. Based on the analysis of multiple factors, it was found that the role of high-tech park agglomerations on CHP technology innovation enterprises is significantly higher than is for the other factors. CHP technology innovation enterprises prefer to gather in high-tech park agglomerations with more preferential policies, such as the High-Tech Park in northern Shanghai and the Fuhua High-Tech Park, which are at the national level near the Gonghe New Road, Central Shanghai. This shows that effective planning and guidance of the government has played an important role in the reasonable selection of the location of CHP technology innovation enterprises and the optimization of the industrial structure of CHP technology innovation.

4 Conclusion and recommendations

Taking enterprise development as the window and cities in the Yangtze River Delta region as the spatial scale, this article selects data from 2005 to 2020, makes use of kernel density estimation and spatial autocorrelation analysis to explore the evolution of spatial heterogeneity pattern and spatial dependence pattern of the CHP technology innovation industry in the Yangtze River Delta in the past 15 years, and uses green life. The main factors affecting the spatial location of CHP technology innovation enterprises were analyzed, and then the influencing mechanism of the layout of the CHP technology innovation industry in the Yangtze River Delta region was discussed. The main conclusions are as follows:

1) The overall Moran's I index of the CHP technology innovation industry in the Yangtze River Delta is between 0.0015 and 0.0631 at four time nodes, which is positive and has passed the significant test at the level of 1%, indicating that the CHP technology innovation industry in the Yangtze River Delta has significant spatial agglomeration and dependence as a whole, that is, the level of CHP technology innovation industry in each city is greatly affected by the positive direction of the adjacent districts and counties.

2) The spatial pattern of the CHP technology innovation industry in the Yangtze River Delta urban agglomeration presents the following characteristics: Shanghai's core position has always been stable. Over time, the subcenter status of Nanjing and Hangzhou has become increasingly prominent, the intensity of agglomeration continues to improve, and the radiation range has expanded significantly, presenting the evolution mode of "One Core of Shanghai"–"Dual Cores of Shanghai and Nanjing"–"Three cores of Shanghai, Nanjing, and Hangzhou."

3) The results of the analysis of cold and hot spots show that the H-H cluster mainly spreads around Shanghai and its surrounding cities. By 2010, Hangzhou and Suzhou, located around Shanghai, also showed H-H clusters, reflecting the enhancement of the radiation of Shanghai's CHP technology innovation industry. In the decade from 2010 to 2020, H-H clusters shrank, basically limited to Shanghai, indicating that its CHP technology innovation industry has developed relatively well, but its radiation is limited, presenting an "island" form.

4) The results of the influencing factors of CHP technology innovation pattern through the analysis of green production show that areas with a high economic development level, areas with a high environmental protection management level, and areas with high energy policy planning and a high market level effectively promote the optimal range of regional all-factor ecological efficiency to stimulate energy technology innovation. The specific performance is that the higher the agglomeration degree of the high-tech parks, the more obvious are the agglomeration characteristics of the CHP technology innovation enterprises.

At present, energy development in China is facing very serious situations and challenges. However, based on the analysis of the great potential of institutional innovation and technological innovation in China's energy field and the series of policies and measures that the Chinese government will implement to promote sustainable energy development, China can still achieve sustainable energy supply for a considerable period in the future. Cogeneration is a new industry with economic benefits, environmental benefits, and social benefits. It is an energy-saving and consumption-reducing mode encouraged by national policies. The construction of the Yangtze River Delta region must develop ecological industries such as cogeneration to purify the environment. As mentioned above, cogeneration is beneficial to

the vital interests of both suppliers and users. Therefore, cogeneration enterprises should seize the opportunity, overcome difficulties, meet challenges, and continue to expand publicity to let more people know the advantages of cogeneration, accelerate the installation of heat and power pipe networks, further improve air quality, and promote the comprehensive and healthy development of the Yangtze River Delta.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by CS, CW, and ZW. The first draft of the manuscript was written by CS and LZ, and all authors commented on previous versions of the manuscript. YT performed the data collection and final draft editing. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Vishal Dagar,
Great Lakes Institute of Management, India

REVIEWED BY
Sumit Dagar,
Delhi Technological University, India
Sakshi Malik,
O.P. Jindal Global University, India

*CORRESPONDENCE
Farah Waheed,
fwaheed.buic@bahria.edu.pk
Kanwar Muhammad Javed Iqbal,
kanwar.javediqbal@gmail.com

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Modeling energy governance index for the adequacy of policy, legal, and institutional response measures for climate compatible development

Kanwar Muhammad Javed Iqbal[1]*, Farah Waheed[2]*, Urooj Azhar[2], Nadia Akhtar[3] and Muhammad Irfan Khan[3]

[1]National Institute of Maritime Affairs, Bahria University, Islamabad, Pakistan, [2]Management Studies Department, Bahria Business School, Bahria University, Islamabad, Pakistan, [3]Department of Environmental Science, International Islamic University, Islamabad, Pakistan

Climate compatible and sustainable expansion of energy resources is a major global challenge. Developing countries, with inadequate resources and incoherent policies, and legal and institutional frameworks must strive hard to achieve targets set by the Sustainable Development Goals (SDGs) while keeping track of Nationally Determined Contributions for Greenhouse Gas (GHG) emissions abatement. Inclusive governance is quite complex due to the interplay of informal and formal systems, rules-based to rights-based approaches, and arrangements in national to local scenarios *vis-à-vis* methodological limitations. In this context, this study aims at developing a governance index for assessing climate compatible development (CCD) by taking case of the energy sector in Pakistan. The study adopted a two-step approach to develop and validate a methodological framework for assessing the adequacy of governance. In the first step, a multivariate analysis model was developed using principle (CP-1), criteria (09), and 43 indicators (PCIs) through stakeholder involvement. In the second step, the model was deployed by combining the Multi Criteria Decision Analysis method with statistical analysis of the dataset. Data were collected from federal and provincial capitals as well as ten districts through a structured scoring matrix consisting of all 43 indicators. The sample population was based on key informant interviews (340), and experts (17) who were engaged through focus group discussion at federal, provincial, and district levels. Respondents were asked to score against each indicator on a ratio scale, which was then aggregated to develop a governance index score. The findings reveal the dearth of a preemptive and comprehensive governance to address climate compatible development in the energy sector in all tiers of constituencies in Pakistan. There is a need for coherent and inclusive policy, and a legal and institutional framework. This study's outcome authenticates the findings of United Nations SDGs Report 2020 that efforts to achieve sustainable energy targets are not up to scale and stresses the need to speed up the efforts and development of the associated governance framework for renewable energy to achieve climate compatible and SDGs.

KEYWORDS

energy sector, climate compatible development (CCD), sustainable development, governance index, principles, criteria and indicators, MCDA

Introduction

The cascading effects of the climatic phenomenon are attributed to all sectoral economies through its convergent evidences and manifestation in everyday life (Carvalho and Peterson 2009; Höök and Tang 2013; Reser, Bradley, and Ellul 2014; IPCC 2018; Iqbal and Khan 2018; Blunden and Arndt 2019; WMO 2019). The energy sector is no exception, where a strong interplay of fossil fuel consumption, lifestyle changes, and growing concerns about environmental security and sustainable development makes the development of this sector more challenging (Ali and Iqbal 2017; Eleftheriadis and Anagnostopoulou 2017; Iqbal et al., 2020; Hassan et al., 2021). The United Nations' SDGs Report of 2020 highlighted the unsustainable use of energy resources worldwide, as the anticipated target (3%) of energy efficiency is not yet achieved. Consequently, the global temperature is anticipated to rise (3.2°C) by 2100. Annual global GHG emissions reduction targets are lagging behind (about 7.6%), mainly due to an injudicious use of energy resources (UN Statistics Division, United Nations, 2020). Sustainable and climate compatible energy development is among the major global challenges, particularly in the governance context of countries with a lack of adequate and coherent policies, and legal and institutional arrangements (Jiang et al., 2017; López-Ballesteros et al., 2020; Naseer, Iqbal, and Khan 2020; Nwedu 2020; Waheed, Fischer, and Khan 2021).

In order to address policy, and legal and institutional arrangements for energy security and sustainability, conformance between SDGs 7 and 13 is a prerequisite and foremost important element. SDG-7 aims at ensuring clean, affordable, accessible, and modern energy for all, while SDG-13 calls for climate action (Kaygusuz 2012; Armin Razmjoo, Sumper, and Davarpanah 2020; Swain and Amin 2020; Elavarasan et al., 2021). In theory, these two goals go hand in hand and form a synergistic relationship. Understanding the linkages between various aspects of SDGs may aid in developing a cross-sectoral program and policies that could lead to a synergistic functioning for developing and promoting renewables (Xu et al., 2019; Wei et al., 2020). However, the developing countries are facing challenges in shifting towards effective, sustainable, and climate compatible renewable energy (RE) solutions while fulfilling their rapidly growing energy demand. A lack of understanding of the linkages, flexible behavior about trade-offs, and poorly designed sectoral synergies have resulted in incoherent policies, adverse impacts of development on different sectors, lost opportunities for sustainable solutions, and a delayed outcome to progress. Overall, major challenges include high financing costs; insufficient infrastructure; inadequate skills for production and transmission; policy, legal, and regulatory barriers; lack of political will and institutional effectiveness; ownership problems; and poor understanding (Galera 2017; Liu et al., 2019; Asante et al., 2020; Mahama, Derkyi, and Nwabue 2020; Usman, Khalid, and Mehdi 2021).

Most important among the aforementioned factors is the issue of an ineffective policy and institutional framework to adapt to clean energy sources (Galera 2017; Sen and Ganguly 2017; Zafar et al., 2018; Erdiwansyah et al., 2019). The highly centralized system that depends on few actors often becomes hostile and non-hospitable for innovative technologies and suppliers. Many countries in the world still have their policies designed around the interests and monopoly of these giant inhospitable suppliers, acting as a policy barrier (Eleftheriadis and Anagnostopoulou 2015; Hu et al., 2018). Thus, modification of the existing laws is an imperative priority to make the industry and the stakeholders open to the idea of a clean energy mix. Overcoming inconsistent standards, compliance requirements, and regulations regarding RE buy-back schemes and feed-in tariffs could help in mainstreaming the RE forms in the developing world (Qazi et al., 2017; Seetharaman et al., 2019; Kamran, Fazal, and Mudassar 2020). This complex interplay of energy markets, technology, policies, social norms, and consumer preferences has affected, and will continue to affect, energy production and consumption and low carbon development, which ultimately links with a climate compatible and sustainable development (Ike et al., 2020). Besides, a lack of clarity and priorities with the crosscutting and rather conflicting nature of institutions also impede the progress on climate compatible energy sector development.

As of 2019, the global installed capacity of RE reached more than 200 GW, with a significant share by the developing countries (IAEA 2020). At present, 17% of the total energy share is RE and this needs a boost, as 789 million people around the globe still lack access to electricity (Armin Razmjoo et al., 2020; UN Statistics Division, United Nations, 2020), provision of which raises serious concerns about its compatibility with climate mitigation targets. In the current scenario, SDGs serve as the primary driving instruments for the international community to set their policies and practices in line with the set and agreed targets. However, under the current policy arrangement status, many countries are lagging behind. For the Association of Southeast Asian Nations (ASEAN), the target (23%) for renewables seems ambitious unless comprehensive reforms in strategies are ensured (Khuong, McKenna, and Fichtner 2019). Similarly, the Nationally Determined Contribution (NDC) Statement (2016) of Pakistan also provided an ambitious commitment of reducing

GHG emissions (26%) which will cost 40 billion US$ (UNFCCC 2016). Like Pakistan, many nations are still far behind in achieving SDG targets due to policy gaps and an ineffective implementation mechanism (Khuong et al., 2019; UN Statistics Division, United Nations 2020).

The sustainability goals for CCD require realizing the milestones of SDG-7 and SDG-13 together, which necessitates an inclusive governance mechanism. The mechanism should be able to put into practice a set of coherent and widely accepted policies, and legal and institutional arrangements with cross-sectoral integrations at all levels. However, the matter of inclusive energy governance is quite complex. It encompasses informal to formal systems and rules-based to rights-based approaches for policies. It will also require rearrangements in national, sub-national, and local institutional setups *vis-à-vis* methodological procedures to assess and review the policies systematically and periodically. The informal governance concept is based on practices and processes without observing formal rules and procedures, and does not provide voting rights to the weak actors. The "formal governance" concept normally revolves around rules. Rules-based approaches are linked with the application of a top-down model, which raises concerns pertaining to stakeholders' participation. Right-based approaches revolve around the rights, participation, and active engagement of all kind of relevant actors and the political economy (Follesdal, Christiansen, and Piattoni 2004; Visseren-Hamakers and Glasbergen 2007; Saunders and Reeve 2010; Stone 2011; Kleine 2014; Pierre and Peters 2020). Besides, the "triple-win" notion of CCD is participatory in nature and involves multi-sector and multi-actor approaches (Mitchell and Maxwell 2010). Thus, adopting traditional governance frameworks is unable to address the challenges faced by the energy sector. These challenges necessitate a proper methodological framework for periodic review about the adequacy, performance, and decision-making process at all levels of the energy governance mechanism in a country. However, a widely acknowledged model for analysis of governance framework for CCD is tenuous in the literature (Pyone, Smith, and van den Broek 2017). The frameworks proposed in the past have limitations and ambiguities due to a lack of clarity about the subject, principles, criteria, and indicators (Douxchamps et al., 2017; FAO 2017; Ha et al., 2018; Oliveira and Hersperger 2018). The concept of CCD is still evolving, and there are no specified principles, criteria, and indicators for sectoral governance for national, sub-national, and local reference scenarios.

As aforesaid, this study aims at evolving a framework based on a governance index for assessing the compatibility of the government's policies, legal instruments, institutional strategies, and management of CCD by taking the case of the energy sector in Pakistan. It comes under the scope of a basic response mechanism which is the first component of overall governance framework (i.e., GC-1). It is extracted from an extensive study regarding the development of a climate governance assessment framework based on mixed-method modeling of PCIs for CCD in different sectors of the economy (Iqbal et al., 2022). In this study, the assessment of energy governance for CCD was done against the first climate response principle, that is, "respect climate policies, processes, strategies, law and the institution." It provides a methodological framework for periodic assessment of the efficacy of energy governance for CCD in terms of the contents of the policies, legal instruments, and institutional setup to promote a state's sustainable and climate compatible energy initiatives.

The research query undertaken for GC-1 was "whether the existing architecture of policies, legal instruments and institutional setup has essential ingredients for emerging CCD needs in energy sector, and is inclusive for national, sub-national and local reference scenarios." The null hypothesis of this research query revolved around the absence of an inclusive governance mechanism.

Methodological framework

The study employed a PCI-based methodological framework for developing a governance index, employing six climate principles which were formulated by the first author as part of his PhD study in relation to six governance components (see Table 1) of the published article in Iqbal et al. (2022). A similar framework was previously used to study the actor's capacity in the energy sector, which was also extracted from the same major study as applicable for this article (Iqbal et al., 2022). The research design for the board study is reflected in the Supplementary Appendix SI. The methodological framework for the limited scope of the present research to the first governance component (GC-1) and Climate Principle (CP-1) is shown in Table 1 and Figure 1. The analysis is based on mixed-method modeling by combining various quantitative and qualitative tools and techniques including the application of MCDA (Multi Criteria Decision Analysis) along with SMART (Simple Multi Attribute Rating Technique) scoring, and clumping the rules and rights-oriented model approaches of the governance (Daim et al., 2009; Amer and Daim 2011; Costa, Gomes, and de Barros 2017; Ishtiaque et al., 2019; McIntosh and Austin 2020). During the course of developing and finalizing the methodological framework for CCD, three consultative sessions with climate change and energy sector experts were conducted, by following the previous practices as reported in the literature (Wellman 1983; Borgatti et al., 2009; Ingie Hovland 2005). The model was logically organized for CCD and the energy sector. The framework provides flexibility to be applied as unabridged or sectional for a governance component and/or climate response principles. Its architecture is simple, and application is easy. The present study used the framework in partial form by using CP-1 and GC-1 (Iqbal et al., 2022) for developing a governance index to gauge the adequacy of the

TABLE 1 Climate response principles and components of the basic governance mechanism (Iqbal et al., 2022).

Code	Climate response principle	Corresponding governance component
CP1	Respect climate policies, processes, strategies, law, and the institution	Policy, legal, and institutional arrangements (GC1)
CP2	Ensure climate competence, capacity, and active role of the line government departments	Role and capacities of the line government departments (GC2)
CP3	Promote vibrant and influential role of the civil society stakeholders with climate competence and capacity	Role and capacities of CSOs and academia (GC3)
CP4	Maintain active engagement of the community-based stakeholders towards climate endeavors	Role and capacities of community-based organizations (GC4)
CP5	Dynamic role of the private sector stakeholders for best climate solutions	Role and capacities of corporate/private sector stakeholders (GC5)
CP6	Achieve and maintain participatory sustainable climate compatible performance	Practice and performance system (GC6)

Source: PhD dissertation of the first author.

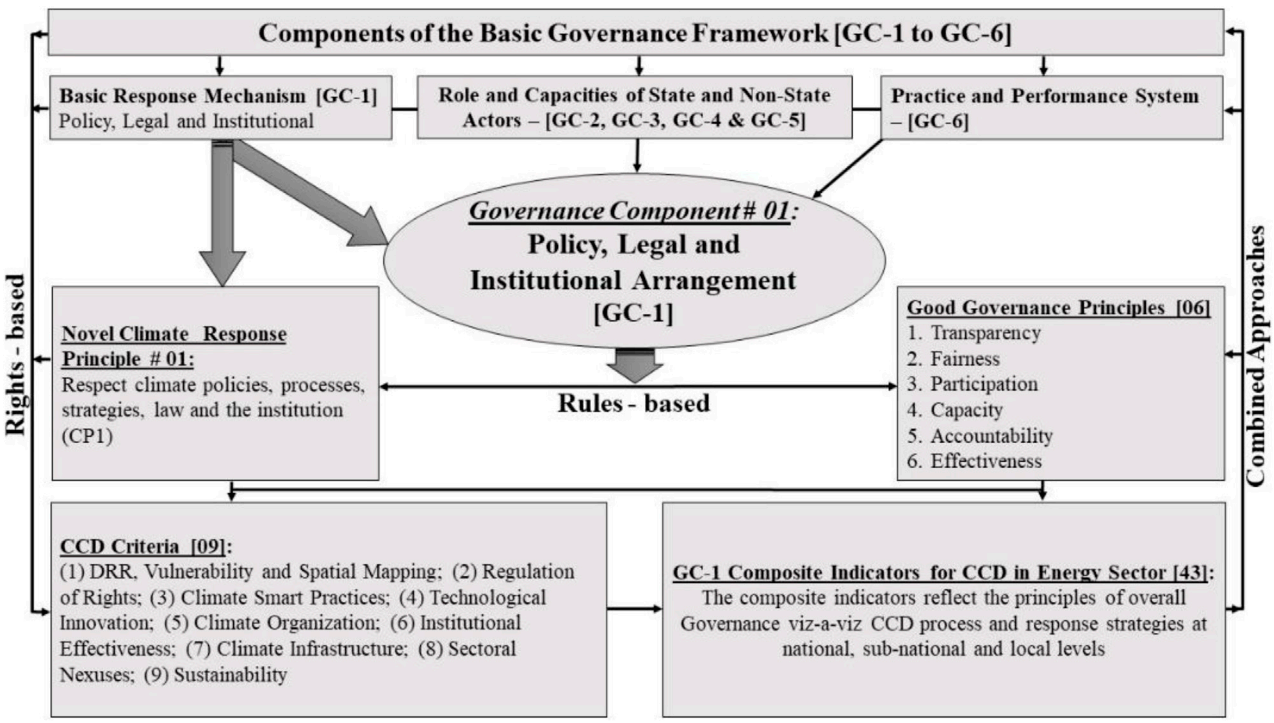

FIGURE 1
GC1 CCD assessment model for energy governance.

government's policies, and legal and institutional strategies and management for CCD. The logical structure adopted for the multivariate governance model is portrayed in Figure 1. The analysis was carried out through a two-step procedure, that is, the first step involved the formulation of a measuring tool, while the second step was a practical application for the determination of a governance index for a basic response mechanism through a case study of the energy sector in Pakistan.

Determination of key variables and primary data collection

The study demands diverse sets of variables to address the newly developed governance model by integrating PCIs. A careful narrowing-down procedure was followed in determining the set of 43 composite indicators against 9 CCD criteria, governance component 1 (GC1), that is, basic response mechanism, CP1, and

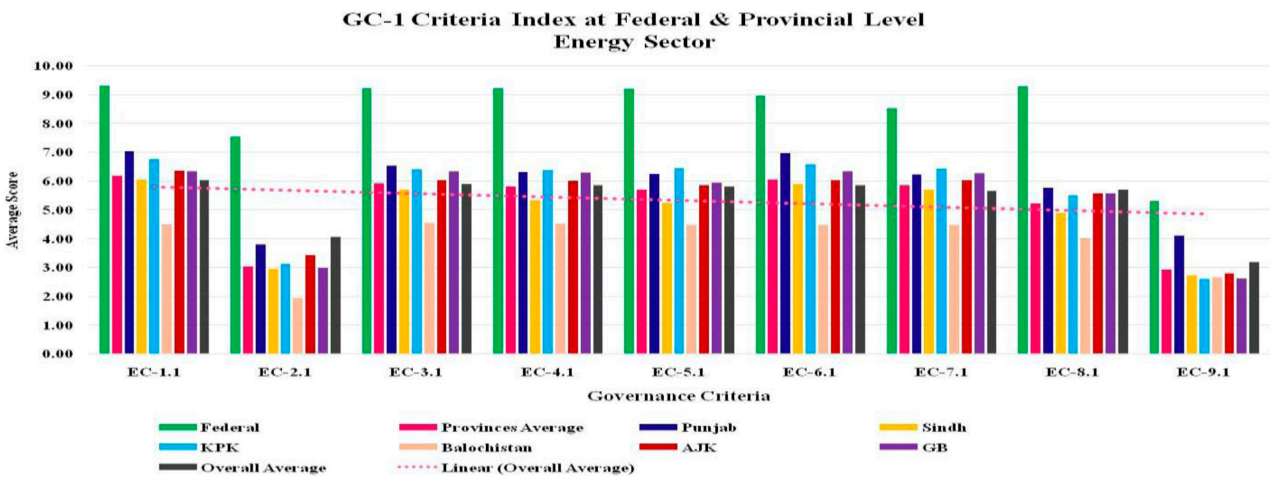

FIGURE 2
Criteria wise governance index for Governance Component-1 at provincial and federal level.

6 World Bank good governance principles (Kartodihardjo et al., 2013), as illustrated in Figure 2. For the purpose, a widely practiced scenario-based learning and situational analysis technique (Dey 2012; Hovland 2005; Norris et al., 2012; Serrat 2017) was employed, using flip charts in three consultative meetings with experts in Islamabad. The consultative meetings concluded a set of nine criteria (i.e., Energy C-1.1 = Disaster Risk Reduction, Vulnerability and Spatial Mapping; Energy C-2.1 = Regulation of Rights; Energy C-3.1 = Climate Smart Practices; Energy C-4.1 = Technological Innovation; Energy C-5.1 = Climate Organization; Energy C-6.1 = Institutional Effectiveness; Energy C-7.1 = Climate Infrastructure; Energy C-8.1 = Agriculture, Water, and Energy Nexus; and Energy C-9.1 = Sustainability) and 43 indicators (see Supplementary Appendix SII). The indicators focused on established and in-practice policies, strategies, legal and institutional mechanism targeting climate vulnerability assessment, renewable energy proliferation, and grievance redressal mechanisms against nine criteria.

MCDA's SMART was employed with a ratio scale presented as 0 = not applicable or no response for CCD yet; 0.01 to 1.99 = very poor response for CCD; 2.00 to 3.99 = poor response for CCD; 4.00 to 4.99 = considerable response for CCD; 5.00 to 5.99 = fair response for CCD; 6.00 to 7.49 = good response for CCD; 7.50 to 8.99 = very good response for CCD; and 9.00 to 10.0 = excellent response for CCD. The responses against each indicator were aggregated for scoring and weighting (Edwards 1977; Leskinen and Kangas 2005; Gärtner et al., 2008; Heinrich et al., 2011) the CCD criteria. For SMART scoring, a structured questionnaire-cum-scoring matrix comprising 9 criteria and 43 indicators of energy governance was used. To validate and normalize the tool, pilot testing was carried out in Islamabad. A purposive sampling plan was designed by keeping in view the geographical requirement and attaining a representative size of the sample from each jurisdiction, including federal and provincial capitals and 10 districts throughout the country (i.e., Khuzdar and Jhal Magsi from the Balochistan province, Rajanpur and Bahawalpur from the Punjab province, Badin and Sanghar from the Sindh province, Ghizer from Gilgit-Baltistan, and Muzaffarabad from Azad Jammu and Kashmir). The existence of climate-related initiatives was duly considered during the selection of the geographical locations under the scope of this study. Data were collected through interviews of key experts/informants (KIIs) and FGD (focus group discussion) sessions. For each location, data through one FGD and 20 KIIs were collected, resulting in a purposive sample of a total of 357 responses. For FGDs and KIIs, experts were selected from energy departments including power generation, transmission, distribution, regulating authorities, as well as allied organizations like National Energy Efficiency and Conservation Authority (NEECA), Provincial Energy Efficiency and Conservation Authority (PEECA), Alternative Energy Development Board (AEDB), and Pakistan Council for Renewable Energy Technology (PCRET). Besides that, for FGD, experts from climate change-related departments including the Ministry of Climate Change, provincial environmental departments, and the Global Change Impact Studies Center (GCISC) were also invited. Flashcards were used to keep the discussion interactive and focused. Besides responses, the discussion of experts was also recorded, which helped in understanding different aspects of the findings.

Analysis of data

MS Excel 2016 was used for tabulating, cleaning, and processing the data and calculating the governance index of GC1 for the energy sector. The results were validated using IBM SPSS Statistics 25 by employing three statistical tests: linear regression, the non-

TABLE 2 Governance index for Governance Component-1 for the energy sector of Pakistan.

Constituency level	CCD criteria										
	Energy C-1.1	Energy C-2.1	Energy C-3.1	Energy C-4.1	Energy C-5.1	Energy C-6.1	Energy C-7.1	Energy C-8.1	Energy C-C9.1	Average score	Ranking
National	9.31	7.53	9.22	9.21	9.19	8.95	8.52	9.28	5.30	**8.50**	Very Good
Sub-national (all provinces)	6.16	3.02	5.91	5.79	5.69	6.04	5.85	5.21	2.90	**5.17**	Fair
Local level (all districts)	2.60	1.59	2.55	2.55	2.54	2.55	2.55	2.54	1.30	**2.31**	Poor
Average score	**6.02**	**4.05**	**5.90**	**5.85**	**5.81**	**5.85**	**5.64**	**5.68**	**3.17**	**5.33**	Fair
Ranking	Good	Considerable	Fair	Fair	Fair	Fair	Fair	Fair	Poor	Fair	-

Bold indicates that the average values.

parametric H-test, that is, Kruskal–Wallis (KW) hypothesis testing, and 1-tailed Pearson Correlation. The H- test helped in understanding and characterizing the sample groups from district, provincial, and federal levels. The tests were preordained to ensure the originality of the sample and to understand the association of the different interlocking variables.

Results

The present study analyzed the adequacy of the current governance framework for the energy sector in relation to the CCD principles at the vertical levels with the constituencies at national (federal), sub-national (all provinces), and local (districts) levels. The responses were collected from the key informants using a structured questionnaire as well as through FGD with the experts in the energy and climate change sectors. The GC-I index was calculated by averaging the individual rating scores against each criterion. Table 2 shows the criteria-wise itemization of the GC-1 index for CCD in relation to the energy sector in Pakistan. The overall results depict the highest score (6.02) for EC-1.1. For other criteria, the score was variable: the EC-2.1 index score of 4.05; EC-3.1 index score 5.90; EC-4.1 score 5.85; EC-5.1 index score 5.81; EC-6.1 index scores 5.85; EC-7.1 index score 5.64; and EC-8.1 index score 5.68. The lowest score is reported for EC-9.1 (average score 3.17). Constituency-wise index scores were highest for the federal (8.50), then the provincial (5.17), and lowest (2.31) for the district levels, signifying poor governance in districts. The overall GC-1 index remained 5.33. With reference to the constituency-wise GC-1 index, the federal area scored (8.50) good (see Figure 2). Figure 3 portrays the constituency-wise index score in the form of a radar to show constituency-wise comparison of the index scores. Figure 4 shows the GC-1 index at district level. The lowest GC-1 index score was from the district of Balochistan—Jhal Magsi and Khuzdar, while the highest score was from Muzaffarbad.

The inferential statistics, that is, KW Hypothesis Test, was performed to test the null hypothesis; that is, *the distribution of governance index score is the same across all nine criteria, constituency- and gender-wise.* It rejects the null hypothesis with an asymptotic significance level 0.05 (against N = 357) for the overall sample of GC-1 in the energy sector. The Pearson correlations (1-tailed) significantly indicate a strong co-relation among all CCD criteria (Table 3), whereas for the multivariate regression analysis (see Tables 4–7), the CCD criteria "Energy C-9.1, that is, Sustainability for GC-1," was taken as the dependent variable. The retrieved R and R Square values were 0.936 and 0.876 respectively. The results of the T-test (values above ±2) inferred a significant relationship of sustainability criteria with other criteria, except EC-1.1, EC-4.1, and EC-5.1. However, the collinearity diagnostics for all correlations (tolerance <0.10, VIF >10) is not indicative of significance, though all criteria showed zero-order correlation with the sustainability criteria.

The normal P-P plot (Figure 5) illustrates relatively low deviation, and upward and downward variations. Figure 6 (scatter plot) indicates four clusters, of which two clusters are submerged to each other while the remaining two are trivial with overall results within the (±3) boundaries. The inferential statistics determine that all nine criteria of the GC-1 index impact each other. Thus, convincingly the null hypothesis cannot be rejected, suggesting the absence of a preemptive and comprehensive response mechanism to govern CCD in the energy sector for its environmental security at federal, provincial, and district levels in Pakistan.

Discussion

Pakistan, with a population (213 million) growing at the rate of 2%, ranks the sixth-most populous country of the world. With a growing population, the energy demand is also increasing from 5% to 7% per year (Irfan et al., 2020; Qiu et al., 2022a; Qiu et al.,

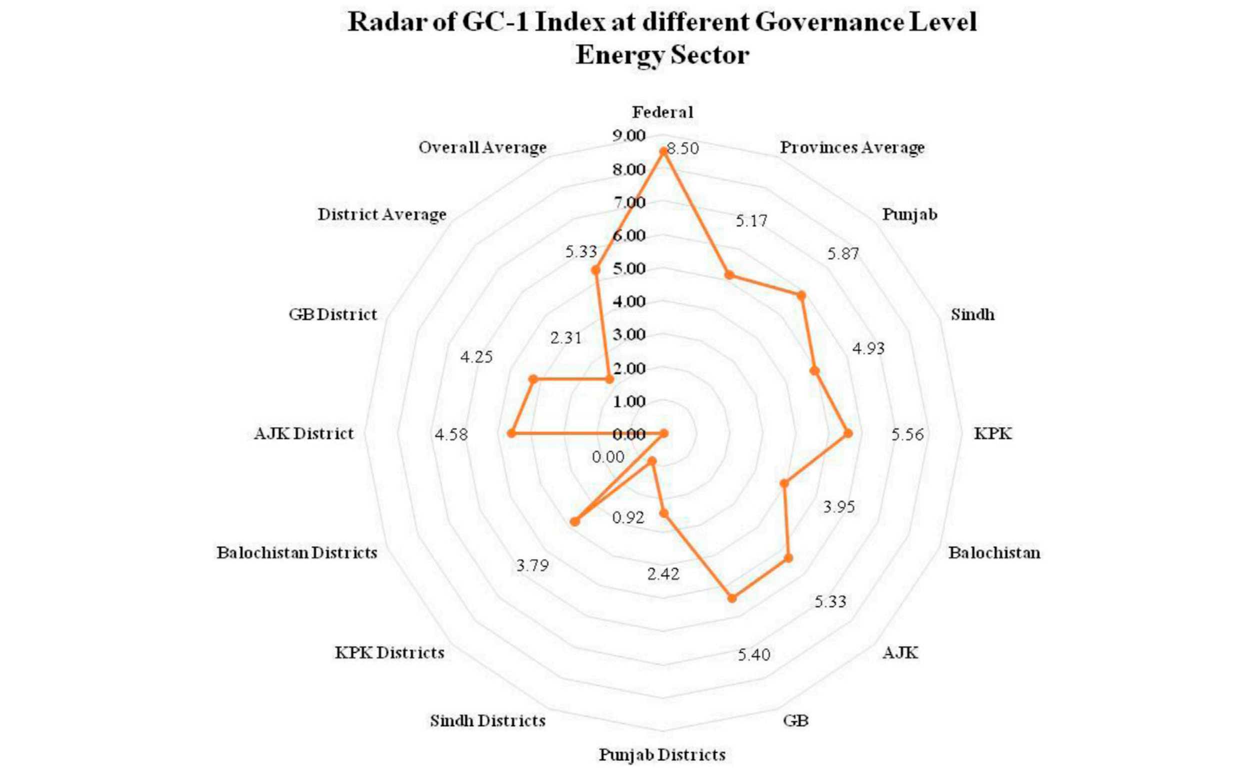

FIGURE 3
Radar graph of governance index for Governance Component-1 in the energy sector.

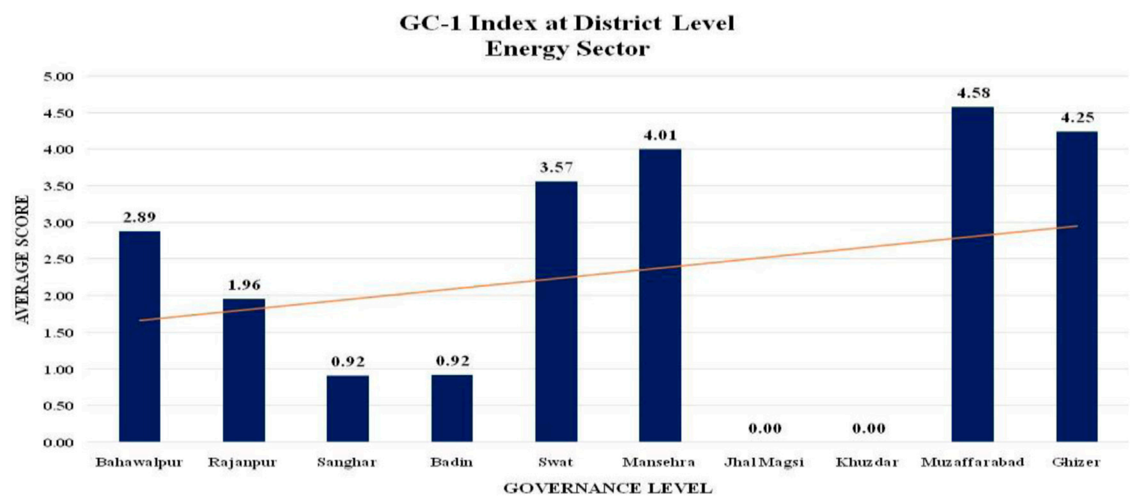

FIGURE 4
GC-1 index at district level.

2022b). As a result, the annual total GHG emissions reached 408 million tons of CO_2 in 2015, with the major share (45.5%) from the energy sector. Zhang et al. (2021a), Zhang et al. (2021b), and Zhang et al. (2021c) demonstrated that the major reason is reliance on fossil fuels as the major energy source. Among the major contributors of GHG emissions from the energy sector,

TABLE 3 Correlation between energy sector GC-1's CCD criteria (EC1.1-EC9.1).

Pearson correlations

CCD criteria	Energy C-1.1	Energy C-2.1	Energy C-3.1	Energy C-4.1	Energy C-5.1	Energy C-6.1	Energy C-7.1	Energy C-8.1	Energy C-C9.1
Energy C-1.1	1								
Energy C-2.1	0.914**	1							
Energy C-3.1	0.994**	0.924**	1						
Energy C-4.1	0.993**	0.927**	0.997**	1					
Energy C-5.1	0.992**	0.931**	0.996**	0.996**	1				
Energy C-6.1	0.995**	0.911**	0.995**	0.994**	0.993**	1			
Energy C-7.1	0.993**	0.906**	0.996**	0.995**	0.993**	0.995**	1		
Energy C-8.1	0.982**	0.951**	0.988**	0.990**	0.991**	0.982**	0.983**	1	
Energy C-9.1	0.893**	0.911**	0.897**	0.895**	0.894**	0.895**	0.882**	0.893**	1

**1-tailed significance level of correlation = 0.01.

TABLE 4 Summary of regression model for GC-1 in the energy sector.

Model summary[b]

Model	R	R square	Adjusted R square	Std. eror of the estimate
1	0.936[a]	0.876	0.873	0.47057

[a]Predictors: (Constant), Agriculture, Water, and Energy Nexus, Climate Infrastructure, Institutional Effectiveness, Regulation of Rights, DRR, Vulnerability and Spatial Mapping, Climate Smart Practices, Technological Innovation, and Climate Organization.
[b]Dependent variable: Sustainability.

TABLE 5 Summary of ANOVA for GC-1 in the energy sector.

ANOVA[a]

Model		Sum of squares	Df	Mean square	F	Sig
1	Regression	543.019	8	67.877	306.535	0.000[b]
	Residual	77.059	348	0.221		
	Total	620.078	356			

[a]Dependent variable: Sustainability.
[b]Predictors: (Constant), Agriculture, Water, and Energy Nexus, Climate Infrastructure, Institutional Effectiveness, Regulation of Rights, DRR, Vulnerability and Spatial Mapping, Climate Smart Practices, Technological Innovation, and Climate Organization.

electricity generation adds 49.065 Gg of CO_2 annually (GoP 2018). The current energy reliance is still on thermal power generation (61%), with renewables contributing only 1% in the total energy mix (Irfan et al., 2020). However, the government targeted to increase reliance on renewables (solar, wind, waste to energy) to 5% of the total energy by 2030 (Iqbal et al., 2018).

TABLE 6 Criteria wise summary of regression coefficients for GC-1 in the energy sector.

Coefficients[a]

	Model	Unstandardized coefficients		Standardized coefficients	t	Sig	Correlations zero-order	Collinearity statistics	
		B	Std. error	Beta				Tolerance	VIF
1	(Constant)	0.340	0.050		6.763	0.000			
	DRR, Vulnerability, and Spatial Mapping	0.094	0.103	0.189	0.916	0.360	0.893	0.008	118.671
	Regulation of Rights	0.605	0.056	0.799	10.904	0.000	0.911	0.067	15.037
	Climate Smart Practices	0.417	0.166	0.800	2.518	0.012	0.897	0.004	282.546
	Technological Innovation	0.208	0.155	0.394	1.345	0.180	0.895	0.004	240.670
	Climate Organization	−0.259	0.142	-0.486	−1.824	0.069	0.894	0.005	198.697
	Institutional Effectiveness	0.487	0.131	0.940	3.725	0.000	0.895	0.006	178.443
	Climate Infrastructure	−0.411	0.148	−0.759	−2.776	0.006	0.882	0.005	209.529
	Agriculture, Water, and Energy Nexus	−0.514	0.102	−0.928	−5.056	0.000	0.893	0.011	94.366

[a]Dependent variable: Sustainability.

TABLE 7 Regression's residual statistics for GC-1 in the energy sector.

Residuals statistics[a]

	Minimum	Maximum	Mean	Std. deviation	N
Predicted value	0.2587	5.7091	2.1038	1.23504	357
Residual	−1.16587	1.35976	0.00000	0.46525	357
Std. predicted value	−1.494	2.919	0.000	1.000	357
Std. residual	−2.478	2.890	0.000	0.989	357

[a]Dependent variable: Sustainability.

Chen et al. (2022) indicated that the current electricity production in Pakistan is less than demand, with a supply–demand gap of more than 3,000 MW. The resultant pressure forced the government to encourage short-term energy supply projects, including importing oil for thermal power generation (Miao et al., 2018; Yin et al., 2022a; Miao et al., 2022).

Pakistan's geographical location provides opportunities to harness 2900 GW of solar energy (Rafique et al., 2020). Similarly, Pakistan's multifarious terrain includes coastal and hill areas that provide excellent potential for wind energy (Shami et al., 2016). Being an agricultural country, Pakistan also has the potential to utilize agricultural biomass as fuel. Sixty percent of the population reside in rural areas. An estimated 230 billion tons of biomass, 652 M kg of manure, and 230 thousand tons of agricultural residues are produced every year. Besides that, an estimated 60,000 tons of solid waste per day is produced (Irfan et al., 2020). However, all these researches emphasized the need to adapt a comprehensive governance framework to tap the potential of renewable resources to achieve the low-carbon development goals for CCD (Iqbal et al., 2018; Irfan et al., 2019, 2020).

The global installed capacity of RE reached more than 200 GW in 2019, with a significant share by the developing countries (IAEA 2020). Fang et al. (2022), Rahman and Islam (2020), and Fofack and Derick (2020) indicated that the largest share of renewables is contributed in the electricity sector; however, the heat and transportation sectors are still far from the desired goals. The heat and transportation sector contributes 80% of the total energy consumption. Similarly, the United Nations SDG Report 2020 also stressed the need for additional efforts to achieve the energy efficiency targets. An enhancement in installation capacity and the spread of RE systems provided clean electricity and cooking fuel to the areas that lacked access to energy resources, especially in many developing nations. The actions helped to achieve

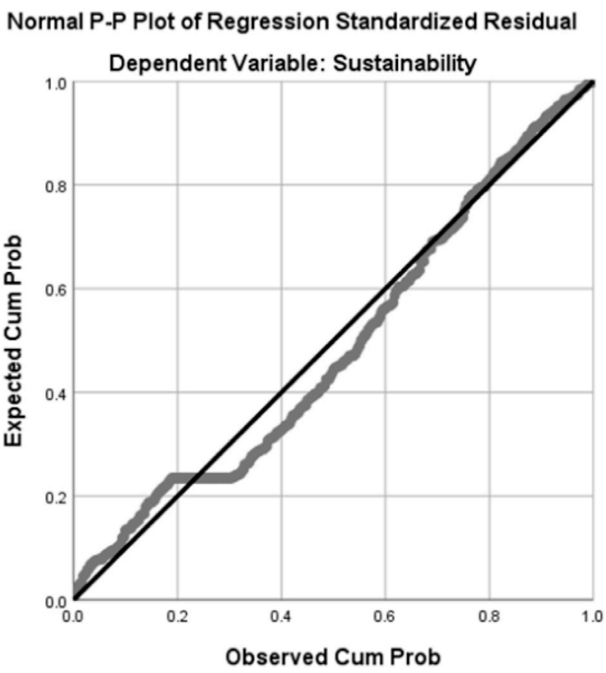

FIGURE 5
Regression's P-P plot for CCD index under GC1 in the energy sector.

access to the energy targets, while ensuring commitment pertaining to the global drive to diversify and shift to cleaner energy sources. However, progress is not the same across the nations; many nations are far behind in achieving a sustainable level of energy production and in meeting the SDG requirements, mainly due to policy gaps and effective implementation. ASEAN nations also lag behind in achieving the 23% renewable energy target by 2025, unless drastic adjustments in strategies are guaranteed (Khuong et al., 2019).

Pakistan is no exception. The renewable energy targets were set as a 20% share of renewables in energy generation by the year 2025 and further enhancement to 30% by the year 2030, while reducing GHG emissions seems ambitious in absence of an inclusive governance mechanism. The emission reduction targets become more challenging, particularly in the case of increasing energy demands under the "China Pakistan Economic Corridor (CPEC)"-related expansion needs and scope of activities (UNFCCC 2016; Iqbal and Haider 2020). At the same time, the United Nations SDGs Report 2020 reflects that international financing in renewable energy has accelerated, reaching up to $21.4 billion in 2017.

The findings revealed gaps in governance for the GC-1 related energy sector's CCD response measures at federal, provincial, and district level in Pakistan. The preparedness of federal level developments for CCD is better than that at the provincial and district levels (Table 1). When comparing the province and district levels, the provinces were rated "fair," but scores for the district level context are not promising transversely in Pakistan (Table 2). The findings corroborate that the energy sector had a strong foundation in the federal region for being a federal subject till the year 2010. Late in 2010, the 18th Amendment in the Constitution of Pakistan, 1973 devolved its powers, by giving autonomy to the provinces for the progression of energy sources. Subsequently, diversification in

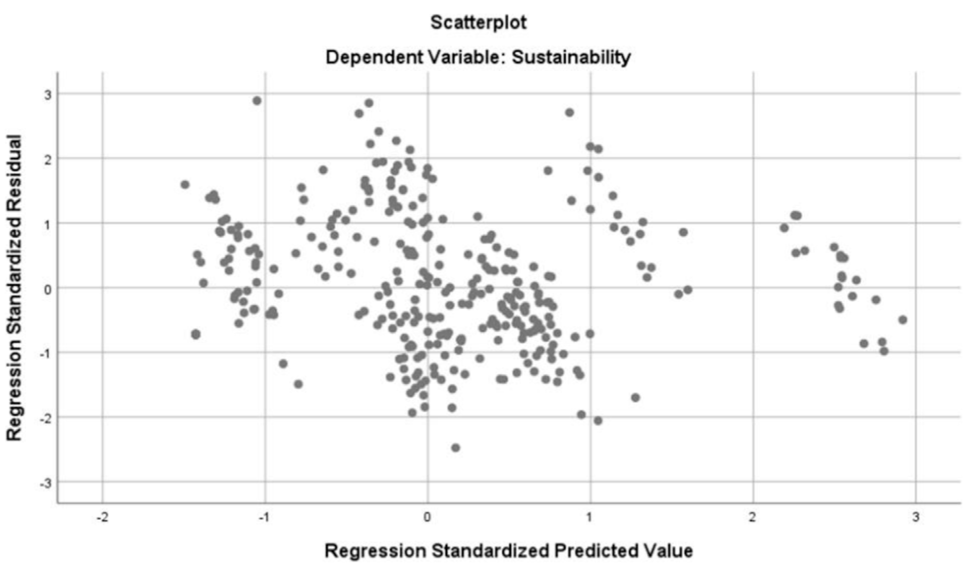

FIGURE 6
Regression's scatter plot for CCD index under GC1 in the energy sector.

the energy resources started targeting wind, solar, and waste to energy projects. The private sector was invigorated to invest in an independent power producer (IPP). The system was restructured to provide a net-metering facility that created prospects for harnessing solar energy at a domestic as well as a commercial scale in Pakistan. Accordingly, the relevant energy sector policies and strategies at the federal level were aligned to have all the mandatory provisions to fulfill the NDCs. However, the findings revealed that the progress in the provincial and local contexts sits far behind the national level development, due to the governance gaps.

Some of the key steps taken at the federal level include the launching of the Clean Development Mechanism (CDM) in August 2005. The CDM cell (Ghumman 2007) promoted clean energy and energy efficiency projects which aimed at reducing GHG emissions. The Local Adaptation Plan for Action (LAPA) started in 2012 as part of a 5-year project without any linkage to policies in the context of nexus of energy, water, and agriculture. During the project, six LAPAs for six districts were initiated, but the mechanism remained informal. So far, there is absence of concrete measures to link up LAPAs for the nexus of energy, water, and agriculture, which is critically important for CCD in the energy sector. Similarly, the Alternative Energy Development Board (AEDB) was established which in 2006 formulated a Renewable Energy Policy to diversify energy sources, stimulate renewable energy projects, and shun dependence on fossil fuels (GoP 2006). The Renewable Energy Policy 2006 was the first policy that intended to increase to a 10% share of renewables in the energy generation mix by the year 2015. Particular attention was given to micro-hydel, solar, and wind power projects. Consequently, renewable energy-based IPPs for selling the produced electricity were given incentives. Later on, the Power Generation Policy 2015 (GoP 2015) also announced incentives and a simplified *modus operandi* for approval and installation of power generation projects to meet the demand-supply gap for the socioeconomic lift of the economy. Vision 2025 of Pakistan also envisages the promotion of RE technologies in the goals to curtail the future upsurge of GHG emissions proportionately to growing energy demands. Later on, the Alternative and Renewable Energy Policy of Pakistan 2019 (ARE Policy 2019) augmented the target (AEDB 2019) to 20% of renewable mix by the year 2025 and 30% by the year 2030 in overall energy generation. It is anticipated that the targeted energy mix will provide environmentally sound, accessible, and affordable solution at the grassroots level while encouraging the stakeholders (AEDB 2019).

Among other important steps at the federal level, the establishment of the National Energy Efficiency and Conservation Authority (NEECA) is a major milestone. NEECA initially started as a project of USAID in 1985 which later become an authority after promulgation of NEECA Act in 2016 (GoP 2016b). Since its inception, NEECA has initiated projects to ensure energy efficiency and conservation in transport, manufacturing, and domestic sectors including energy auditing, building codes, and energy labeling of products (GoP 2016a).

Similarly, the National Climate Change Policy of Pakistan (GoP 2012) also stipulates commitment to GHG emission abatement as targeted in the NDCs. However, the policy also envisions that provisions related to the growth of RE technologies such as the promotion of distributed grid solutions, deployment of hydropower generation, utilizing rooftops for solar power generation, and installation of more waste to energy projects need to be in line with energy sector planning. Subsequently, the Framework for Implementation of Climate Change Policy (FICCP) further elaborates strategies and engagements for the advancement of RE-based energy diversification to control GHG emissions (GoP 2014). The strategies comprise the preferment of hydel power projects, the installation of more power plants based on municipal waste, and provision of incentives for desirable projects to gear progress towards low-carbon energy sources. However, all these steps also require institutional reforms for the transmission and distribution of the energy produced, tariff setting, and other fiscal reforms to promote RE technologies.

The role of the government in the progression of RE is crucial in any nation. RE brings opportunities such as the creation of a large number of jobs, energy security, and improved quality of life. Globally, governments are implementing policies to stimulate the utilization of RE sources and technologies (Sweetnam et al., 2013). Currently, the feed-in tariff (FIT) mechanisms are widely practiced across the globe, particularly in the developing nations (REN21, 2011). Pakistan adopted the FIT mechanism to promote renewable energy in connection with net-metering policies in 2015. The scheme set remuneration for a solar power project of up to 10 MW for 25 years in accordance with capacity and region. Ostensibly, 19 solar power generation projects with more than 50 MW of capacity gained licenses during 2020–21. Besides that, 8,417 net metering licenses of above 145 MW capacity were issued during the same year. However, Pakistan is facing deterrence pertaining to insecurity for FITs in relation to high capital investment, and investors' and consumers' interests (Sweetnam et al., 2013). Other challenges include financial obstacles, a dearth of competition, institutional obstructions, and a lack of access to technology (Yazdanie and Rutherford 2010). Consequently, setting FITs high by the National Electric Power Regulatory Authority (NEPRA) will maximize the profits of the investors. In such case, the consumers will suffer from high costs of RE. Likewise, setting FITs to a lower rate will result in benefitting consumers while investors bear high capital investment costs. These challenges compromise the desired results that can be achieved by implementing the FIT framework in Pakistan. The analysis of respondents' feedback reveals that sustainability under GC-1 is fair at the federal level, while in the range of very poor to poor at the provincial and district levels respectively. However, the vertical coherence of policies and legal instruments is necessary for the sustainability of the federal level commitments. In this context, the

role of the provincial governments is critical to complement all the provincial policies and plans with the federal endeavors. The findings also reveal that the development of compulsory mechanisms to strengthen the institutional capabilities and capacities is important. However, such a roadmap is non-existent in strategies, policies, and planning documents resulting in the low governance index score.

The energy sector requires intensive investment which is necessary to boost the economy, ensure social well-being, and strengthen the technology base and thus the overall development of a country. Awareness and the capacity building of relevant institutions remain a major hurdle in the inclusive development energy sector in the developing world. Most of the current initiatives are project based, temporary, and thus inadequate for capacity building and training of human resources (Lawonski et al., 2018). Consequently, gaps in innovation, management, analytical research base, and general awareness need to be overcome in order to achieve the 20–30% contribution of RE in the overall energy mix to achieve the NDCs (Lo et al., 2019). This can be achieved by decommissioning policies that revolve around conventional energy forms, and the promotion of RE-based initiatives adopting cross-sectoral approaches.

Awareness and relevant capacity-building remain a major hurdle in the inclusion of RE in the developing world, as the current efforts have project-based orientation rather than context-dependent and long-term efforts envisaged (Lawonski et al., 2018). Perspective gaps in innovation, management, analytical research base, and general awareness need to be understood well in order to assess the effectiveness and demand of RE from the bottom up (Lo et al., 2019), by rationalizing and decommissioning the shortcomings of the policies that revolve around conventional energy forms and their promotion in the business-as-usual scenario. This is greatly needed in the context of Pakistan where policy coherence and overlaps have created great confusion, particularly for the trickle-down effect from federal to the provincial and local contexts.

Conclusion

Study of the Governance Component-1 (the basic response mechanism for policy, legal, and institutional arrangements), intended for first climate response principle 1 in the energy sector at federal, provincial, and district levels, showed that the model proved well in developing, validating, and interpreting the governance index against the basic research query. The developing countries including Pakistan have great potential and prospects for renewable and sustainable energy development. However, they have several challenges due to the lack of an adequate and coherent policy, and legal and institutional arrangements which are necessary for devising strategies as well as planning and execution processes. This occurs due to the complex governance mechanism. The results of this study reveal that climate response is more visible at the federal level. The relevant sectoral policies and strategies have all the essential provisions that are obligatory for CCD in the energy sector. However, the provincial and local contexts sit far behind the national level development, due to governance gaps, thus it shows a very strong disconnect and does not appeal to the audience. After the 18th Amendment in the Constitution of Pakistan, 1973, provinces were given autonomy to develop their energy resources. Private sector companies were given the choice to become independent power producer (IPP); particularly, the net-metering facility created the opportunity to tap the solar energy potential in Pakistan. A poor uptake was found in provinces. However, all nine criteria of GC-1 influence each other; in totality, the null hypothesis could not be excluded for the case of GC-1 in the energy sector. So, GC-1 index scores are indicative of the lack of a preemptive and inclusive governance framework to ensure climate compatible development in the energy sector at the federal, provincial, and district levels in Pakistan. The study reveals that the governance mechanisms pertaining to energy generation, distribution and regulation of the consumption, and efficiency lack clarity in their objectives as well as in their execution. Due to the energy crises in the past few years, the predominant goal of the energy sector was to bridge the gap between supply and demand, irrespective of the commitments made under climate change policy and action plan. Consequently, Pakistan's energy mix skewed towards thermal power generation from imported fuel, posing a risk for climate as well as energy security and accessibility issues. The study also revealed a lack of coordination among the vertical hierarchy of governance, that is, federal, provincial, and district level departments.

The findings of the study pave the way to restructure the energy sector policies, strategies, and institutions in line with the principle, criteria, and indicators stipulated in the study to ensure environmental security and sustainable development. The study recommends aligning the energy sector development objectives in line with climate change and SDGs. This reflects rethinking the agreements of imported fuels as well as the diversification of existing energy resources. For this purpose, policies and strategies should support technological innovation in all segments of the energy sector.

As far as the limitation of the study is concerned, all aspects related to the basic response mechanism comprising policy, legal, and institutional measure to feature CCD in the energy sector have been covered well. However, it has been carried out by involving a large dataset based on indictors and constituencies, due to which it required more time and resource input. Data recording from the respondents was a difficult process, due to poor understanding of the subject, particularly at provincial and district levels. The outcome of the study could have been even better if adequate financial resources had been available for 1) increasing the number of districts and 2) having a comparative analysis by adding a few more developing countries under the scope of this study (Yin et al., 2022b).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Ethics statement

Ethics review and approval/written informed consent were not required as per local legislation and institutional requirements.

Author contributions

All the authors contributed substantially to the entire work reported in this article. They read and approved the final manuscript, which was extracted from a novel and original research dissertation of the first author submitted to the International Islamic University, Islamabad, for partial fulfillment of his PhD degree. KI extracted and shaped the basic idea, methodology, results, discussion, and conclusion. MK supervised the work by reviewing and editing the overall paper, technically and academically. NA helped in drafting the introduction, discussion, and abstract sections. FW complemented in discussion, logical conclusion, proofreading, and processing the paper with Frontiers in Environmental Science. UA assisted in referencing and formatting.

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Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.985340/full#supplementary-material

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EDITED BY
Cem Işık,
Anadolu University, Turkey

REVIEWED BY
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Sakarya University, Turkey
Imran Ali Baig,
Aligarh Muslim University, India

*CORRESPONDENCE
Md. Qamruzzaman,
qamruzzaman@bus.uiu.ac.bd

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Nexus between green investment and technological innovation in BRI nations: What is the role of environmental sustainability and domestic investment?

Zhuopeng Xiao[1] and Md. Qamruzzaman[2]*

[1]SILC Business School, Shanghai University, Shanghai, China, [2]School of Business and Economics, United International University, Dhaka, Bangladesh

The critical role of technological innovation has been extensively investigated by considering various aspects of macro-fundamentals across the world. Although the determents of technological innovation have been investigated predominantly from the perspective of firms, the role of macro-fundamentals is yet to be extensively explored. The aim of the study is to investigate the effects of green investment, measured by renewable energy; domestic investment measured by gross capital formation; and environmental sustainability measured by carbon emission on technological innovation in BRI nations for the period 2000–2021. The study used a cross-sectional dependency test, a unit root test following CADF and CIPS, an error correction-based panel cointegration test, ARDL, CS-ARDL, and a nonlinear ARDL. Furthermore, the directional causalities were documented by performing the heterogeneous causality test. Taking into account the findings of the study, it is revealed that green investment and domestic investment are positively connected with technological innovation in BRI nations, while environmental sustainability is correlated negatively and statistically significant to technological innovation. Furthermore, the asymmetric investigation established asymmetric effects from green investment, environmental sustainability, and domestic investment to technological innovation. According to the asymmetric coefficients, the positive and negative shocks of green and domestic investment disclosed positive and statistically significant links with technological innovation, whereas the asymmetric shocks in environmental sustainability revealed adverse ties to technological innovation in BRI nations. The study documented the unidirectional causal effects from green investment to technological innovation [GI→TI] and technological innovation to environmental sustainability [TI→ES]. Furthermore, the study documented bidirectional casualties between domestic investment, foreign direct investment, financial development, and technological innovation [TI←→DI; TI←→FDI; TI←→FD]. The study suggested that domestic capital formation and environmental protection in BRI nations should be actively promoted to accelerate technological innovation. Furthermore, the study postulated that

investment in research and development should be encouraged with incentives for technological innovation.

KEYWORDS

green investment, environmental sustainability, domestic investment, ARDL (autoregressive distributed lag), CS-ARDL, NARDL asymmetric

1 Background of the study

From time immemorial, scholars and policymakers have found the significance of technical innovation, as well as its role in explaining domestic production, developing job possibilities, and enhancing social welfare, to be an incredibly intriguing issue (Solow, 1957; Romer, 1986; Aghion and Howitt, 1990). It is interesting to note that innovative possibilities are available to leading and trailing nations. Researchers have paid significant attention to technological innovation over time, particularly since the beginning of the fourth industrial revolution, characterized by technological transformations, artificial intelligence, and digital revolution. Based on theoretical contributions, it has been recognized for a long time that innovation is the driving force behind economic development (e.g., (Aghion and Howitt, (1990); Romer, (1990)). In a similar line, empirical evidence suggests that the main drivers of economic growth are technological improvement, national creative capabilities, and productivity advantages associated with innovation (for example, (Geroski, 1995; Fagerberg et al., 2012)). Furthermore, recent decades have shown an increase in technical capabilities. The development of new technology, especially information technology (IT), has rapidly progressed. It is commonly accepted that financial investment in this technology is a crucial component of a solid infrastructure for managing knowledge (Youndt et al., 2004). Despite the widespread belief that technological innovation positively affects business performance, empirical evidence on the link between technical innovation and enhanced firm success remains inconsistent.

Acknowledging the importance of technological innovation, existing literature has produced two lines of evidence: the role of technological innovation and the determinants of technological innovation. Referring to the first line of the assessment, the existing literature postulated that technological innovation accelerated economic growth (Nosheen et al., 2021), foreign trade (Márquez-Ramos and Martínez-Zarzoso, 2010), FDI (Qamruzzaman, 2014; Qamruzzaman and Ferdaous, 2014; Qamruzzaman, 2015; Razzaq et al., 2021; Zhuo and Qamruzzaman, 2021), ecological efficiency (He et al., 2021), climate change (Lin and Zhu, 2019; Huang et al., 2021), environmental sustainability (Sinha et al., 2020), energy efficiency (Pan et al., 2019), among others. The study of Bong and Premaratne (2019) established the importance of technological innovation in enhancing both environmental protection and the economic performance of businesses. They argued that not only does it help cut down on the price tag for keeping pollution at bay but also boosts output, productivity, and profits by introducing novel products and refining existing ones. This is accomplished through the introduction of novel products and refinement of existing ones. Furthermore, a group of researchers have investigated the impact of technological innovation with specific assessments of firms (Wachira, 2013; Ince et al., 2016; Ferdousi and Qamruzzaman, 2017; Jianguo and Qamruzzaman, 2017; Qamruzzaman, 2017).

The present study considered green investment measured by renewable energy, environmental sustainability measured by carbon emission, and domestic investments measured by gross capita formation in the assessment of technological innovation. Green development, also known as environmentally adjusted multifactor productivity growth, depends on cleaner and more sustainable energy sources. Countries worldwide are trying to restructure their industrial and economic systems to promote green development with cleaner and more sustainable energy sources (Işık, 2013; Wang et al., 2021). Because of the emergence of the Fourth Industrial Revolution, environmentally friendly technologies have significantly improved the environment's condition in modern economies. These technologies have also helped repair environmental damage. Eco-innovation is gaining recognition across governments and businesses as an effective strategy in combating climate change and support green development (GG), most importantly for sustainable, equitable development. Equitable development demands substantial support from the economy through the channels of environmental sustainability, climate protection, quality of life, and economic growth. Technological advancement assists the economy in ensuring climate protection with environmentally friendly technological integration, energy efficiency, and efficient natural resource allocation. An innovation-led economic development strategy accelerated economic growth through environmental protection by lowering carbon emissions (Andriamahery and Qamruzzaman, 2022).

The aim of the study is to investigate the effects of green investment, environmental sustainability, and domestic investment on technological innovation in BRI nations for the period 2005–2020 with the implementation of both symmetric and asymmetric frameworks. As a sample, the study considered a panel of 56 (fifty-six) BRI nations, and the following facts induced their selection.

The novelty of this study lies in the following facts. First, to our best knowledge, this is the first-ever empirical study that has initiated exploring the role of green investment, measured by

renewable energy consumption, environmental sustainability, and domestic investment, in technological innovation in BRI nations. It is assumed that the study findings will extend the existing literature by offering a development avenue for technological innovation in the economy with the understating of the key macro determinants. Second, referring to the existing literature survey dealing with the determinants of technological innovation, it is apparent that very less literature is available focusing on the nexus between technological innovation and macro-fundamentals, whereas an increasing number of studies have been performed dealing with firms' specific determinants. This study's findings will be considered an informative way to mitigate the existing literature gap dealing with technological innovation and macro-fundamentals. Furthermore, the study considered both symmetric and asymmetric frameworks in investigating the empirical relation and firmly believes that asymmetric assessment will open an avenue in effective policy formulation. Third, technological innovation focusing on BRI nations is yet to be investigated in empirical studies, and a few studies have been initiated to discover the role of technological innovation in environmental sustainability (Khan et al., 2021), environmental quality (Zuo et al., 2021), employment (Van Reenen, 1997), and green development (Xu et al., 2022). However, dealing with the key determinants of technological innovation in BRI is completely ignored in the empirical assessment.

Taking into account the study findings, it is revealed that green investment and domestic investment are positively connected with technological innovation in BRI nations, while environmental sustainability is correlated negatively and statistically significant to technological innovation. Furthermore, the asymmetric investigation established asymmetric effects from green investment, environmental sustainability, and domestic investment to technological innovation. According to the asymmetric coefficients, the positive and negative shocks of green and domestic investment disclosed positive and statistically significant links with technological innovation, whereas the asymmetric shocks in environmental sustainability revealed adverse ties to technological innovation in BRI nations. The study documented the unidirectional causal effects from green investment to technological innovation [GI→TI] and technological innovation to environmental sustainability [TI→ES]. Furthermore, the study documented bidirectional casualties between domestic investment, foreign direct investment, financial development, and technological innovation [TI←→DI; TI←→FDI; TI←→FD].

The remaining structure of the study is as follows: Section II deals with the related literature, focusing on the nexus between green investment, environmental sustainability, domestic investment, and technological innovation. Model specification, variable definition, and estimation strategies are displayed in Section III. Empirical model estimation and its interpretation are available in Section VI. Section V contains the discussion of the study. Finally, the conclusion and policy suggestions are explained in Section VI.

2 Literature review and hypothesis development

To maintain national economic competitiveness in the face of growing global awareness of the effects of economic activity on resource consumption and the environment, new production and consumption patterns are becoming increasingly popular as a means of spurring innovation in business sector activities, particularly technology (Galende, 2006; Li and Qamruzzaman, 2022). The innovation process depends on external variables; the development of new technologies results from interactions with consumers, suppliers, rivals, and numerous other public and private organizations. This helps explain why clusters, competitions, and other business connections are vital for technological advancement (Wang and Yan, 2022). In this context, innovation, understood as a system in terms of spatial parameters at the regional or national level, allows for the study and analysis of these interactions which influence the innovation propensity and performance of innovation activity (Qamruzzaman et al., 2021; Liu et al., 2022).

In the last few decades, greater human well-being and worldwide economic development have been accompanied by a rapid depletion of natural resources and an increase in environmental sustainability, resulting in a heightened focus on environmental issues. The Environmental Kuznets Curve (EKC) theory demonstrates economic expansion and environmental protection trade-offs. This concept suggests that as economic development develops, environmental conditions will degrade and then improve (Grossman and Krueger, 1991; Abdo et al., 2022). According to the endogenous economic growth hypothesis, an increase in expenditure on research and development (R&D) may enhance economic output efficiency and resource usage efficiency. Despite this, it is uncertain as to how much technical innovation can contribute to advances in environmental quality, especially in CO_2 emissions (Howitt, 2000; Pablo-Romero and Sánchez-Braza, 2015; Li and Qamruzzaman, 2022; Xia et al., 2022). Technology advancement is expected to boost productivity and efficiency during the Fourth Industrial Revolution as a supply-side miracle. The digital revolution is also expected to usher in cost-effective transportation and communication solutions. These factors, taken together, are expected to generate a new market and hasten its growth. Acknowledging the importance of technological innovation, existing literature has produced two lines of evidence: the role of technological innovation and the determinants of technological innovation. Referring to the first line of the assessment, existing literature postulated that

technological innovation accelerated economic growth (Nosheen et al., 2021), foreign trade (Márquez-Ramos and Martínez-Zarzoso, 2010), FDI (Razzaq et al., 2021; Zhuo and Qamruzzaman, 2021), ecological efficiency (He et al., 2021), climate change (Lin and Zhu, 2019; Huang et al., 2021), environmental sustainability (Sinha et al., 2020), energy efficiency (Pan et al., 2019), among others. The study of Guntur et al. (2021) established the importance of technological innovation in enhancing both environmental protection and the economic performance of businesses. They argued that not only does it help cut down on the expenses for keeping pollution at bay but also boosts output, productivity, and profits by introducing novel products and refining existing ones. This is accomplished through the introduction of novel products and the refinement of existing ones. Furthermore, a group of researchers have investigated the impact of technological innovation with specific assessments of firms (Wachira, 2013; Ince et al., 2016).

In the case of China, Shi et al. (2022) investigated the effect of technological innovation and application on development considering provincial data. The study postulated that the efficiency value of China's technological innovation and technological application has to be developed and there is positive and effective inventive activity between technological innovation and technological application. In order to foster an environment that is conducive to the healthy development of technological innovation and application, as well as to boost the vitality of the technological market, important policy proposals have been made. For Pakistan, Abbasi et al. (2022) revealed technological innovation support in carbon mitigation.

The findings of the academic study provide unequivocal evidence in favor of the premise that technological innovation plays a significant role in both the competitiveness of industries and the development of nations (Tidd and Bessant, 2020; JinRu and Qamruzzaman, 2022; Zhao and Qamruzzaman, 2022). Some businesses are more innovative in their use of technology than others, and the factors that influence their inventiveness are of interest to management academics, managers in practice, innovation consultants, and policymakers in the technology field. According to Popp et al. (2011), increasing technology does lead to greater investment, but it is a small effect. Hydropower and nuclear power can be substituted for renewable energy sources as they are carbon-free. A study based on Brazil by Pao and Fu (2013) indicates that Brazil is an energy-independent economy and that economic growth is vital to sustainable development in renewable and non-renewable energy. By utilizing renewable energy, Brazil will not only enhance its economic growth and curb the degradation of its environment but will also achieve a leadership role in the international system and improve its competitiveness against more advanced nations. More evidence can be found in the study of Apergis and Payne (2010), where the authors mentioned a positive and significant relationship between renewable energy and economic growth. The authors also mentioned that economic growth is imperative for renewable energy to be developed and used in the future. Foxon et al. (2005) argued that sustained investment is needed for technologies to achieve their potential and a stable and consistent policy framework is needed to facilitate it. The study by Akella et al. (2009) shows that emission reduction in different years is exponentially increasing after installing renewable energy systems. Again, renewable electricity generation sources such as wind and water are very well-suited to sustainable development (Varun et al., 2009). The study also mentioned that as new technologies and mass production of these systems become more common, the cost of generation of these systems and the emission of GHGs will decrease significantly in the near future. Lund (2007) conducted a study on Denmark and found that there are sufficient renewable energy sources on hand, and if technology can be improved on the energy system, a renewable energy system can be achieved. A study by Kaygusuz (2007) stated that at the micro-to-medium scale, renewable energy could provide homes, schools, and hospitals with clean, flexible power and create jobs simultaneously.

The study by Croezen and Korteland (2010) suggests that several promising technologies will be available by 2020 and 2030 that will help reduce emissions from steel, paper, and cement manufacturing, which will collectively account for 41% of the European industrial CO_2 emissions by 2050. According to Zhang and Cheng (2009), China can pursue a conservative energy policy and reduce carbon emissions without slowing economic growth in the long run. Chen and Lee (2020) disclosed that introducing new technologies does not significantly contribute to reducing global CO_2 emissions. However, group-based studies have shown that technological innovation in countries with high incomes, high levels of technology, and high levels of CO_2 emissions can significantly reduce CO_2 emissions in neighboring countries, whereas the level of R&D intensity in other countries can increase CO_2 emissions. Soytas et al. (2007) mentioned that carbon emissions in the US are not caused by growth in income in the long run but by energy use. As such, income growth alone might not be sufficient to protect the environment. Further evidence can be found in Apergis and Payne (2009), where a study revealed that energy consumption and emissions are positively correlated in long-run equilibrium, while the Environmental Kuznets Curve (EKC) hypothesis predicts a U-shaped pattern. Similar findings can be found in the study by Pao and Tsai (2010), where the authors noted that energy-dependent BRIC countries could reduce emissions by increasing both energy supply investments and energy efficiency and stepping up energy conservation policies to reduce unneeded energy waste. Akella et al. (2009) found that the tendency to reduce emissions has doubled after installing renewable energy systems. Varun et al. (2009) noted that new technologies and mass production of these systems are predicted

to reduce the cost of generation and emissions of greenhouse gases as the cost of new technologies and mass production become more widely available. On the other hand, based on the study by Acaravci and Ozturk (2010), the overall results show that energy conservation policies, such as rationing energy consumption and reducing carbon dioxide emissions, are unlikely to harm the real output growth of most countries studied, and the EKC hypothesis is unlikely to hold.

In terms of economic development, global competitiveness, financial systems, quality of life, and trade openness, the many effects of innovations on the economy are readily apparent. When corporations are important contributors to the innovation process, the government's role in enhancing the private sector's ability to absorb, improve, and develop new technologies is evident (Baig et al., 2022). The government provides the required infrastructure and a platform for commerce that institutions supply to enhance enterprises' capabilities. Governments, industries, and academics have emphasized the importance of scientific research and development to economic progress from time immemorial. Research and development operations provide knowledge and technology, both of which boost productivity at the business, industrial, and national levels. As a consequence, the chain effect of productivity will result in improved returns on investment, which represent higher income levels and, therefore, enhanced economic growth. Tang et al. (2008) revealed that China's FDI has contributed to overcoming capital shortages and complemented domestic investment to stimulate economic growth. In the case of Pakistan, Ghazali (2010) conducted a study revealing that FDI inflow in Pakistan supplements domestic investment and stimulates economic growth.

Further evidence can be found in the study of Faeth (2006), where the FDI was found to directly increase domestic investment growth, GDP growth, and FDI itself but decrease export growth. However, according to the findings of Agosin and Machado (2005), FDI effects on domestic investment are not always positive, simplistic policies toward FDI are unlikely to be optimal, and, above all, economic policies that encourage domestic investment need to be given more scrutiny. More evidence can be found in the study by Adams (2009), where the author initially mentioned a negative effect of FDI on DI but later found a positive one. Again, based on the study's results, the country requires a targeted approach to FDI, higher absorption capacity for local firms, and greater collaboration between governments and MNEs for mutual benefit. An industry-level analysis by Arndt et al. (2010) of the German economy found evidence that FDI positively impacts the domestic capital stock over the long run. Another study based on U.S. multinationals by Desai et al. (2009) stated that the domestic activity of U.S. multinationals increases as they go for more investment in foreign countries. Similarly, Herzer and Schrooten (2008) studied both countries and found that outward FDI positively impacts long-term domestic investment in the US. These complementary relationships only exist in Germany for a short period.

In the case of Saudi Arabia, Kahouli et al. (2022) investigated how green energy supports achieving environmental sustainability. The study documented that in the long run, the negative association between technological innovation, green energy, and environmental sustainability implies that green energy inclusion and technological advancement prompt environmental sustainability, which leads to economic progress. Wang et al. (2020) assessed technological innovation's effects on environmental protection in N-11 from 1990 to 2017. The study revealed that technological innovation prompts environmental sustainability through carbon reduction. Further evidence is available in the study of Su et al. (2022). According to the study's findings, improving technological innovation and clean energy inclusion support achieving carbon neutrality. The study further suggested that industries should increase environmental awareness and provide TI-related incentives to encourage structural energy adjustment and reduce carbon footprint REC. The government should develop appropriate policies and procedures to emphasize and expand the use of renewable energy, particularly in regions with high emission levels.

3 Limitations in the literature

1. First, referring to the existing literature survey dealing with the determinants of technological innovation, it is apparent that very few literature are available focusing on the nexus between technological innovation and macro-fundamentals, whereas an increasing number of studies have been performed dealing with firms' specific determinants.
2. Second, technological innovation focusing on BRI nations is yet to be investigated in empirical studies, and a few studies have been initiated to discover the role of technological innovation in environmental sustainability (Khan et al., 2021), environmental quality (Zuo et al., 2021), employment (Van Reenen, 1997), and green development (Xu et al., 2022). However, dealing with the key determinants of technological innovation in BRI is completely ignored in the empirical assessment.
3. Third, referring to the methodological aspect, the existing literature extensively relies on the symmetric framework in assessing the key determinants of technological innovation. The present study has extended the empirical assessment by incorporating the asymmetric framework in empirical relation investigation. Including an asymmetric framework will support effective policy formulation with an in-depth understanding of innovation.

Author	Country	Period	Explanatory variable	INV	TI	EG	PO	ES	Job	ORG	ES	SD
Pao and Fu (2013)	Brazil	1980–2010	EG			+						
Popp et al. (2011)	26 OECD nations	1991–2004	INV	+								
Apergis and Payne (2010)	20 OECD nations	1985–2005	EG			+						
Varun et al. (2009)	10 countries	1995–2006	TI and SD		+							+
Akella et al. (2009)	India	n/a	ES								+	
Kaygusuz (2007)	International	2001	Job and ORG						+	+		
Lund (2007)	Denmark	n/a	TI		+							
Foxon et al. (2005)	The United Kingdom	n/a	INV and GP	+			+					

Author	Country	Period	Explanatory variable	TI	INV	PO	EG	IN	EC	ES	SD
Acaravci and Ozturk (2010)	17 EU countries	1960–2005	EG				+/-				
Pao and Tsai (2010)	BRIC countries	1971–2005	INV and EC		-		+		+		
Croezen and Korteland (2010)	EU	1994–2004	IT	-							
Varun et al. (2009)	Countries	1995–2006	TI and SD	-							-
Akella et al. (2009)	India	n/a	ES							-	
Zhang and Cheng (2009)	China	1960–2007	GP and EG			-	+				
Apergis and Payne (2009)	Central America	1971–2004	EC						+		
Soytas et al. (2007)	The US	1960–2004	IN and EC					None	+		

Author	Country	Period	Explanatory variable	EG	FDI	PO	EXP	IMP
Ghazali (2010)	Pakistan	1981–2008	FDI and EG	+	+			
Arndt et al. (2010)	Germany	1991–2004	FDI		+			
Adams (2009)	42 sub-Saharan countries	1990–2003	FDI		−/+			
Desai et al. (2009)	U.S. multinational companies	1982–2004	FDI		+			
Tang et al. (2008)	China	1988–2003	EG and FDI	+	+			
Herzer and Schrooten (2008)	Germany and US	1970–2004	FDI		+			
Faeth (2006)	Australia	1985–2002	EG, FDI, EXP, and IMP	+	+		- (depends on FDI)	+ (depends on FDI)
Agosin and Machado (2005)	12 developing countries	1971–2000	FDI and PO		Unchanged	+		

EXP, export; IMP, import; SD, sustainable development; ORG, organization; IN, income; PO, policy; ES, environmental sustainability; EG, economic growth; FDI, foreign direct investment; EC, energy consumption; TO, trade openness; INV, investment.

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Summary of the literature survey focusing on the nexus between green investment, environmental sustainability, domestic investment, and technological innovation.

3.1 Hypothesis development

Considering the empirical association between green investment, environmental sustainability, domestic investment, and technological innovation, the following conceptual model (see Figure 1.) has proposed the possible causalities among them. The heterogeneous causality model has been implemented for assessing the proposed causal association.

The following hypothesis is to be tested:

$H_1^{A,B}$: Technological innovation Granger causes green investment and vice versa.

$H_2^{A,B}$: Technological innovation Granger causes domestic investment and vice versa.

$H_3^{A,B}$: Domestic investment Granger causes environmental sustainability and vice versa.

$H_4^{A,B}$: Environmental sustainability Granger causes green investment and vice versa.

$H_5^{A,B}$: Technological innovation Granger causes environmental sustainability and vice versa.

$H_6^{A,B}$: Green investment Granger causes domestic investment and vice versa.

4 Data and methodology of the study

4.1 Model specification

The purpose of the study is to investigate the effects of green investment, environmental sustainability, and domestic investment on technological innovation in the BRI nations for the period 1995–2020. The selection of the study period completely relies on data availability, and it is notable that due to missing variables, we purposively omitted the study period 2021.

Referring to research variable selection, especially for the explanatory variables, the study considered green investment measured by the development of renewable energy consumption, assuming that reducing destructive environmental nature due to carbon emissions could be mitigated with clean energy. Furthermore, renewable energy inclusion is a sign of technological innovation in energy production. Thus, green investment possibility is anticipated to prompt technological innovation in the economy. Environmental sustainability refers to managing environmental adversity by effectively including energy efficiency and operational efficiency. It indicates that environmental concern creates urgency in the economy for innovation in managing the environmental consequences; therefore, the study believes technological innovation has accelerated environmental sustainability as a control mechanism. Capital adequacy in the economy requires investment in R&D, positively suggesting a national innovation act with the promotion of technological innovation. Considering the explanatory and dependent variables, the basic functional model for empirical assessment is as follows:

$$TI_{it} = \int GI_{it} ES_{it} DI_{it} FDI_{it} FD_{it}, \quad (1)$$

where TI denotes technological innovation, GI stands for green investment, DI explains domestic investment, ES stands for environmental sustainability, FDI stands for foreign direct investment, and FD stands for financial development. The abovementioned Eq. 1 is transformed into an econometric form with variable coefficients as follows:

$$TI_{it} = \beta_1 GI_{it} + \beta_2 ES_{it} + \beta_3 DI_{it} + \beta_4 FDI_{it} + \beta_5 FD_{it}, \quad (2)$$

where "it" explained the cross-sectional unit and time. The coefficients $\beta_1 \beta_5$ deal with the explanatory variable magnitudes on technological innovation.

It is anticipated that every nation has been seeking eco-friendly investment for sustainable economic growth with environmental protection, that is, clean energy inclusion instead of fossil fuel, with a motivation of energy transition from conventional to renewable energy sources. The evolution of renewable energy sources in the economy has ensured operation and energy efficiency while controlling environmental adversity. The energy efficiency with renewable energy inclusion in the economy has augmented technological development. Thus, it is anticipated that the magnitudes of green investment, which are measured by renewable energy, have a positive impact on technological innovation; in other words, $\beta_1 = \frac{TI}{GI} > 0$. Environmental protection is the key to sustainable economic development, and controlling environmental degradation with carbon intensity reduction is possible. The continuous emission of greenhouse gases has openly challenged the prospect of equitable development, especially for developing nations. The controlled carbon emission adversely affects their aggregated output level; therefore, they have shown disinclination in managing the carbon emission. Thus, it is assumed that carbon emission has a negative association with technological innovation; in other words, $\beta_2 = \frac{TI}{es} < 0$. Capital adequacy in the economy prompts sustainable development, characterized by technological advancement, which predominately encourages the economy to adapt to technological upgradation in every aspect. Domestic capital formation intensifies the aggregated economic activities, operational efficiency, and demand for improved technological inclusion. Therefore, it is expected to have boosting effects of domestic investment on technological innovation; in other words, $\beta_3 = \frac{TI}{DI} > 0$.

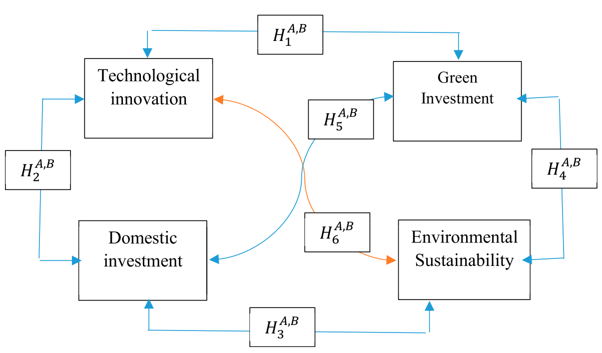

FIGURE 1
Conceptual model for the study of hypothesis testing.

4.2 Estimation strategy

4.2.1 Correctional dependency

Because of globalization and increased collaboration in the economic sphere, variables' effects on one nation may affect other countries. Because of the interconnection of the countries, there is a possibility that cross-sectional dependency problems may appear in the panel data. Previous analysis techniques were flawed because they assumed the cross sections were independent of one another. The findings of the research that was carried out using these approaches may be skewed if it is impossible to consider the cross-sectional dependency in the panel data (Qamruzzaman and Jianguo, 2020; Li and Qamruzzaman, 2022; Mehta et al., 2022; Xia et al., 2022). We successfully overcame this obstacle by first carrying out tests of cross-sectional dependency. To determine whether or not there is cross-sectional dependency, the LM test established by Breusch and Pagan (1980) and the CD test developed by Pesaran (2004) and Pesaran et al. (2008) presented the bias-adjusted LM test, which is the method of choice in instances in which the cross section (N) is much less than the amount of time (T). We can create LM test statistics using the following equation as our guide:

$$y_{it} = \alpha_i + \beta_i x_{it} + u_{it} \text{ i} = 1\ldots\text{N, t} = 1\ldots\text{T}, \tag{3}$$

where y-it denotes a dependent variable, x-it represents an independent variable, and the subscripts t and I stand for cross-section and period, respectively. The iteration number is denoted by the iteration symbol. The coefficients I and I are used in the equation to indicate a nation's specific intercept and slope, respectively. These coefficients are denoted by the symbols I and I, respectively. The alternative hypothesis of cross-sectional dependence is tested using the LM cross-sectional dependency test. This test compares the null hypothesis of cross-sectional independence with the alternative hypothesis of cross-sectional dependence by comparing H-O. = COV, u-it,u-jt = 0 for all t and tj, with the alternative hypothesis of cross-sectional dependence.

In addition to this, the statistics of the LM test may be determined by utilizing the equation that is shown here:

$$: LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{IJ\to d}X^2N(N+1)2, \tag{4}$$

where $\hat{\rho}_{ij}$ represents the pairwise correlation of the residuals.

The Lagrange multiplier (CD_{lm}) is the scaled version of the LM test:

$$CD_{lm} = \sqrt{\frac{N}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(T\hat{\rho}_{ij}-1\right). \tag{5}$$

The following CD test is suitable in a situation when N is larger than T:

$$CD_{lm} = \sqrt{\frac{2T}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(\hat{\rho}_{ij}\right). \tag{6}$$

The bias-adjusted LM statistics can be computed with the following equation:

$$CD_{lm} = \sqrt{\frac{2}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(\frac{(T-K)\hat{\rho}_{ij}^2-u_{Tij}}{v_{Tij}^2}\right)\vec{d}(N,0), \tag{7}$$

where k refers to the number of regresses and u_{Tij} and v_{Tij}^2 specify the mean and variance of $(T-K)\hat{\rho}_{ij}^2$, respectively.

4.2.2 Panel unit root test

In empirical estimation, identifying the properties of the variables that are the subject of the estimation has historically been seen as an important stage. This is especially true in the case of panel data analysis. Research determining the stationarity of variables used three distinct first-generation unit root tests, including the Levin et al. (2002), the Im et al. (2003), and the ADF-Fisher Chi-square test. These tests were utilized to detect variables' stationarity (Maddala and Wu, 1999). The issue of cross-sectional dependency (CSD) required the utilization of second-generation unit root tests, such as the cross-sectional augmented Dickey–Fuller (CADF) and the cross-sectional augmented Im, Pesaran, and Shin (CIPS) models, both of which were well-known to Pesaran, who was also familiar with both of these models. Despite this, the investigation made use of these tests. The following forms the framework for the unit root test when utilizing CADF, in line with Pesaran's (2007) recommendations:

$$\Delta Y_{it} = \mu_i + \theta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \vartheta_i \bar{y}_t + \tau_{it}. \tag{8}$$

Substituting long-term coefficients in Eq. 9 results in the subsequent Eq. 10:

$$\Delta Y_{it} = \mu_i + \theta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \sum_{k=1}^{p}\gamma_{ik}\Delta y_{i,k-1} + \sum_{k=0}^{p}\gamma_{ik}\overline{\Delta y}_{i,k-0} + \tau_{it}, \tag{9}$$

where $Y_{it} - 1$ and $\bar{y}_{t-1}$ represent lagged level average and first difference operator for each cross-section, respectively, and the CIPS unit root test is displayed in Eq. 11.

$$CIPS = N^{-1}\sum_{i-1}^{N}\partial_i(N,T), \tag{10}$$

where the parameter $\partial_i(N,T)$ explains the test statistics of CADF, which can be replaced in the following manner:

$$CIPS = N^{-1}\sum_{i-1}^{N}CADF. \tag{11a}$$

4.2.3 Westerlund cointegration test

Once stationarity in the research variables has been confirmed, the next stage in panel data analysis is to test for the long-run cointegration of the investigated series. Given issues with CSD and heterogeneity, it was important to conduct second-generation panel cointegration tests to learn more about the nature of the long-run cointegration relationship between variables. In order to address the issue mentioned earlier, this study used Westerlund's (2007) error-correction–based cointegration. Error-correcting cointegration tests provide two kinds of data: test statistics for two groups (Gt and Ga) and two panels (Pt and Pa). Assuming that there is no long-run relationship between FDI, FDI, GLO, and EC in BRI countries is a good starting point for a Westerlund cointegration test.

The error correction techniques for long-run cointegration assessment are as follows:

$$\Delta Z_{it} = \partial_i' d_i + \varnothing_i\left(Z_{i,t-1} - \delta_i' W_{i,t-1}\right) + \sum_{r=1}^{p}\varnothing_{i,r}\Delta Z_{i,t-r} + \sum_{r=0}^{p}\gamma_{i,j}\Delta W_{i,t-r} + \epsilon_{i,t}. \tag{12a}$$

The results of group test statistics can be derived with Eqs 14, 15.

$$G_T = \frac{1}{N}\sum_{i-1}^{N}\frac{\varphi_i}{SE\varphi_i} \tag{13a}$$

;

$$G_a = \frac{1}{N}\sum_{i-1}^{N}\frac{T\varphi_i}{\varphi_i(1)}. \tag{14}$$

The test statistics for panel cointegration can be extracted by implementing the following Eqs 16, 15:

$$P_T = \frac{\varphi_i}{SE\varphi_i} \tag{15}$$

;

$$P_a = T\varphi_i. \tag{16}$$

4.2.4 Panel autoregressive distributed lag

Pooled grouped mean, hereafter PGM, can estimate both long-run and short-run magnitude by addressing heterogeneity issues. The following ARDL (p, q. . .. n) as an empirical structure:

$$TI_{it} = \epsilon_{it} + \sum_{j=1}^{p}\beta_{ij}TI_{i,t-j} + \sum_{j=0}^{q}\gamma_{ij}GI_{i,t-j} + \sum_{j=0}^{q}\rho_{ij}DI_{i,t-j} + \sum_{j=0}^{q}\pi_{ij}ES_{i,t-j} + \epsilon_{it}, \tag{17a}$$

where

$$\epsilon_{it} = \omega_t' G_t + \epsilon_{it}, \tag{18a}$$

$$Q_{i,t-j} = \alpha_i + \beta_{ij}TI_{i,t-j} + \omega_t' G_t + \mu_{it}, \tag{19}$$

where TI_{it} denotes the dependent variable for sample I, Q_{ij} denotes explanatory variable for group I, and γ_{ij} embodies the factors of explanatory variables. The sample is denoted by i = 1,2,. . ..N, and time by t = 1,2 . . . .T, whereas, μ_i. The generalized empirical ARDL model is as follows:

$$\Delta TI_{it} = \alpha_i + \xi_i\left(TI_{it-1} - \omega_t' Q_{it-1}\right) + \sum_{J=1}^{M-1}\gamma_{iJ}\Delta TI_{it-J} + \sum_{J=0}^{N-1}\beta_{ij}\Delta Q_{it-J} + \mu_{it}, \tag{20}$$

where $\xi_i = -1\left(1 - \sum_{j-1}^{M}\gamma_{iJ}\right)$, $\omega_t' = \xi_i^{-1}\sum_{j=0}^{N}\beta_{ij}$, $\gamma_{i,j}^{*} = -\sum_{I=J+1}^{M}\gamma_{il}$ for J = 1, 2, ..M-l, and $\beta_{i,j}^{*} = -\sum_{I=J+1}^{N}\beta_{il}$ for J = 1, 2... .. N-l. $(Q_{it-1} - \omega_t' X_{it-1})$. The short-run dynamics is represented by $\gamma_{i,j}^{*}$, β_{ij}.

4.2.5 CS-ARDL

In analyzing long- and short-run coefficients, we estimated a cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model developed by Chudik and Pesaran (2015). This method offers advantages not displayed by other methods. First, it may produce precise estimates even when the variables are provided in alternative orders, such as I (0) or if I is absent (1). Second, it can offer exact data on the prevalence of both short-term and long-term CSD (Chudik and Pesaran, 2015). Third, it is a group mean estimate with variable slope coefficients for each group member. The CS-ARDL model, based on the mean group, is an upgraded form of the ARDL model that depends on cross-sectional estimates with averages. This model additionally uses the unobserved common components and their delays (Chudik et al., 2017). As a consequence of the lagged dependent variable in the model, this method is useful in instances when there is a low level of homogeneity. In addition, the authors claim that the endogeneity problem will be overcome when the lagged cross-sectional averages are included in the model (Yang et al., 2021; Zhuo and Qamruzzaman, 2021).

The mean group variant of the CS-ARDL model is based on the addition of cross-sectional averages as proxies for unobserved

common components and their lags to the ARDL estimates of each cross-section. The Canadian Society for Applied Research in Development and Learning (CS-ARDL) created this model (Chudik et al., 2017). This approach also works well when the lagged dependent variable is included in the model and weak homogeneity is present. Specifically, the issue arises during the addition of the lagged dependent variable. The authors argued that the endogeneity problem might be largely circumvented by including lagged cross-sectional averages in the model.

$$\overline{TI}_{it} = \bar{\alpha}_{it} + \sum_{j=1}^{p}\bar{\beta}_{ij}\overline{TI}_{i,t-j} + \sum_{j=0}^{q}\bar{\gamma}_{ij}\bar{Q}_{i,t-j} + \bar{\omega}_t' G_t + \bar{\epsilon}_{it}, \quad (21)$$

where $\bar{\alpha}_{it} = \frac{\sum_{i=1}^{N}\alpha_i}{N}$.

$$\overline{TI}_{t-j} = \frac{\sum_i^N TI_{i,,t-j}}{N}, \quad \bar{\beta}_j = \frac{\sum_i^N \beta_{i,j}}{N} \quad j = 0,1,2 \;\; p$$

$$\bar{Q}_{t-j} = \frac{\sum_i^N Q_{i,,t-j}}{N}, \quad ,\bar{\gamma}_j = \frac{\sum_i^N ,\gamma_{i,j}}{N}, \quad J = 0,1,2 \;\; q$$

$$\bar{\omega}_j = \frac{\sum_{i=1}^N \omega_i}{N}, \; \bar{\epsilon}_t = \frac{\sum_i^N \epsilon_{i,t}}{N}$$

$$TI = \bar{\alpha}_{it} + \sum_{j=1}^{p}\bar{\beta}_{ij}\overline{TI}_{i,t-j} + \sum_{j=0}^{q}\bar{\gamma}_{ij}\bar{Q}_{i,t-j} + \bar{\omega}_t' G_t \quad \downarrow \quad \bar{\omega}_t' G_t = \overline{ES}_{it}$$

$$-\bar{\alpha}_{it} + \sum_{j=1}^{p}\bar{\beta}_{ij}\overline{TI}_{i,t-j} + \sum_{j=0}^{q}\bar{\gamma}_{ij}\bar{Q}_{i,t-j}\downarrow G_t = \overline{TI}_{it} - \bar{\alpha}_{it} + \sum_{j=1}^{p}\bar{\beta}_{ij}\overline{TI}_{i,t-j} + \sum_{j=0}^{q}\bar{\gamma}_{ij}\bar{Q}_{i,t-j} \Big/ \bar{\omega}_t'. \quad (22)$$

The general form of the CS-ARDL framework is as follows:

$$\overline{TI}_{it} = \epsilon_{it} + \sum_{j=1}^{p}\beta_{ij}\overline{TI}_{i,t-j} + \sum_{j=0}^{q}\gamma_{ij}\bar{Q}_{i,t-j} + \sum_{j=0}^{p}\bar{\partial}'_t\bar{Z}_{i,t-j} + \epsilon_{it}, \quad (23)$$

where $\bar{Z} = (\overline{GI}, \overline{ES}, \overline{DI},)$ and $S_{\bar{Z}}$ is the number of lagged cross-sectional average. Finally, the error correction from CS-ARDL is as follows:

$$TI_{it} = \alpha_i + \xi_i\left(TI_{it-1} - \omega_t' Q_{it-1}\right) + \sum_{J=1}^{M-1}\gamma_{iJ}\Delta TI_{it-J} + \sum_{J=0}^{N-1}\beta_{ij}\Delta Q_{it-J} + \sum_{j=1}^{p}\lambda_j\overline{\Delta TI}_{i,t-j} + \sum_{j=0}^{q}\delta_j\overline{\Delta Q}_{i,t-j} + \sum_{j=0}^{S_{\bar{Z}}}\bar{\partial}'_t\bar{Z}_{i,t-j} + \mu_{it}, \quad (24)$$

where $\overline{\Delta TI}_{t-j} = \frac{\sum_i^N \Delta ES_{i,,t-j}}{N}$ and $\overline{\Delta Q}_{t-j} = \frac{\sum_i^N \Delta Q_{i,,t-j}}{N}$.

4.3 The asymmetric panel ARDL

This kind is usually referred to as an asymmetric panel investigation, and it incorporates both positive and negative shocks of the equation's explanatory variables. A symmetric investigation is the more traditional form of research. In other words, the sign of the coefficients of positive and negative shocks may not be the same when they are produced by shocks of a positive or negative sign depending on the kind of shock. Following the steps in the following equation, Eq. 7 may be rewritten as the nonlinear Eq. 12 (Shin et al., 2014).

$$\begin{aligned}\Delta TI_{it} &= \beta_{0i} + \beta_{1i}TI_{it-1} + \beta_{2i}^{+}GI_{t-1}^{+} + \beta_{2i}^{-}GI_{t-1}^{-} + \beta_{3t}^{+}ES_{t-1}^{+} \\ &+\beta_{3t}^{-}ES_{t-1}^{-} + \beta_{4t}^{+}DI_{t-1}^{+} + \beta_{4t}^{-}DI_{t-1}^{-}, \\ &+ \sum_{J=1}^{M-1}\gamma_{iJ}\Delta TI_{i,t-J} + \sum_{J=0}^{N-1}\left(\gamma_{ij}^{+}\Delta GI_{i,t-j}^{+} + \gamma_{ij}^{-}\Delta GI_{i,t-j}^{-}\right)+ \\ &\sum_{J=0}^{O-1}\left(\left(\delta_{ij}^{+}\Delta DI_{i,t-j}^{+} + \delta_{ij}^{-}\Delta DI_{i,t-j}^{-}\right)\right), \\ &+ \sum_{J=0}^{P-1}\left(\mu_{ij}^{+}\Delta ES_{i,t-j}^{+} + \mu_{ij}^{-}\Delta ES_{i,t-j}^{-}\right) + \epsilon_{it},\end{aligned} \quad (11b)$$

where $GI^{+}$and GI^{-} stand for the positive and negative shock of green investment, $DI^{+}$and DI^{-} represent positive and negative shock of domestic investment, and $ES^{+}$and ES^{-} denote positive and negative shocks of environmental sustainability, respectively. The long-run coefficients are computed as $GI^{+} = \frac{-\beta_{2i}^{+}}{\beta_{1i}}$, $GI^{-} = \frac{-\beta_{2i}^{-}}{\beta_{1i}}$, $DI^{+} = \frac{-\beta_{3i}^{+}}{\beta_{1i}}$, $DI^{-} = \frac{-\beta_{3i}^{-}}{\beta_{1i}}$, $ES^{+} = \frac{-\beta_{4i}^{+}}{\beta_{1i}}$, and $ES^{-} = \frac{-\beta_{4i}^{-}}{\beta_{1i}}$. These shocks are computed as positive and negative partial sum decomposition of financial development, trade openness, and capital flows in the following ways:

$$\begin{cases} GI_i^{+} = \sum_{k=1}^{t}\Delta GI_{ik}^{+} = \sum_{K=1}^{T}MAX\left(\Delta GI_{ik}, 0\right) \\ GI_i^{-} = \sum_{k=1}^{t}\Delta GI_{ik}^{-} = \sum_{K=1}^{T}MIN\left(\Delta GI_{ik}, 0\right) \end{cases}. \quad (12b)$$

$$\begin{cases} DI_i^{+} = \sum_{k=1}^{t}\Delta DI_{ik}^{+} = \sum_{K=1}^{T}MAX\left(\Delta DI_{ik}, 0\right) \\ DI_i^{-} = \sum_{k=1}^{t}\Delta DI_{ik}^{-} = \sum_{K=1}^{T}MIN\left(\Delta DII_{ik}, 0\right) \end{cases}. \quad (13b)$$

$$\begin{cases} ES_t^{+} = \sum_{k=1}^{t}\Delta CF_{ik}^{+} = \sum_{K=1}^{T}MAX\left(\Delta ES_{ik}, 0\right) \\ ES_t^{-} = \sum_{k=1}^{t}\Delta CF_{ik}^{-} = \sum_{K=1}^{T}MIN\left(\Delta ES_{ik}, 0\right) \end{cases}. \quad (17b)$$

The error correction version of Eq. 12 is as follows:

$$\Delta TI_{it} = \tau_{1i}\xi_{it-1} + \sum_{J=1}^{M-1}\gamma_{iJ}\Delta TI_{i,t-J} + \sum_{J=0}^{N-1}\left(\gamma_{ij}^{+}\Delta GI_{i,t-j}^{+} + \gamma_{ij}^{-}\Delta GI_{i,t-j}^{-}\right) + \sum_{J=0}^{O-1}\left(\left(\delta_{ij}^{+}\Delta DI_{i,t-j}^{+} + \delta_{ij}^{-}\Delta DI_{i,t-j}^{-}\right)\right). + \sum_{J=0}^{P-1}\left(\mu_{ij}^{+}\Delta ES_{i,t-j}^{+} + \mu_{ij}^{-}\Delta ES_{i,t-j}^{-}\right) + \epsilon_{it} \quad (18b)$$

4.4 Dumitrescu–Hurlin panel causality test

The study implements the Granger causality test following the procedure initiated by Dumitrescu and Hurlin (2012); the test statistics are to be derived with the following equation:

$$Y_{it} = \alpha_i + \sum_{K-1}^{P} \gamma_{ik} Y_{i,t-k} + \sum_{K-1}^{P} \beta_{ik} X_{i,t-k} + \mu_{it}. \quad (25)$$

The test forms the average statistic linked with the homogeneous null non-causality (HNC) hypothesis as follows:

$$W_{NT}^{Hnc} = N^{-1} \sum_{i-1}^{N} W_{i,t}. \quad (26)$$

This test reveals the harmonized Z-test statistic is as follows:

$$Z = \sqrt{\frac{N}{2P} \times \frac{T-2P-5}{T-P-3}} \times \left[\frac{T-2P-3}{T-2P-1}\bar{W} - P\right]. \quad (27)$$

5 Model estimation and interpretation

5.1 Cross-sectional dependency, slope of homogeneity, and unit root test

In the initial assessment, the study implemented the cross-sectional dependency test following the studies by Breusch and Pagan (1980), Pesaran (2004), Pesaran (2006), and Pesaran et al. (2008) and the slope of homogeneity following the study by Pesaran and Yamagata (2008). Table 1 reports the results of the test mentioned earlier. According to the test statistics from the cross-sectional dependency test, all the test statistics are statistically significant at a 1% significance level, indicating the rejection of the null hypothesis of cross-sectional independent test. Alternatively, the test-established research units share common dynamics among them. Furthermore, the test statistic from homogeneity, that is, Δ and Adj.Δ is statistically significant and reveals heterogeneous properties among the research variables in the study.

In this step, the study executed the unit root test for documenting the variable's stationarity properties, which are critical in selecting the appropriate econometrical models for coefficient investigation. Referring to the results of the cross-sectional dependency test and test of homogeneity, we implemented the second-generation unit root tests introduced by Pesaran (2007), commonly known as CIPS and CADF. The results of second-generation panel unit root tests are displayed in Table 2. According to the test statistics, all the variables are exposed non-stationary at a level, but all the variables become stationary in the estimation with the first differences.

5.2 Panel cointegration test

The study's long-run association between technological innovation and explanatory variables has been assessed by implementing the panel cointegration test following Pedroni (2004). The results of the cointegration test are displayed in Table 3. According to the test statistics, the rejection of the null hypothesis of no-cointegration is established. Alternatively, we reveal the presence of long-run association in the empirical equation.

Furthermore, the study implemented a cointegration test with an error correction term familiarized with the study by Westerlund (2007), and the test results are displayed in Table 4. All the test statistics are statistically significant at a 1% level, suggesting rejecting the null hypothesis. This is the presence of a long-run association between technological innovation and other explanatory variables.

5.3 Baseline assessment

This section deals with a preliminary assessment of empirical equations with the implementation of pooled OLS, random effects, and fixed-effects models. The baseline estimation results are given in Table 5, and the H-test statistics confirmed that fixed-effects models are robust in elementary assessment. Referring to estimated model coefficients, the study documents green investment, which is measured by renewable energy consumption, positively influencing technological innovation (a coefficient of 0.0841). The similar line of association was revealed for domestic investment (a coefficient of 0.0367), foreign direct investment (a coefficient of 0.0749), and financial development (a coefficient of 0.1232), while environmental sustainability, measured by carbon emission, showed a negative connection to technological innovation (a coefficient of −0.0467).

5.4 Panel ARDL and CS-ARDL

The following section deals with empirical model estimation following the framework offered by Pesaran and Chu. The result of panel ARDL and CS-ARDL displayed in Table 6 includes Panel A for long-run coefficients and Panel B for short-run coefficients.

In the long run, according to empirical model estimation with ARDL (CSARDL), the study documented a positive and statistically significant linkage between green investments measured by renewable energy consumption and technological innovation in BRI nations with a coefficient of 0.0878 (0.1223). More specifically, a 10% further development in green investment focusing on renewable energy development will accelerate technological innovation by 0.878% (1.223%) in BRI

nations. For the short run, green investment has revealed a similar line of association that is positive and statistically significant with a coefficient of 0.0182 (0.0759).

The study documented adverse effects from environmental sustainability to technological innovation in BRI nations with a coefficient of 0.179 (−0.1802) in the long-run assessment. Study findings suggest that excessive carbon emission due to inefficiency in environmental protection discourages countries from investing in technological innovation. In particular, a 10% excess carbon emission results in the degradation of technological innovation in the BRI nations by 1.79% (1.802%). Alternatively, effective environmental policies and protection are boosting factors in technological advancement with environmental sustainability. In the short run, environmental sustainability produces the same line of association as in the long run.

Domestic investment, measured by gross capital formation, revealed a positive and statistically significant linkage to technological innovation in BRI nations with a coefficient of 0.0992 (0.1522). Specifically, a 10% growth in domestic capital formation in the economy will result in technological innovation inclusion and progress by 0.992% (1.522%). For the short-run assessment, the study documented a similar line of association that is positive and significant.

Referring to control variables' effects on technological innovation in BRI nations, for the long-run assessment, the study documented that foreign direct investment (financial development) is positively connected to technological innovation. The study findings suggest that foreign direct investment and financial development prompt technological innovation.

5.5 Asymmetric assessment of long-run and short-run coefficients

In the following section, the study implemented the nonlinear framework following the study by Shin et al. (2014) to document the asymmetric effect of green investment, domestic investment, and environmental sustainability on technological innovation both in the long and short run. The study executed two empirical models focusing on panel composition, that is, with China [1] and without China [2]. The results displayed in Table 7.

Referring to the asymmetric nexus between green investment and technological innovation, the study documented that positive (negative) shocks have a positive and statistically significant connection with technological innovation in both model estimations. According to model [1] coefficients, a 10% positive (negative) shock in green investment will result in increasing (decreasing) technological innovation by 1.403% (1.814%) in BRI nations. Furthermore, in empirical model [2] excluding China, a 10% positive (negative) innovation results in technological innovation augmentation (degradation) by 0.734% (1.745%) in BRI nations. In particular, the negative shock of green investment has revealed more significance in technological innovation than the positive innovation of green investment. Taking into account the long-run asymmetric coefficients, the study advocated that degradation of green investment and investment in renewable energies will result in adversity in developing technological progress in the economy.

The asymmetric shocks of environmental sustainability that are positive (negative) variations in carbon emission established a negative and statistically significant linkage to technological innovation with a coefficient of −0.1037 (−0.0984). The study advocated controlled environmental protection, that is, the reduction of carbon emissions accelerated the technological integration of the BRI nations. In particular, a 10% positive (negative) variation in carbon emission will result in degradation (growth) in technological advancement, especially in the energy efficiency and efficient production process by −1.037% (−0.984%). Furthermore, the short-run asymmetric assessment revealed that a 10% acceleration (degradation) in carbon emission results in increase in technological innovation by −0.198% (−0.227%).

Domestic investment, measured by the economy's gross capital formation, is a motivating factor in promoting technological innovation. In the long run, the asymmetric coefficients of domestic investment that are positive (negative) shocks establish a positive and statistically significant linkage with technological innovation with a coefficient of 0.1605 (0.1124). Study findings suggest that a 10% growth (decline) in domestic capital formation can boost (restrict) technological innovation in BRI countries by 1.605% (1.124%), while in the short-run, a 1% positive (negative) innovation in domestic investment results in technological innovation acceleration (degradation) by 0.0798% (0.0437%).

Referring to the symmetry test, the result of the standard wild test revealed that all the test statistics for the long run and short run are statistically significant at a 1% level, suggesting the rejection of the null hypothesis of the symmetric association. Alternatively, an asymmetric association between green investment, environmental sustainability, domestic investment, and technological innovation has been established.

5.6 Country-wise assessment with DOLS estimation

The results of country-wise investigation displayed in Table 8. Referring to the nexus between green investment and technological innovation, according to country-specific assessment, a group of 44 (forty-four) BRI nations has shown a positive and statistically significant linkage in Romania, Saudi Arabia, Israel, Panama, Albania, Slovenia, Myanmar, Oman, Estonia, UAE, South Africa, Singapore, Tajikistan, Ukraine, Russia, Georgia, Kuwait, Poland,

TABLE 1 Results of cross-sectional dependency and homogeneity test.

	LM_{BP}	LM_{PS}	LM_{adj}	CD_{PS}	Δ	Adj.Δ
TI	415.394***	28.787***	130.571***	15.678***	31.969***	113.679***
GI	206.638***	31.35***	100.593***	49.074***	84.464***	116.315***
ES	435.769***	42.752***	167.6***	33.368***	50.026***	122.95***
DI	428.615***	18.079***	127.538***	35.621***	75.757***	59.046***
FDI	378.181***	42.189***	170.433***	25.798***	63.765***	57.386***
FD	243.672***	18.273***	240.243***	18.108***	28.08***	136.448***

Note: the superscript *** denotes a 1% level of significance.

TABLE 2 Results of the second-generation unit root test.

	CIPS		CADF	
	At a level	After first difference	At a level	After first difference
TI	−1.367	−5.761***	−1.213	−7.169***
GI	−1.787	−2.613***	−1.525	−2.611***
ES	−2.911**	−5.803***	−1.986	−7.719***
DI	−1.887	−3.889***	−2.109	−4.595***
FDI	−1.684	−5.11***	−1.389	−7.541***
FD		−6.625***	−2.525	−5.933***

Note: the superscript *** denotes a 1% level of significance.

TABLE 3 Results of Padrones' panel cointegration test.

Panel v-statistic	2.295**	Panel v-statistic	−1.262*
Panel rho-statistic	−6.487***	Panel rho-statistic	−6.127***
Panel PP-statistic	−10.464***	Panel PP-statistic	−10.468***
Panel ADF-statistic	−5.823***	Panel ADF-statistic	−9.422***
Group rho-statistic	−6.399***		
Group PP-statistic	−10.707***		
Group ADF-statistic	−3.159***		

TABLE 4 Results of panel cointegration test-error correction term.

Model	Gt	Ga	Pt	Pa
TI|GI, DI, ES, FDI, and FD	−15.946***	−13.476***	−15.312***	−13.594***

Kyrgyz Republic, Croatia, Turkey, Bosnia, New Zealand, Macedonia, Colombia, Azerbaijan, Indonesia, Qatar, China, Kazakhstan, Hungary, India, Bulgaria, Pakistan, the Republic of Korea, Lebanon, Brunei Darussalam, Morocco, Slovak Republic, and Ethiopia. However, the adverse connection between green investment and technological innovation is negative in 14 BRI nations: Bangladesh, Belarus, Malaysia, Nepal, Moldova, Armenia, Czech Republic, Iraq, Cambodia, Egypt, Iran, Vietnam, Bahrain, and Mongolia.

The study documented that environmental protection prompts technological innovation in 23 (twenty-three) BRI nations, and those are Moldova, Qatar, Macedonia, Cambodia, Bulgaria, Kazakhstan, Malaysia, Mongolia, New Zealand, Israel, Thailand, Colombia, Estonia, Jordan, Pakistan, Iran, Sri Lanka, Belarus, Bahrain, Hungary, Poland, Albania, China, Armenia, and Tajikistan. On the other hand, the adverse association that excess carbon emission degrades technological innovation is found in 34 (thirty-four) nations: India, Egypt, Philippines, Brunei Darussalam, the Republic of Yemen, South Africa, Russia, Nepal, Turkey, Bangladesh, Croatia, Azerbaijan, Romania, Slovenia, Czech Rep,

TABLE 5 Results of baseline estimation.

	Pooled OLS			RE			FE		
	Coefficient	Std. error	t-stat	Coefficient	Std. error	t-stat	Coefficient	Std. error	t-stat
GI	0.1505***	0.0133	11.3157	0.0312***	0.0145	2.1517	0.0841***	0.0099	8.4848
ES	0.1686***	0.0114	14.7894	0.1636***	0.0105	15.5809	−0.0462**	0.0165	−2.801
DI	0.131***	0.0109	12.0183	−0.0047	0.0117	−0.4017	0.0367**	0.0182	2.01648
FDI	0.1253***	0.0128	9.7890	0.066***	0.0126	5.2381	0.0749***	0.015	4.9933
FD	0.1595***	0.0132	12.0833	0.0929***	0.0131	7.0916	0.0348**	0.0161	2.1614
C	0.1669***	0.016	10.4312	0.0088	0.0147	0.5986	0.1232***	0.0166	7.4216

TABLE 6 Results of ARDL and CS-ARDL.

Variables	ARDL			CS-ARDL		
	Coefficient	Std. error	t-stat	Coefficient	Std. error	t-stat
Panel A: long-run coefficient						
GI	0.0878***	0.0328	2.6768	0.1223**	0.0662	1.8474
ES	−0.179***	0.0465	−3.8494	−0.1802***	0.0736	−2.4483
DI	0.0992**	0.0626	1.5846	0.1522***	0.037	4.1135
FDI	0.1208***	0.0258	5.8062	0.025***	0.0048	5.2083
FD	0.1565***	0.0722	2.1675	0.038***	0.0155	2.4516
	0.0306	0.0859	0.3562	0.0604	0.0561	1.0766
C	4.68759	0.0163	287.5822	−2.541	0.049	−51.8571
Panel B: short-run coefficient						
GI	0.0182***	0.0081	2.2347	0.0759**	0.053	1.432
ES	−0.0185	0.0030	−6.0423	−0.01658	0.0984	−1.6849
DI	0.0248	0.042	0.5904	0.0359	0.0637	0.5635
FDI	0.0314	0.0713	0.4403	0.0413	0.0543	0.7605
FD	0.0557	0.0584	0.9537	0.0543	0.0882	0.6156
CointEq (-1)	−0.270381	0.0264	−10.2417	−0.2274	0.0719	−3.1627
CD test	11.911			15.5124		
H-Test	0.175			0.511		

Lebanon, the Republic of Korea, Panama, Indonesia, Kuwait, Oman, Morocco, Singapore, Vietnam, Iraq, Ukraine, Kyrgyz Republic, Slovak Republic, UAE, Georgia, Bosnia & Herzegovina, Ethiopia, Saudi Arabia, and Myanmar.

The study focuses on domestic investment in technological innovation, and it is revealed that domestic capital adequacy accelerates the technological advancement in 40 (forty) BRI nations, namely, Slovenia, Albania, Georgia, Bahrain, Jordan, Qatar, Myanmar, Hungary, Bosnia & Herzegovina, Malaysia, Colombia, Thailand, Macedonia, Armenia, Moldova, Egypt, Panama, China, Cambodia, Kyrgyz Republic, Bangladesh, Mongolia, Bulgaria, Azerbaijan, Sri Lanka, Romania, Iran, the Philippines, the UAE, Turkey, the Republic of Yemen, Iraq, Croatia, Singapore, the Republic of Korea, Russia, Czech Republic, Morocco, Vietnam, and New Zealand.

5.7 Dumitrescu−Hurlin panel causality

The study implemented a heterogeneous panel causality test following Dumitrescu and Hurlin (2012), and the results are displayed in Table 9. The study documented several directional associations between technological innovation and explanatory

variables. The study documented the unidirectional causal effects from green investment to technological innovation [GI→TI] and technological innovation to environmental sustainability [TI→ES]. Furthermore, the study documented bidirectional casualties between domestic investment, foreign direct investment, financial development, and technological innovation [TI←→DI; TI←→FDI; TI←→FD].

6 Discussion

Innovation in energy technologies is essential for cleaner manufacturing (Lin and Zhu, 2019). Technology innovation may increase the energy efficiency of fossil fuels, hence reducing production energy consumption (Sohag et al., 2017). Technology innovation may strengthen renewable energy technologies, increasing the production of environmentally friendly renewable energy as a future energy source. Furthermore, innovations in renewable energy may increase the ability to meet energy demands and alter energy portfolios (Tilt, 2019). RETI and air pollution have not received sufficient attention. We know no empirical studies or just a few indirect ones (Álvarez-Herránz et al., 2017; Miao and Qamruzzaman, 2021; Zhuo and Qamruzzaman, 2021). The study documented that the coefficient of green investment is positive and statistically significant with the symmetric assessment. Furthermore, the asymmetric assessment established that positive and negative innovation in green investment is positive and statistically tied with technological innovation both in the long-run and short-run assessment. Our study findings are supported by the existing literature, such as Johnstone et al., (2010), Geng and Ji, (2016), Qamruzzaman, (2021), Mehta et al., (2022), and Serfraz et al., (2022).

Investing money in renewable energy sources such as wind, solar, geothermal, ocean, biomass, and waste might significantly contribute to realizing public environmental objectives. In addition, it is frequently suggested that increasing proportions of renewable energy contribute to other public policy goals, such as better energy security in the face of uncertain markets for fossil fuels. Considering the importance of energy to sustainable development, making investments in environmentally friendly energy forms is very important to fulfill the prerequisites for attaining economic, social, and environmental sustainability (Danish and Ulucak, 2021). As a result, renewable energy sources have become essential in promoting economic growth, reducing pollution, and moving toward social progress. The utilization of green energy technology, which is required for consumption of renewable energy, is an environmentally preferable alternative to the burning of carbon-intensive fossil fuels. Every industry has to adopt cleaner technologies to maximize renewable energy sources and reduce overall energy consumption (Mensah et al., 2019). There is no controversy about the need to expedite the development, dissemination, and deployment of renewable energy technologies (RETs) (JinRu and Qamruzzaman, 2022; Karim et al., 2022). RETs are the most efficient means of mitigating existing energy systems' wasteful and dangerous effects. In addition to its environmental advantages, the renewable energy industry delivers a compelling economic potential (Amankwah-Amoah, 2019; Tabrizian, 2019). Nations that realize the need to strengthen their renewable infrastructures will enjoy global competitive advantages. To do so, however, one needs knowledge of the variables that restrict the development and spread of renewable energy (Brodny et al., 2021; Andriamahery and Qamruzzaman, 2022).

Environmental sustainability, measured by carbon emission, revealed negative and statistically significant associations both in the long run and short run according to ADRL and CS-ARDL estimation. Furthermore, the asymmetric assessment disclosed negative and statistically significant effects from asymmetric shock on environmental sustainability and technological innovation, indicating that environmental control and protection induce the economy to adopt technological innovativeness in energy and production processes for energy efficiency. Our study findings are supported by the existing literature (Karmaker et al., 2021). To solve the environmental problems that the world's countries are experiencing, it is crucial to use the best possible technology and scientific understanding for cleanup, yet this may be prohibitively expensive. Taxes on polluting activities are one tool that might be used to fund the research and development of new, cleaner technologies and help meet other environmental objectives. If new approaches and technology for decreasing pollution are developed, environmental interventions may be made possible with much lower costs (Li and Masui, 2019). Zhang et al. (2017) identified the impact of innovation on environmental deterioration. The authors used data from thirty Chinese provinces from 2000 to 2013. Using the empirical approach of SGMM methodology, the research investigated the impact of technological innovation on decreasing environmental degradation in China's regions. The investigation's findings indicated that innovation is significant in reducing the negative impacts of carbon emissions on the environment; hence, it is recommended that policymakers see innovation as the most effective method for limiting environmental deterioration.

In order to address problems associated with global warming and other environmental threats, a synergistic approach to control excessive CO_2 emissions is essential. Investing in innovation and technology may prove to be an advantageous strategy. This is because the development of environmentally friendly innovation and technology is required for the reduction of carbon emissions and the promotion of the growth of green economies (Ganda, 2019; Ulucak et al., 2020).

The study documented that domestic capital adequacy fosters technological innovation both in the long-run and short-run assessment. Furthermore, the asymmetric

TABLE 7 Result of nonlinear long-run and short-run assessment.

Variables	[1] With China			[2] Without China		
	Coefficient	Std. error	t-stat			
Panel A: long-run asymmetric coefficient						
GI_NEG	0.1403	0.04375	3.2068	0.0734	0.0068	10.7407
GI_POS	0.1814	0.01041	17.4255	0.1745	0.0161	10.7748
ES_POS	−0.1037	0.01566	−6.62196	−0.1057	0.01849	−5.7303
ES_NEG	−0.0984	0.0452	−2.1769	−0.0481	0.0056	−8.5340
DI_POS	0.1605	0.03864	4.15372	0.1477	0.0410	3.5961
DI_NEG	0.1124	0.04142	2.7136	0.0673	0.0143	4.6754
FDI	0.1167	0.03994	2.9218	0.0739	0.0287	2.5661
FD	0.1838	0.03979	4.6192	0.1752	0.0458	3.8243
W_{SR}^{RE}						
W_{SR}^{FDI}		8.951			11.02	
W_{SR}^{CO}		8.796			9.647	
Panel B: short-run asymmetric coefficient						
C	10.5105	0.01814	1.9201	−0.3819	0.016	−23.8734
GI_NEG	0.01247	0.0021	4.3915	0.23081	0.02616	8.82301
GI_POS	0.01782	0.0018	2.3424	−0.145	0.01192	−12.1644
ES_POS	−0.0198	0.0032	−6.1875	−0.0811	0.0426	−1.9037
ES_NEG	−0.0227	0.0066	−3.4394	−0.0268	0.0351	−0.76494
DI_POS	0.0798	0.0131	6.1385	−0.0659	0.0367	−1.79363
DI_NEG	0.0437	0.0089	4.9102	−0.0391	0.0486	−0.8053
FDI	0.1696	0.0439	−2.3496	0.0245	0.0405	0.60467
FD	−0.172	0.0121	3.7929	−0.0476	0.0220	−2.1575
CointEq (−1)*	−0.14178	0.0444	−6.9344	−0.3308	0.0365	−9.0533
W_{SR}^{RE}		11.05			9.678	
W_{SR}^{FDI}		9.479			6.709	
W_{SR}^{CO}		12.584			11.041	
H-test		0.576			0.6589	
Likelihood		231.41			191.32	‘

investigation revealed positive and negative shocks of domestic investments positively linked to technological innovation in the long and short run, suggesting that the domestic capital formation induces technological innovation in BRI nations with the motivation to achieve operational and energy efficiency. Our study findings are supported by the existing literature studies (Massell, 1960; Howitt and Aghion, 1998; Satrovic et al., 2021). The multiple effects of technical innovation on the economy are readily apparent in terms such as economic growth, global competitiveness, financial systems, quality of life, and trade openness (Satrovic et al., 2021). Regarding innovation, businesses are considered crucial factors, and the government is viewed as enhancing their ability to absorb, improve, and develop new technologies. The government offers the required infrastructure and a platform for engagement that institutions supply to enhance enterprises' capabilities. Governments, industries, and academics have emphasized the significance of scientific research and development to economic growth from time immemorial (Rani and Kumar, 2019). Research and development operations provide knowledge and technology, both of which boost productivity at the business, industrial, and national levels. Consequently, the productivity chain effect will result in better returns on investment, reflecting higher income levels and, therefore, stronger economic growth (Dhrifi, 2015; Bernier and Plouffe, 2019).

6.1 Conclusion and policy suggestions

Economists believe that technological innovation is a primary factor contributing to economic expansion. Improvements in the technological frontier are linked to resource reallocation and subsequent economic development

TABLE 8 Results of country-wise DOLS estimation.

	GI	ES	GI	FDI	FD
Albania	0.045***	−0.006**	0.009**	0.035***	0.038***
Armenia	−0.042	−0.002	0.093	0.112	−0.001
Azerbaijan	0.199	0.11	0.159	−0.164	0.039
Bahrain	−0.028	−0.058	0.021	0.177	−0.048
Bangladesh	−0.073	0.095	0.131	−0.071	0.132
Belarus	−0.052	−0.061	−0.054	0.092	0.049
Bosnia & Herzegovina	0.175	0.236	0.055	0.164	0.214
Brunei Darussalam	0.256	0.049	−0.039	−0.114	−0.059
Bulgaria	0.245	−0.135	0.157	0.102	0.267
China	0.241	−0.004	0.115	0.186	−0.001
Colombia	0.192	−0.105	0.061	−0.174	0.242
Cambodia	−0.036	−0.141	0.121	0.05	0.097
Croatia	0.144	0.11	0.22	−0.019	0.216
Czech Republic	−0.042	0.13	0.241	0.079	0.177
Egypt	−0.036	0.012	0.112	−0.042	−0.042
Estonia	0.084	−0.102	−0.091	−0.038	0.178
Ethiopia	0.274	0.242	−0.056	0.255	0.237
Georgia	0.13	0.234	0.016	0.149	0.129
Hungary	0.244	−0.046	0.051	−0.115	0.093
India	0.244	0.003	−0.016	−0.11	0.237
Indonesia	0.202	0.149	−0.084	0.205	0.151
Iran	−0.033	−0.083	0.177	−0.072	0.166
Iraq	−0.041	0.177	0.216	−0.061	−0.002
Israel	0.033	−0.111	−0.032	0.238	0.146
Jordan	−0.005	−0.097	0.036	0.225	0.175
Kazakhstan	0.241	−0.129	0	−0.033	0.047
The Republic of Korea	0.249	0.14	0.222	−0.166	0.048
Kuwait	0.135	0.153	−0.024	0.136	0.122
Kyrgyz Republic	0.141	0.181	0.13	0.101	−0.031
Lebanon	0.254	0.136	−0.11	−0.095	0.198
Macedonia	0.182	−0.155	0.08	−0.064	0.055
Malaysia	−0.051	−0.12	0.056	0.176	0.003
Moldova	−0.05	−0.158	0.094	0.215	0.272
Mongolia	−0.018	−0.112	0.147	0.131	0.241
Morocco	0.258	0.164	0.25	0.213	0.058
Myanmar	0.081	0.262	0.044	−0.073	0.231
Nepal	−0.051	0.078	−0.077	−0.109	0.163
New Zealand	0.178	−0.112	0.255	−0.158	0.185
Oman	0.083	0.162	−0.092	0.06	−0.042
Pakistan	0.245	−0.085	−0.055	−0.04	0.111
Panama	0.044	0.147	0.113	−0.101	0.155
The Philippines	−0.004	0.024	0.196	−0.114	0.038
Poland	0.137	−0.038	−0.035	0.026	−0.026
Qatar	0.214	−0.158	0.044	0.172	0.215
Romania	0	0.124	0.167	0.206	0.201
Russia	0.124	0.073	0.223	−0.039	−0.001
Saudi Arabia	0.02	0.246	−0.018	0.238	−0.061
Singapore	0.109	0.165	0.221	0.178	0.165

(Continued in next column)

TABLE 8 (*Continued*) Results of country-wise DOLS estimation.

	GI	ES	GI	FDI	FD
Slovak Republic	0.27	0.192	−0.047	0.215	0.025
Slovenia	0.061	0.127	0.004	−0.084	0.155
South Africa	0.093	0.066	−0.081	−0.011	0.049
Sri Lanka	−0.01	−0.067	0.162	0.119	0.179
Tajikistan	0.109	−0.002	−0.049	−0.022	0.266
Thailand	−0.015	−0.11	0.067	0.038	0.082
Turkey	0.149	0.078	0.204	−0.052	0.035
Ukraine	0.11	0.178	−0.084	0.031	−0.069
The UAE	0.086	0.2	0.203	−0.126	−0.069
Vietnam	−0.032	0.168	0.253	−0.146	0.053
Republic of Yemen	−0.013	0.051	0.216	−0.077	0.268

via endogenous growth models, which offer extensive testable predictions regarding aggregate quantities and the cross-section of enterprises. The motivation of the study is to assess the role of green investment measured by renewable energy consumption, environmental sustainability proxied by carbon emission, and domestic investment explained by gross capital formation on technological innovation in BRI nations for the period 2000–2020. The study used several econometrical tools such as a cross-sectional dependency test, panel unit root test with CADF and CIPS, panel cointegration test with error correction term, panel ARDL, CS-ARDL, NARDL, and causality test.

Taking into account the study's findings (see Figure 2), it is revealed that green investment and domestic investment are positively connected with technological innovation in BRI nations, while environmental sustainability is exposed negatively and statistically significant to technological innovation. Furthermore, the asymmetric investigation established asymmetric effects from green investment, environmental sustainability, and domestic investment to technological innovation. According to the asymmetric coefficients, the positive and negative shocks of green and domestic investment disclosed positive and statistically significant links with technological innovation, whereas the asymmetric shocks in environmental sustainability revealed adverse ties to technological innovation in BRI nations. The study documented the unidirectional causal effects from green investment to technological innovation [GI→TI] and technological innovation to environmental sustainability [TI→ES]. Furthermore, the study documented bidirectional casualties between domestic investment, foreign direct investment, financial development, and technological innovation [TI←→DI; TI←→FDI; TI←→FD].

Considering the study findings, the following policy suggestions regarding the policy implications have been proposed.

1. According to a study, green investment accelerated technological innovation, implying that including clean energy instead of fossil fuel in industrial production will open an avenue for

TABLE 9 Results of Dumitrescu and Hurlin's (2012) panel causality test.

	TI	GI	ES	DI	FDI	FD
TI		(5.8533)*** [6.1694]	1.1955 [1.26]	(5.6992)*** [6.007]	(4.5069)** [4.7502]	(3.1987)** [3.3714]
GI	0.9936 [1.0472]		1.5696 [1.6543]	(1.9479) [2.0531]	(4.2592)** [4.4893]	(5.6567)*** [5.9622]
ES	(5.7151)*** [6.0238]	(6.2529)*** [6.5905]		(3.3719) [3.554]	(2.2964) [2.4205]	(4.6865)** [4.9395]
DI	(5.4346)*** [5.7281]	(5.119)*** [5.3954]	(3.0201)** [3.1832]		(4.8299)*** [5.0907]	(5.1232)*** [5.3999]
FDI	(4.0425)** [4.2608]	(2.9776) [3.1384]	(3.4442) [3.6301]	(5.9734)*** [6.2959]		(3.1083) [3.2762]
FD	(5.3443)*** [5.6329]	0.9192 [0.9688]	(2.001) [2.1091]	(5.6216)*** [5.9252]	1.2858 [1.3553]	

Note: the values in [] and () explain the test statistics of W-Stat and Zbar-Stat.

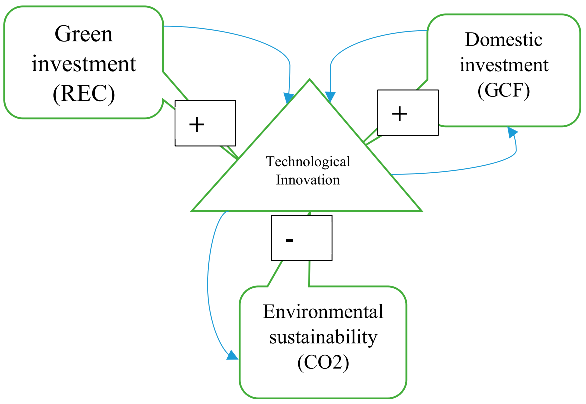

FIGURE 2
Empirical association and causal association.

technological advancement. Therefore, the study advocated that the inclusion of green energy should be promoted in BRI nations as a fostering factor for technological innovation.

2. Environmental sustainability has been revealed to be a catalyst factor in thriving technological innovation in BRI nations, indicating that controlled and restrictive carbon emissions in the economy will boost technological innovation. Thus, it is suggested that BRI nations formulate and ensure effective implementation of environmental regulation, which eventually prompts technological innovation. Furthermore, to foster technological innovation, BRI nations have come up with solid environmental protection policies, which eventually lead to adaptation of technological efficiency in aggregated output levels.
3. Efficient financial intermediation in the financial system leads to reallocation of domestic investment into productive areas, especially in innovation. The study advocates that domestic capital accumulation and reallocation into research and development must be ensured to promote technological innovation.

In concluding note, the present study is not devoid of certain limitations. The study pointed out that the data homogeneity might reveal diverse results for further insight development. In addition, the outcomes of this research indicate that green investment and domestic capital accumulation should be incorporated into technological innovation assessment models as independent variables in addition to the conventional variables connected to economic considerations. Today's complicated and unstable global economy makes this concern more important than ever. There may be a need for further empirical investigations using other methodology and data sets, including various nations such as the target economy can be sub-grouped according to income distribution.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found here: World Development Indicator and International Financial Statistics.

Author contributions

ZX: introduction, empirical estimation, and final version. MQ: literature survey, methodology, empirical estimation, first draft, and final version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Cem Işık,
Anadolu University, Turkey

REVIEWED BY
Nudrat Fatima,
Beijing Technology and Business University, China
Haozhi Pan,
Shanghai Jiao Tong University, China
Lei Jinhuo,
Anhui University of Technology, China

*CORRESPONDENCE
Muhammad Kamran Khan,
mkkhan.buic@bahria.edu.pk

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Do regional government green innovation preferences promote industrial structure upgradation in China? Econometric assessment based on the environmental regulation threshold effect model

Shoukat Iqbal Khattak[1], Aarif Mohammad Khan[2], Muhammad Kamran Khan[3]*, Chen Li[1], Jiating Liu[1] and Zhuojie Pi[1]

[1]School of Business Administration, Jimei University, Xiamen, China, [2]Department of Finance, College of Business Administration, Prince Sattam Bin Abdulaziz University, Alkharj, Saudi Arabia, [3]Management Studies Department, Bahria Business School, Bahria University, Islamabad, Pakistan

China has been upgrading the industrial structure (ISU) at the regional level through innovation to achieve socioeconomic progress, but there is less known about the complex intermediary mechanisms regulating the government's green innovation preference (GGIP)-ISU nexus from a regional perspective in China. Experts agree that varying environmental regulations (ER) intensity alters the relationship dynamics between innovation and ISU. Thus, using regional panel data (2005–2019), the paper develops an ER-based threshold regression model to assess the GGIP-ISU nexus under various ER levels in China. Following the statistically acceptable stationarity test outcomes, the regression corroborated the GGIP had disrupted ISU in China. Second, the ER-threshold model depicted that GGIP flexibility and ER rigidity were found interconnected, while the GGIP-ISU connection was characterized by a U-shaped relationship in which ER acted as a threshold variable. Third, the region-based heterogeneity test reflected that there was significant disparity in the inhibitory effect of GGIP on ISU between resource and non-resource-based regions, i.e., GGIP had a more significant inhibitory influence on the ISU in the non-resource-based regions than in the resource-based regions. The paper recommends critical policy implications for the enhancement of ISU in China.

KEYWORDS

government green innovation preference, environmental regulation, industrial structure upgrade, threshold effect, innovation, China

1 Introduction

Rapid economic progress in the emerging and developed economies has uplifted human living standards, but it has simultaneously produced ecological issues, e.g., desertification and pollution. As environmental governance issues and high economic quality have become important issues for sustainable development, many economies have optimized and upgraded their industrial structures (hereafter ISU) to accomplish sustainable development and growth. As an emerging global economy, China mainly relies on cheap labor, abundant resources, and large-scale production. China has been facing the problem of excess capacity in traditional industries and a low proportion of high-tech, low-carbon, and environmental protection industries (Ali et al., 2021; Alvarado et al., 2022; Baig et al., 2022; Hussain et al., 2022; Isik et al., 2022). Experts argue that an imbalanced industrial structure creates improper resource allocations and environmental pollution (cf. Hsieh & Klenow, 2009; Sarwar et al., 2019), posing a threat to sustainable development goals. In the 19th congress, many top Chinese Communist Party leaders emphasized the need to shift the Chinese economic growth model from high-speed to high-quality. The government has been trying to replace the traditional economic growth model of high energy consumption and pollution with an intensive economic growth model dominated by high-end manufacturing and the tertiary industry. Therefore, the central and provincial governments of China are promoting rationalization and ISU as the way forward for economic transformation. Chinese President Xi Jinping, in the Fourth Plenary Session of the 19th CPC Central Committee, stated that the innovation would promote the mechanism transformation of scientific and technological achievements by actively developing new driving forces, strengthening standardized guidance, and improving the essential capacity of the industry and the modernization of the industrial chain. Green technology innovation (GTI) is an effective way to promote the transformation of environmental governance from end-to-end governance to cleaner production and to achieve ISU (Zhong et al., 2022). Li and Zou (2018) noted that government preference for GTI could meet the practical needs of ISU and technology transformation in China. ISU is a vital way to achieve coordinated development, resource efficiency, and environmental up-gradation to address the current constraints of resources, energy, environment, and other factors. Beyond the above, ISU can enable China to manage the new domestic and international "dual-circulation" patterns while addressing the challenges of global climate change (Liao et al., 2020).

From a research viewpoint, growing global emphasis on achieving economic transformation using high-quality development has attracted significant academic focus where many studies have factors promoting ISU. Advocates of urban development recognize technological innovation (TI) and ISU as central to modern and sustainable urbanization while recognizing the role of government as critical to the whole process (e.g., Mieg, 2012; Wei et al., 2021). While Nilssen (2019) emphasized innovation typology as a critical matrix for defining smart urban cities and development, others (e.g., Pan et al., 2020) recommended inter-industry spillovers as a vital instrument for efficient urban land uses and economic prosperity. In a series of studies, Yao et al. highlighted the significance of social and innovation networks in shaping urban communities and cities (Yao et al., 2020; Yao et al., 2022). Academically, ISU is driven by different factors, including domestic enterprises (Brandt & Thun, 2010), regional innovation capability (Pickles, 2006), human capital level (Zhou, 2018), financial development (Jiang et al., 2020; Wang & Wang, 2021), economic growth (Dong et al., 2020), digital economy (Su et al., 2021), openness (He & Zeng, 2013), and environmental policies (Blair & Hite, 2005; Liu X. et al., 2021). In the development of cities, there is a coupling effect between ER, TI, and green development (Yin et al., 2022). Based on the causal inference framework of policy spillover effect, Gao and Yuan (2022) proved that the innovation intervention represented by the national innovative city pilot has a positive impact on the urban innovation performance and innovation convergence of the local and surrounding areas. Past academic view supports a close relationship between TI and green development (Zhao et al., 2019), which provides a series of theoretical bases for the relevant research in this paper. To summarize, there is a consensus among scholars that ISU and government support for innovation enable coupling, coordination, and innovative industrial development for socioeconomic development.

Therefore, many economists have mainly focused on the internal mechanisms governing the relationship between government innovation and industrial structure (Zhou & Li, 2012; Li & Lin, 2017; Zhu, 2022). Governments shape the market and drive the upgrading of enterprises through task-oriented innovation investment (TOII) and R&D subsidies (Mazzucato, 2016). The role of ISU can be traced back to Schumpeter's "innovation theory." Varum et al. (2009) used the same notion to defend that government innovation facilitates high productivity and growth in different industries to realize ISU, yet there are mixed views concerning this argument. For instance, Cai and Wang (2018) argued that government innovation stimulates industrial development by improving TI, production efficiency, and demand structure. Li and Yang (2015) contradict that inappropriate and unreasonable innovation investments hinder the ISU advancement to an advanced level, leading to ISU solidification. He and Zeng (2013) state that, under the existing capacity levels in China, only TI and improvement of production efficiency can break through the development of the low-end position of the industrial chain but marginally promote ISU as a whole. These contrasting views and the scarcity of empirical data

make it difficult to claim whether [or not] GGIP's influence on ISU is positive, negative, linear, or non-linear across regions in China. More so, there is little data on the relationship dynamics of GGIP, ISU, and ER in resource and non-resource-based regions.

In terms of the knowledge gap, there is an absence of a unified research framework combining GGIP, ER, and ISU, although many studies have documented various influencing factors of ISU, including environmental regulations (hereafter ER), technological innovation, financial policy, human capital, and other aspects (Martić and Savić, 2001; Ngai & Pissarides, 2007; Guo & Yuan, 2020; Han & Ma, 2020; Luo & Qi, 2021). Despite the plethora of previous academic research on ISU, the existing research has the following limitations: Firstly, the existing literature mainly focuses on the internal mechanism of government innovation and the influencing factors of the industrial structure or generally classifies the government's influence on the industrial structure as an external driving factor. Only a few studies have explored the precise influence mechanism of government innovation preference on industrial structure. Moreover, scholars have studied the relationship between ER, GGIP, and industrial structure transformation. Yet, there is scarce information on the relationship between ER preference, GGIP, and ISU from the perspective of green motivation (Chen J. et al., 2021; Liu S. et al., 2022; Quan et al., 2022).

The main purpose of this paper is to explore the influence mechanism of GGIP and ISU in resource-based and non-resource-based areas of China. Taking ER as a threshold variable, this paper uses panel data from 30 provinces in China from 2005 to 2019 to verify the non-linear relationship using the double-threshold regression model. This paper uses green patents as a proxy for the GGIP. This factor has important implications for deeply understanding the importance of technological innovation and implementing appropriate ER. At the same time, ISU means that several high-polluting, high-energy-consumption, and low-value-added enterprises will be eliminated, thereby optimizing the industrial structure (Pan and Chen 2021; Deng and Zhao 2022; Miao et al., 2022). Therefore, this study is devoted to the influence of the GGIP on ISU and explores the threshold effect of ER and the linkage effect between the "flexible" GGIP and "rigid" ER, a novel aspect distinguishing this paper from existing literature.

The current research contributes to existing theory and research. First, the paper constructs a novel ER-based threshold model to explain the internal mechanism of ISU from an under researched context (China) while explaining how "flexible" GGIP and "rigid" ER are interconnected. Second, existing research generally regards GGIP as a general concept from the macro perspective (Tao et al., 2020). This paper discusses the influence of government innovation on ISU from the perspective of green motivation, providing a new perspective for studying ISU.

The rest of this paper can be divided into four parts: The second part is a literature review, which introduces the research status of government green innovation preference, environmental regulation, and industrial structure. The third part elaborates on the research design and empirical model analysis, variable selection, and data sources. The fourth section makes recommendations based on previous empirical evidence.

2 Literature review

The topic of innovation has gained popularity in the urban development literature. Technological innovation (TI) and ISU are considered the main ways to promote new urbanization (Wei et al., 2021). Green TI and ISU can achieve the economy's green transformation through environmental regulation (Du et al., 2021). Therefore, scholars have incorporated innovation into various studies of urban development. For instance, Mieg (2012) discussed commonalities between sustainable urban development and innovation, further explaining that identity seems as a particular governance-related resource in the relationships based on a resource-based view of urban project management. Nilssen (2019) comprised four dimensions of innovation (i.e., technological, organizational, collaborative, and experimental) to analyze empirical data from a Norwegian urban development project triggered by a critical juncture. The author supported the need for a typology of smart cities as multifaceted urban innovation. Furthermore, Pan et al. (2020) considered cross-industry spillovers as a missing link between land-use planning and urban economic futures and found that cross-industry spillovers positively impacted local employment on growth. Adopting a social network perspective, Yao et al. (2020) linked urban innovation with its location in the urban network. They confirmed that city innovation is not only determined by local innovation activities but also is enhanced when cities are deeply embedded in inter-city innovative networks. Yao et al. (2022) focused on the relationships between compact city indicators and comprehensive/technical efficiency, a multi-indicator system of compact cities, including population density, boundary limitation, and road density. The following part reviews the important studies on the relationships of ISU with ER and GGIP.

2.1 Green innovation preference and industrial structure upgrading

Economists agree that science and technology development is pivotal for industrial structure transformation (Ma & Yuan, 2004; Fu et al., 2013). Low-cost growth based on labor-intensive products is not sustainable without technological innovation (TI). Industrial upgradation and success often push wage rates

and multiply costs in developing economies, yet the developing or under-developed competing countries benefit from low wage rates. Tech innovation can break through the original technical level, improve production efficiency, create new emerging industries and new markets (Zhou et al., 2016), adjust the structure of production and utilization demand, and promote the flow of factors (Ji, 2018), a few factors enabling ISU. Yan et al. (2020) noted that renewable energy-led TI significantly and positively uplifted green productivity in cases where a region's relative income level exceeded a critical turning point. In another study, Jiang and Ji (2019) observed that, besides optimizing ISU at the local level, TI had contributed to the rational development of the adjacent regional economies. The authors stressed that the direction and intensity of the impact of innovation on the ISU vary among different regions, especially in China. Thus, there may be a non-linear relationship between innovation and ISU due to the synergistic and crowding effect of industrial agglomeration.

In the same vein, Endrikat et al. (2014) stated that achieving a win-win scenario appears impossible because green production and economic interests may be at odds with each other or sometimes even in a severe conflict. When the degree of outward diffusion of TI is relatively low, the demand for technological products will become the main driving force pushing the adjustment of the industrial structure. When the technological diffusion level is large, the allocation of technological elements and the demand for technological products are two factors (Chen Y. et al., 2021; Wu and Zhu 2021; Sheng et al., 2022). The combined effect of various aspects has reduced the industrial efficiency, thus making the industrial structure adjustment develop in the opposite direction. Therefore, the ISU adjustment and optimization (due to TI) create an inverted U-shaped relationship (Li & Dong, 2018). In a series of studies, Wang et al. (2020) found that green TI can promote total factor productivity, thereby driving the transformation of the economy to green and sustainable growth. In another study, Wang L. et al. (2021) asserted that implementing green innovation strategies can improve the resource utilization rate of enterprises, encourage the conversion of development models (from traditional labor-intensive to knowledge-based), enabling sustainable development of firms, a view consistent with many studies (e.g., Zhang et al., 2019; Zhang et al., 2020).

2.2 Industrial structure upgrading and environmental regulation

Previous works reflect an acute emphasis on the effects of the pollution-haven hypothesis on the adjustment of industrial structure. Most studies have concluded that variations in the standards of ER contribute to the production cost of carbon-intensive industries, affecting the industrial structure in a region (Kheder & Zugravu, 2012). Based on the relevant US data (1979–1990), Shadbegian and Gray, (2004) empirically analyzed the ER-production efficiency nexus for the steel, paper, and petroleum industries. The author observed a significant upsurge in the production costs and lower productivity due to ER in the selected industries. In another study, Gray and Shadbegian (1995) found that the high intensity of ER inhibits polluting enterprises from improving their production efficiency and offers a low financial incentive for adopting environmentally friendly production methods. Therefore, some experts assert the need for balanced and incremental implementation of ER policies, enabling enterprises to improve innovation capabilities and scientifically allocate resources, thereby enhancing their competitiveness (Michael et al., 1995). Another study by Cole et al. (2005) examined how formal and informal ER affect ISU. The author observed that ISU demonstrated a significant U-shaped threshold characteristic when the intensity of formal ER increased. Chen L. et al. (2022) found that informal ER exhibited a double-threshold effect in China. In another study, Wang M. et al. (2021) empirically tested the impact of heterogeneous ER on ISU, deducing that compared to command-controlled ER (CER) and the voluntary public participation ER (VER), market-incentive ER (MER) had a stronger effect on ISU.

Nonetheless, the majority of previous findings reflect two opposing views: 1) ER pushes ISU; 2) the relationship between ER and ISU is uncertain. In line with the former perspective, Lu (2007) found that ER pushes technological progress and promotes ISU. In another study, Gao et al. (2012) observed a positive correlation between the intensity of ER and the optimization of the industrial structure of the manufacturing industry. As per Qu and Wang (2002), the implementation of strict ER standards is conducive to ISU in the long run. Xue (2016) stated that ER affects the industrial structure of the regional equipment manufacturing industry by affecting economic growth. Alternatively, in support of the second perspective, Wu et al. (2019) drew from previous studies to conclude that the effect of ER on ISU in the manufacturing industry differs across different regions in China, i.e., the progress in East China is superior to the Central and West China. Some recent studies show that ER suppresses ISU if the industries exhibit a low level of TI. If the industry holds a medium and high level of scientific and TI, ER can promote the ISU (Sun et al., 2020). Another study explained that ER significantly inhibits ISU in industries with a low level of human capital, but it encourages ISU in industries with a medium or high level of human capital. Considering the industrial modernization of China, some economists argue that ER has played a substantial role in ISU of major cities, even though it is not easy to gauge the intensity and scope of such effect across different stages

(early-middle) of development in different cities in China (Cheng et al., 2017).

2.3 Green innovation preference and environmental regulations

Per the traditional neoclassical economic theory, ER produces a cost effect of compliance, inhibiting enterprises from actively carrying out TI (Altman, 2001). The revisionist school represented by Porter believes that ER generates innovation compensation effects. ER effectively incites firms to pursue innovation (scientific or technological) and develop green technologies, processes, and products for the following reasons: 1) enhance enterprise core competitiveness; 2) partially or entirely offset economist costs generated by environmental regulations (Song et al., 2022a; Chen Y. et al., 2022). Only when the innovation's compensation effect (led by environmental regulation) exceeds the cost-effectiveness of compliance can enterprises get the opportunity to promote their transformation and upgrading through green TI, which unifies the Porter hypothesis and traditional neoclassical economic theory (Liu X. et al., 2022). At present, the current literature on the topic is dominated by the following three main viewpoints. The first perspective, built on the compensation cost theory, advocates that environment-related laws and legislation inhibit green TI. Extra funds for waste disposal (in response to ER) drain out the capital investment of firms for TI (Qiao et al., 2022). Yuan (2022) analyzed A-share listed data (2011–2019) to conclude that environmental protection tax significantly inhibited the green TI of firms based in Shanghai and Shenzhen, China. Compared to the non-state-owned enterprises, the environmental protection tax significantly inhibited the green TI ability of state-owned enterprises.

The second perspective, based on the tenets of the innovation compensation theory, proposes that ER promotes green TI (Song et al., 2022b; Chen L. et al., 2022). The increasing intensity of ER can indirectly stimulate enterprises to enhance scientific and TI, offsetting the cost of pollution prevention and control, thereby promoting TI (Lanoie et al., 2008). Drawing from the strong Porter hypothesis, Jaffe and Palmer (1997) state that stimulating enterprises to innovate in production technology can benefit enterprises in two ways. While the benefits obtained by ER can significantly offset the cost of improving the environment, they can simultaneously trigger an innovation compensation effect, enabling enterprises to yield sustainable development dividends. Strict and efficient ER and high-intensity R&D investment, coupled with independent R&D at the core, can generate a high level of regional green TI (Gao et al., 2022). Based on the uncertainty theory, the third perspective considers the ER-green TI nexus as non-linear, claiming no significant relationship exists between the two factors. Lu (2022) used the panel data of thirty provinces in China (2011–2019) to support the U-shaped connection between green TI and ER.

3 Methodology

3.1 Data and variables

This paper selected the panel data of thirty provinces in China, covering a period from 2005 to 2019. Tibet data were excluded from the sample due to missing items. Table 1 shows the data sources, descriptions, annotations, and variables.

3.2 Variables

In GGIP, the independent variable, was adopted in this study, measured by the sum of green patents. Previous studies (e.g., Pei et al., 2019) have used the sum of the number of utility models (granted) and invention patents as the measurement index. A high index number reflects that GTI is high. The natural logarithm processing of the index was used to obtain GGIP.

Advanced industrial structure (*ln* TS), a proxy of ISU, was adopted as the dependent variable. Even though most researchers, following Clark's Law, have used the proportion of non-agricultural output value as the measure of the ISU, it fails to reflect the new trend, i.e., service-oriented economy. The information technology revolution after the 1970s greatly impacted the industrial structure of major industrialized countries. The servitization of the economic structure driven by informatization is a key feature of the ISU, in that tertiary industries have grown faster than secondary industries in the economic servitization. Following the work of Gan et al. (2011), the paper adopted the tertiary-secondary industry output ratio as a measure of the advanced industrial structure. This indicator reflects the servitization tendency of the economic structure and indicates whether the industrial structure is developing in the direction of servitization. An increase in the advanced industrial structure value represents the economy moving toward superior servitization and the industry structure improving.

This study integrated environmental regulation (ER) into the model as the threshold variable. Following the approach of Ye et al. (2018), Hao and Zhang, (2016), and Ren et al. (2020), the current study incorporated the emissions of three industrial wastes to obtain the intensity of comprehensive ER. A high ER value indicates high pollution emissions, while a weak ER intensity denotes low pollution. ER was computed in the following way. First, the steps involved standardizing the industrial wastewater discharge per unit of output value, the industrial SO_2 discharge per unit of output value, and the industrial smoke and dust discharge per unit of output value, as seen in Eq. 1 below:\

$$UE^S_{ij} = \left[UE_{ij} - \min\left(UE_j\right)\right] / \left[\max\left(UE_j\right) - \min\left(UE_j\right)\right] \quad (1)$$

Where, UE_{ij} = the discharge/per unit output value of the *j*th pollutant in city i, and UE^S_{ij} is the standardized result of the index;

TABLE 1 Summary of the variables.

Variables		Notation	Description	Source
Dependent variable	Advanced industrial structure	TS	Advanced industrial structure	Statistical Yearbook of China (2005–2019)
Independent variable	Government green innovation preference	lnGR	Invention patents plus utility model patents granted	Chinese Research Data Services
Control variable	Financial input	FN	Total Fiscal Expenditure/GDP	Statistical Yearbook of China (2005–2019)
	Human capital level	lnHC	The logarithm of employment at the end of the year	Statistical Yearbook of China (2005–2019)
	Financial development	FD	Financial sector value added/GDP	Statistical Yearbook of China (2005–2019)
	Regional economic development	lnED	The logarithm of GDP	Statistical Yearbook of China (2005–2019)
	Degree of openness	lnOP	The logarithm of total exports	Statistical Yearbook of China (2005–2019)
	Infrastructure	lnINF	Take the logarithm of the length of the city road	Statistical Yearbook of China (2005–2019)
Threshold variable	Environmental regulation	ER	A comprehensive index of environmental regulation intensity	China Stock Market & Accounting Research Database

$\max(UE_j)$ = the maximum value of emission per unit output value of the *j*th pollutant in all cities; $\min(UE_j)$ = the minimum value of the emission per unit output value of the *j*th pollutant in all cities.

As depicted in Eq. 2, the weight of various pollutants was computed as follows:

$$W_j = UE \Big/ \overline{UE_{ij}} \tag{2}$$

Where, $\overline{UE_{ij}}$ = the average level of emission per unit output value of the *j*th pollutant of thirty municipalities, provinces, and autonomous regions directly under the central government each year.

As shown in Eq. 2, the comprehensive index of environmental regulations for the city *i* was calculated as follows:

$$ER_i = \frac{1}{3}\sum_{j=1}^{3} W_j UE_{ij}^S \tag{3}$$

Following Hansen (1999), Eq. 4 reflect the basic model for testing the effect of government green innovation preference on industrial structure upgrading, whereas Eq. 5 depicts the panel threshold regression with ER as the threshold variable.

$$TS_{it} = \alpha_0 + \alpha_1 ln\ GR_{it} + \beta \sum Control + Year_i + \mu_i + \varepsilon_{it} \tag{4}$$

$$TS_{it} = \alpha_0 + \alpha_1 LNGR_{it}(ER \le \lambda) + \alpha_2 ln\ GR_{it}(ER > \lambda) + \beta \sum Control_{it} + Year_i + \mu_i + \varepsilon_{it} \tag{5}$$

Where, i = region; t = year; $Year_i$ = the year fixed effect; μ_i = the individual fixed effect; ε_{it} = the residual item; λ = the threshold value.

The paper incorporated different control variables, including financial input (FN), human capital level (*ln*HC), financial development (FD), regional economic development (*ln*GDP), degree of opening to the outside world (*ln*OP), and infrastructure (*ln*INF)—for the following reasons. Firstly, the quantity and quality of human capital directly determine the success or failure of upgrading the industry at the local and national levels. Secondly, financial support and financial investments provide a certain financial guarantee for ISU (TS) by providing necessary economic support for ISU (TS). Thirdly, the level of regional economic development facilitates ISU (TS), determining whether the ISU (TS) can be realized. Fourthly, the degree of opening to the outside world (*ln*OP) is reflected in the absorption of advanced technologies and experience from developed countries and international trade of products, thereby affecting ISU (TS) to varying degrees. Fifthly, infrastructure (*ln*INF) provides the basic material guarantee for ISU (TS).

TABLE 2 Descriptive statistics.

Variable	N	Mean	Std. Dev	Min	Max
TS	450	1.174	0.65	0.527	5.234
*ln*GR	450	6.798	1.657	0.693	10.436
FN	450	0.237	0.108	0.092	0.758
*ln*INF	450	8.952	0.865	6.323	10.805
*ln*HC	450	7.589	0.797	5.696	8.853
*ln*OP	450	14.361	1.666	10.134	17.984
FD	450	5.69	3.182	1.465	19.628
*ln*GDP	450	9.432	0.988	6.298	11.587
ER	450	0.534	0.529	0	2.585

Note: ***, **, * represent significant at the 1%, 5%, and 10% levels, respectively, with t values in brackets. Abbreviations: TS, Industrial structure upgrading; LNGR, Government green innovation preference; FN, Financial input; LNINF, Infrastructure; LNHC, Human capital level; LNOP, Degree of opening; FD, Financial development; LNGDP, Regional economic development; ER, Environmental regulation.

TABLE 3 Stationarity and unit-root outputs: Augmented Dickey-Fuller (ADF) test.

Stationary testing			
At level			
Variables	Z	Pm	P
ISU (TS)	1.40	−0.28	56.90
GGIP (ln GR)	1.17	−0.26	57.11
*ln*INF	5.17	−3.24	24.49
FN	−4.32***	13.60***	208.95***
*ln*HC	3.88	−2.07	37.35
*ln*OP	2.64	−2.21	35.84
FD	3.61	−2.66	3.62
*ln*GDP	5.93	−4.13	14.79
At first difference			
TS	−6.83***	10.71***	177.35***
InGR	−15.13***	34.92***	442.48***
*ln*INF	−17.89***	46.16***	565.68***
FN	−7.28***	9.76***	166.90***
*ln*HC	−9.88***	15.06***	224.96***
*ln*OP	−7.13***	9.76***	166.89***
FD	−8.07***	11.96***	191.00***
*ln*GDP	−4.01***	6.04***	126.18***

Note: ***, **, * represent significant at the 1%, 5%, and 10% levels, respectively. Abbreviations: TS, Industrial structure upgrading; *ln*GR, Government green innovation preference; FN, Financial input; *ln*INF, Infrastructure; ln HC, Human capital level; *ln*OP, Degree of opening; FD, Financial development; *ln*GDP, Regional economic development; ER, Environmental regulation.

4 Result and Discussion

4.1 Descriptive statistical analysis of variables

The descriptive statistics of each variable are illustrated in Table 2. The mean value, standard deviation, maximum value, and minimum value of ISU (TS) was 1.174, 0.65, 5.234, and 0.527, respectively, reflecting a large gap in different provinces. The GGIP (LNGR) average was 6.798. More so, the standard deviation was 1.657. The min-max values were 0.693–10.436, indicating that the innovation level was largely unbalanced during the study period in different regions of China.

4.2 Stationarity testing

The unit root and stationarity test results provided empirical ground for the stationary of all variables at the first difference level (depicted in Table 3).

4.3 Regression model: Random- and fixed effect

Preliminary Hausman test results offered support for the application of regression analysis with fixed (FE)- and random effect (RE) model as a reference, as shown in Table 4. The two models corroborated the inhibitory effect of GGIP (*ln*GR) on ISU (TS) in China (i.e., RE = −0.0752 and FE = −0.1757), supporting the FE model outputs of Li and Yang (2015). A logical explanation is that government grants more green patents to the secondary industries, stimulating a market change from tertiary to secondary industry. This shift effects GGIP (*ln*GR) in a manner that (rather than supporting) it inhibits the advancement of ISU (TS) to the next stage. Consistent with the previous studies (e.g., Liu & Wang, 2021), the FE coefficient indicated the following effects of different variables on ISU (TS) at 1% significance: insignificant (financial investments, FN = 0.0449, Ln GDP = 0.449); negative (infrastructure, *ln* INF = -0.1962, degree of openness, *ln*OP = -0.0809), and positive (human capital level, *ln*HC = 0.3690).

4.4 Threshold regression

The threshold regression results with ER as the threshold variable are shown in Table 5. The model only passed the single-threshold test (threshold value = 0.0041), reflecting an inverted U-shaped effect of ER on ISU (TS). As seen below, GGIP (*ln*GR coefficient = 0.212, 1% significance level) promoted ISU (TS) when the ER value was less than 0.0041. In contrast, GGIP (*ln*GR coefficient = −0.0648) disrupted ISU (TS) when the ER value exceeded 0.0041. The threshold predictions implied that technological advancement and cost reduction (through patents and other tolls) in the early stages of ER implementation had facilitated industrial transformation and upgrading (ISU) in China. The model outputs signaled that the government restrained the development of polluting industries through various measures (e.g., ER taxation and pollution fines) after reaching a certain threshold in the development of environmental protection technology and formalization of ER laws, consequently slowing down the new round of development and progress of ISU.

4.5 Robustness estimation

The robustness check results are given below in Table 6. The robustness check of the research results was carried out in the following two ways. Method one comprised change of the time interval (cf. Zhang et al., 2022), while the

TABLE 4 Panel regression output: Random- and fixed effect.

	Random-effects regression	Fixed-effects regression
Variables	**Model (1)**	**Model (2)**
GGIP (*ln*GR)	−0.0752**	−0.1757***
	(0.0309)	(0.0299)
FN	−0.7096***	0.0449
	(0.2157)	(0.2213)
*ln*INF	0.0310	−0.1962***
	(0.0505)	(0.0531)
*ln*HC	−0.0759	0.3690***
	(0.0669)	(0.0968)
*ln*OP	−0.1677***	−0.0809***
	(0.0225)	(0.0230)
FD	0.1532***	0.0834***
	(0.0082)	(0.0094)
*ln*GDP	0.2427***	0.0449
	(0.0681)	(0.0846)
Constant	1.3984**	1.2031
	(0.5473)	(0.9493)
N	450	450

Note: ***, **, * represent significant at the 1%, 5%, and 10% levels, respectively, with t values in brackets. Abbreviations: ISU (TS), Industrial structure upgrading; *ln*GR, Government green innovation preference; FN, Financial input; *ln*INF, Infrastructure; *ln*HC, Human capital level; *ln*OP, Degree of opening; FD, Financial development; *ln*GDP, Regional economic development; ER, Environmental regulation.

TABLE 5 Threshold estimations.

Threshold effect and level			
Threshold variable	Threshold quantity	Threshold value	F-value
ER	Single threshold	0.0041***	147.59
	Double threshold	0.0006	32.65
Variable		Threshold coefficient	*t*-value
GGIP (lnGR) (ER ≤ 0.0041)	0.212***	5.91	
GGIP (lnGR) (ER > 0.0041)	−0.0648**	−2.41	
Constant		2.125**	2.55
Control variable	control		
N	450		

Note: ***, **, * represent significant at the 1%, 5%, and 10% levels, respectively. Abbreviations: ISU (TS), ndustrial structure upgrading; GGIP (*ln*GR), Government innovation preference; ER, Environmental regulation.

explanatory variables was replaced in Method 2. Instead of using the sum of invention patents and utility model patents for GGIP (*ln*GR), ISU (TS) was regressed with the replacement of authorized invention patents. Overall, the signs and coefficient valves of all variables in the two methods of the robustness test were in line with Table 4, indicating that the model fitting and construction of regression results were robust.

4.6 Heterogeneity analysis: Resource-based vs non-resource-based regions

As the policy environment and industrial structure vary among different regions in the vast territory of China, the sample was divided into resource-based and non-resource-based regions according to the differences in regional industrial structure and resource endowments. Resource-based regions included Hebei,

TABLE 6 Robustness test results.

Variable	Method (1)	Method (2)
GGIP (*ln*GR)	−0.244***	
	(−7.37)	
*ln*AIP		−0.0672***
		(−2.66)
FN	2.252***	0.132
	(7.56)	(0.54)
*ln*INF	0.0267	−0.240***
	(0.36)	(−4.43)
*ln*HC	0.482***	0.353***
	(3.24)	(3.52)
*ln*OP	−0.0946***	−0.0782***
	(−4.22)	(-3.23)
FD	0.0820***	0.0755***
	(8.88)	(7.90)
*ln*GDP	0.216**	−0.0482
	(2.53)	(−0.57)
Year	control	control
Constant	−2.899**	1.826*
	(−2.55)	(1.88)
N	300	449

Note: ***, **, * represent significant at the 1%, 5%, and 10% levels, respectively, with t values in brackets. Abbreviations: ISU, Industrial structure upgrading; GGIR, Government green innovation preference; LNAIP, authorized invention patents; FN, Financial input; LNINF, Infrastructure; LNHC, Human capital level; LNOP, Degree of opening; FD, Financial development; LNGDP, Regional economic development.

TABLE 7 Region-based heterogeneity analysis results.

Variable	Resource-based (1)	Non-resource-based (2)
GGIP (*ln*GR)	−0.0912**	−0.2327***
	(0.0413)	(0.0404)
FN	1.7749***	0.0182
	(0.3459)	(0.2704)
*ln*INF	−0.0746	−0.0816
	(0.1438)	(0.0624)
*ln*HC	−0.2889**	0.8634***
	(0.1132)	(0.1495)
*ln*OP	−0.1457***	−0.0464
	(0.0291)	(0.0310)
FD	0.1314***	0.0599***
	(0.0160)	(0.0116)
*ln*GDP	0.3223***	−0.2912**
	(0.1054)	(0.1446)
Constant	2.6022***	−0.6624
	(0.8902)	(1.6346)
N	150	300

Note: ***, **, * represent significant at the 1%, 5%, and 10% levels, respectively, with t values in brackets. Abbreviations: TS, Industrial structure upgrading; *ln*GR, Government green innovation preference; FN, Financial input; *ln*INF , Infrastructure; *ln*HC, Human capital level; *ln*OP, Degree of opening; FD, Financial development; *ln*GDP, Regional economic development; ER, Environmental regulation.

Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Sichuan, Guizhou, Yunnan, Shaanxi, and Xinjiang, while the remaining provinces were considered non-resource-based regions. As reported in Table 7, GGIP had a stronger inhibitory effect on the ISU (TS) in non-resource-based regions (*ln*GR = −0.2327) than resource-based regions (*ln*GR = = −0.0912) of China. For control factors, government financial expenditure (FN) and the degree of opening (*ln*OP) had a significant controlling role in the resource-based regions, yet the impact of these factors on ISU (TS) was weak.

5 Conclusion and discussion

The key objective of this article was to measure the impact of GGIP on ISU under different levels of ER using Chinese provincial panel data from 2005 to 2019. All the variables in the study passed the unit root test and stationarity testing. The regression analysis suggested that GGIP prevented ISU in Chinese regions, while FN and GDP had insignificant effect on ISU, infrastructure and OP had a negative effect on ISU, and HC positively impacted ISU. The main regression method, with ER as a threshold variable, confirmed the non-linear inverted U-shaped relationship between GGIP and ISU through the coefficient of the quadratic term (e.g., Zhang et al., 2022). The threshold regression delineated that the ER rigidity controlled the inhibitory role of GGIP in improving ISU. More so, the heterogeneity analysis demonstrated non-resource-based region and resource-based region differed in the intensity of inhibitory influence of GGIP on ISU, as the inhibitory effect was relatively more significant in non-resource-based regions.

The paper proposes the following recommendations according to the current findings. First, the government should create a conducive atmosphere and continuously improve the level of TI. Regional governments can enhance emphasis on basic research and original innovation to provide a source for GTI progress by continuously expanding the R&D frontiers in different regions; deepening the protection of intellectual property rights in GTI; by actively introducing market mechanisms to build a platform for the transformation of GTI projects to promote advanced technology for enhancing the development of enterprises; by mobilizing the role of ER in promoting ISU. Second, the current findings assert the need for simultaneous development of GTI and ER. The central and local governments should introduce a balanced approach in terms of implementation, rules, incentives, and penalties, considering the restraining effect of GTI on ISU. Third, the current findings indicate that the rationalization of the industrial structure should be realized in cooperation with ER. With nascent insight into the dynamics of ER, the rapid

expansion of the tertiary industry in China could be harmful. Under the self-regulating action of the market, the government should give good play to the dispatching role of government regulations so that the industrial structure can be upgraded at an appropriate speed and the industrial structure can be rationalized appropriately in a systematic manner. Fourth, the current findings call for promulgation of indigenous policies tailored to local conditions to prevent the inhibitory effects of GGIP on ISU in different regions, particularly non-resource-based regions. It is necessary to provide corresponding industrial policy support to realize the adaptive development and balance between resource-based and non-resource-based regions. While achieving green development, the government should support the industrial policy of various regions and achieve coordinated and high-quality development.

Although the paper brings fresh insight into regional innovations in China, it has the following shortcomings. First, the current findings are limited in representing the interaction among GGIP and ISU of provincial governments in thirty provinces of China. Second, the paper explored the impact of GGIP on the rationalization of ISU in addition to ISU. As the results were not ideal, they were excluded. It appears that GTI has not sufficiently affected the rationalization of the industrial structure, yet its significant impact on the rationalization of the industrial structure cannot be underestimated in other parts of the world. Third, it is assumed that the province panel data cannot fully reflect the effect of GGIP on industrial structure. Given that prefecture-level city or micro-enterprise data may be able to make the research more representative (Long et al., 2017), follow-up research is expected to bring fresh insight.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

SK: Supervision, conceptualization, Editing. AK: Proofreading MK: Supervision JL: Introduction part, preparation ZP: Literature review part, preparation CL: Data handling, methodology, statistical software.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Government innovation support for green development efficiency in China: A regional analysis of key factors based on the dynamic GMM model

Shoukat Iqbal Khattak[1], Muhammad Kamran Khan[2]*, Taipeng Sun[1], Uzma Khan[3], Xiaoman Wang[1] and Yating Niu[1]

[1]School of Business Administration, Jimei University, Xiamen, China, [2]Management Studies Department, Bahria Business School, Bahria University, Islamabad, Pakistan, [3]Department of Finance, College of Business Administration, Prince Sattam Bin Abdulaziz University, Alkharj, Saudi Arabia

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Shaheed Benazir Bhutto Women University, Pakistan

*CORRESPONDENCE
Muhammad Kamran Khan,
mkkhan.buic@bahria.edu.pk

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Local government innovation support (LGIS) is an exogenous pulling force for high-quality economic development. Accurately identifying the mechanism by which LGIS affects green development remains practically and theoretically significant for building a long-term framework for driving green development. Based on provincial panel data (2010–2019), this paper uses the Super-SBM model to measure the green development efficiency (GDE) of different provinces in China. A dynamic panel GMM model is constructed to evaluate the significant relationship between LGIS and GDE and to explore the potential impact mechanism of other key factors such as fixed asset investment (FAI), environmental regulation (ER), industrial structure (IS), and foreign direct investment (FDI) on GDE. The estimation showed that LGIS had a positive impact on GDE. The data analysis indicated that GDE in the lag period significantly affected the GDE in the current period. More so, as per the results, the promoting effect of GDE in the second lag period gradually weakened due to the decline of LGIS and ER restrictions. The current model also revealed that FAI and ER inhibited the GDE progress, while IS and FAI had improved the state of GDE in the region. The research findings imply that China should further increase the government innovation expenditure, FDI utilization, and IS upgrade to promote high-quality economic development.

KEYWORDS

government innovation support, green development efficiency, regional analysis, GMM model, China

1 Introduction

With the general improvement of people's environmental awareness, more and more countries have begun to recognize the importance of ecological and environmental protection. It has become a common agenda of all countries to relieve the pressure on resources and the environment to realize sustainable economic development (Donald and

Gordon, 2016). Recently, the local governments in China have been focusing on strategies to address environmental issues to improve green and sustainable development to an unprecedented level. In 2018, the Chinese government called for speeding up the formation of a green development model, reducing pollutant emissions from the source, and taking green development as a fundamental strategy to solve pollution (air, water, and land) and enhance the quality of the ecological environment. In 2019, the Chinese Government Work Report indicated that green development is an inevitable requirement for creating a modern economic system (Chen H et al., 2021; Chen and Sivakumar, 2021; Miao et al., 2022). At the same time, the Chinese government has stressed at many important domestic meetings to adhere to the new development philosophy and achieve sustained and sound economic development based on significantly improving quality and efficiency (Pan and Chen, 2021; Qiu et al., 2022a; Qin et al., 2022). The spirit of green development mandates coordination and unification of economic growth and environmental protection (Jari et al., 2018; Zhang et al., 2018; Li et al., 2019) to manage economic growth while addressing ecological constraints by improving energy utilization, reducing pollution emissions, promoting industrial transformation and upgrading (Luo et al., 2021), promoting economic growth, and improving environmental quality, is an important strategic choice to encourage high-quality development of economy in China (Na et al., 2020).

Green development has been continuously promoted in China, but many believe that the current state of overall green development still needs considerable improvements (e.g., Yang and Wen, 2017). Experts argue that regional green development can play a vital role in the improvement of GDE (Guo and Zhang, 2020; Qiu et al., 2020). Following the concept of economic development efficiency, resource input and environmental pollution are integral factors of GDE in China and are used as key indicators to measure regional green development (Li and Jing, 2019). With the decentralization of fiscal power in China, local governments have become the main players steering and implementing the central green development policy, promoting sustainable economic development, and institutionalizing regional green development policies (Li et al., 2020). They are responsible for guiding, regulating, and monitoring the efficiency of regional green development in their respective administrative units (Li, 2021) in the following ways: 1) effectively alleviate the shortage of R&D funds for local enterprises, universities, and scientific research institutions (Gao et al., 2022); 2) promote regional green technology innovation to provide financial support (Yang et al., 2022); 3) issue green development-related policies, e.g., environmental regulations (Guo and Chen, 2021; Hu et al., 2022); 4) formalize and integrate the environmental information disclosure system (Yang and Zhao, 2018) and green credit (Pei et al., 2018); 5) effectively standardize corporate behavior and provide policy support for their green technology innovation; 6) align green support measures to suit local conditions, e.g., the implementation of trade opening (Qi et al., 2022) and market-oriented reforms; 7) provide a good innovation environment for enterprises in the region to implement green technology innovation; 8) promote the construction of innovative cities (Wang H et al., 2022), low-carbon cities (Lan, 2021), smart cities (Du et al., 2020; Zhang and Zhong, 2022); 9) construct pilot green city areas for broader implementation. Despite the critical role of LGIS in facilitating regional and national GDE in China (Ding et al., 2022), most previous studies have predominantly restricted to antecedents or consequences of regional green technology innovation or specific policies and measures. However, the overall impact of government innovation on the regional green development efficiency in China remains largely unexplored.

In response to the above knowledge void, the main aim of this work is to explain the continuous promotion of government innovation construction and the continuous implementation of green development practices (Qiu et al., 2022b; Sheng et al., 2022). Firstly, the study systematically analyzes the influence mechanism of regional government innovation subsidies on GDE, as asserted in earlier studies (e.g., Jiang et al., 2021). From the perspective of government innovation governance and support, it generally evaluates the effect of LGIS and other key influencing factors (e.g., FAI, ER, IS, and FDI) on GDE improvement. Secondly, the paper uses two novel and robust estimators in the study: 1) the Super-SBM model to measure the efficiency of green development comprehensively; 2) the dynamic GMM model as the main analysis framework to empirically analyze the mechanism of government innovation support to improve the GDE. Third, taking into account the current situation of regional green development, the article also analyzes the heterogeneity of different regions and compares the differences between regions.

The following parts of this work are divided as follows. An overview of the study area and the academic literature on the interactions among the main study variables are given in Section 2. The details of the study methodology are discussed in Section 3. Section 4 provides empirical analysis based on the outcomes of various methods used in the study. The last section, Section 5, concludes the main study findings, offers policy implications, highlights limitations, and puts possible future directions forwards.

2 Literature review

Government, market, and enterprise are the key components of a modern market economy system. For social transformation in China, government innovation can act as an essential tool for improving the ability, systems, and allocation of resources in the local administration. Local governments have adjusted the economic and administrative power of market allocation of resources, including financial subsidies, tax incentives, business license issuance, and investment restrictions (Tian et al., 2021a; Tian et al., 2021b; Tan et al., 2022). Of these expenditures, government financial science and technology

expenditure is an important instrument for the government to participate in regional innovation activities. Previous literature on government innovation support is mainly divided into the following streams. The first stream, *the connotation of government innovation*, attempts to define the scope and objective of government innovation. For instance, He (2011) argued that the goal of government innovation is to establish a service-oriented government with political, economic, social, and cultural coordination and sustainable development, starting from the theory, system, personnel, and operation of government innovation. As a criterion for winning projects of the "Local Government Innovation Award," the content of government innovation can be divided into four categories, i.e., political reforms, administrative reforms, public services, and social management. The content of government innovation can be roughly divided into two levels (Yan et al., 2021; Wang Q et al., 2022). One is the internal management of the government organization systems, whereas the other relates to the government's management and services to society. The second stream of literature, the *driving force and influencing factors of government innovation*, unwraps the determinants of government innovation (Chen, 2015; Yu and Huang, 2017). Researchers have found that moderate decentralization ability (Wu and Wu, 2018) and performance appraisal system (Huang, 2017) are among the important factors promoting government innovation. The third stream, *the influence mechanism of government innovation diffusion*, explores the precise framework through which government innovation occurs in a certain region (e.g., Guo and Zhang, 2020; Yuan et al., 2022). The diffusion of government innovation refers to the process through which government innovation policies or projects are spread in a certain social system through certain channels. For example, Zhang et al. (2015) explained the driving force of government innovation diffusion from the perspective of neo-institutionalism theory and found that the driving force of government innovation diffusion has the characteristics of stages. Liu et al. (2021) studied the multi-factor combination path of the comprehensive promotion of LGIS.

Public policy experts argue that government-relevant policy formulation and resource allocation significantly impact the operation of enterprises (Xu, 2014; Han and Gao, 2018), encouraging enterprises to carry out innovative activities (Long et al., 2012). As an exogenous driving force to promote the high-quality development of the national economy, government innovation support is the management and service of the government to the society, and it has a basic, guiding, and stimulating effect on innovative economic activities. Through scientific and technological innovation subsidies, the government urges social entities to increase scientific and technological research investment and development, indirectly reduces the cost of enterprise research and development or makes up for the gap in research and development funds, eases the financial constraints of innovation activities, and encourages innovation activities in the region. Beyond that, government innovation can promote independent scientific research institutions, universities, and related enterprises to jointly conquer core technologies, strengthen industry-university-research cooperation, and promote the transition from technological imitation to cutting-edge technological innovation. Enterprises are further encouraged to conduct green (low-carbon/zero-carbon) technologies focused on research and development by reducing taxes and fees to promote green economy development. The key to improving the quality of green development is to develop green development efficiency (Yu et al., 2016). For China, green development efficiency is a critical indicator to measure the economy entering a stage of high-quality development in the new age.

Green development and green efficiency literature offer three main research directions: the concept of green development and green development efficiency. For instance, Pearce et al. (1996) define a green economy as "an economic growth model that will not lead to ecological crisis and social fragmentation." As per Hu and Zhou (2014), the green development concept needs three key dimensions: function definition, mechanism analysis, and development strategy. The author added that green development emphasizes the relationship between economic, social, and natural systems. Liu (2017) divided the concept of green development into five dimensions: economic development, political construction, ecological environment, social development, cultural value. The author pointed out that green development is innovation-driven, high-level, sustainable, and improves people's livelihood, harmonious and upward development. Secondly, the second literature theme is focused on the evaluation and evolution green development efficiency (in time and space). In this context, economists have constructed an evaluation index system for green development and green development efficiency based on the SBM model and its extensions to measure the green development efficiency of different areas (Yue and Xue, 2020; Shi and Lan, 2021), provinces, regions (Xu and Ouyang, 2022), economic belts (Chen J et al., 2021; Xiang et al., 2021), and urban agglomerations (Chen and Wu, 2021; Weng et al., 2022; Zhang et al., 2022). Based on the *input-output theory*, authors often incorporate resource consumption, environmental pollution, ecological benefits, and social benefits into the Super-SBM model to analyze the efficiency of the input-output allocation of economic, social, and environmental complex ecosystem elements, crucial factors of green economic efficiency. Among other methods, researchers usually predict green development efficiency through the Super-SBM model, directional distance function model, total factor productivity model or vector autoregressive model (VAR), and gray support vector-machine-regression model GM(1,1) (Cao, 2011; He et al., 2020) from a regional macro perspective to predict the green development efficiency of national inter-provincial, urban or rural, urban agglomerations. Chen et al. (2022) used the Super-SBM model and Malmquist index to

measure the green development efficiency of the Chengdu-Chongqing economic circle from 2007 to 2019 based on dual perspectives. The authors analyzed the spatial-temporal evolution characteristics and influencing factors and then predicted green development efficiency using Went's linear and seasonal exponential smoothing method.

Considering the stream of research on the influence mechanism and ascension path of green development efficiency based on the Tobit regression, Bootstrap truncation regression, and spatial autoregression models indicate that the level of economic development, technological innovation, and environmental regulations (Ma and Jin, 2022), green finance (Zhu et al., 2022), fiscal decentralization, ecological civilization pilot zones (Fan et al., 2022), and low-carbon cities affect the efficiency of green development, and specific progression paths (Wang et al., 2014; Song et al., 2018; Zhao et al., 2018; Wen, 2021). Guo et al. (2022) and others used the SBM-undesirable model to construct an input-output indicator system for green development efficiency in the Yellow River Basin. They conducted a spatial statistical analysis of the green development efficiency of the Yellow River Basin and its temporal and spatial pattern characteristics. Through different models (SE-SBM model, GML index and its decomposition index, and Tobit regression model), the above researchers have concluded that there is still room for improvement in green development efficiency in the sample area and the overall stage is characterized by a leap from low-level to high-level. The GML index revealed a fluctuating growth trend, where differences were found in the growth rate of local green development efficiency in China. The study further showed that urbanization and environmental policies promote regional green development, while industrial structure, degree of opening-up, and energy structure inhibit regional green development. Zirui (2021) used the DID model and the propensity matching score method to examine the influence mechanism of low-carbon pilot policies on regional GDE. The results demonstrated that the implementation of low-carbon pilot policies could significantly improve the level of regional GDE in Chinese provinces, and the effect of policies varies with different regions and cities.

Retrospectively, it is not difficult to find that government-led reforms and innovations, such as market-oriented reforms, low-carbon cities, ecological civilization pilot zones, green financial inclusion policies, and environmental information disclosure systems, play a significant effect on the regional green development efficiency. An important limitation of prior works resides in examining a specific policy or reform as the starting point and undermining the influence of government reform or innovation on the regional green development efficiency (as a whole). Therefore, in the case of unbalanced local government innovation levels and uncoordinated regional green development, it is indispensable to analyze the influence mechanism and improvement path of government innovation and its processes on green development efficiency from the national and regional perspectives. Exploring its impact on green development efficiency from the view of government governance innovation can enrich and supplement relevant research about the improvement path and impact mechanism of green development efficiency to a certain extent. The literature summary is shown in Table 1.

Keeping in view the mechanism of local government innovation support and green development efficiency, the innovation-driven development strategy has attracted significant attention from governments worldwide. Studies have shown that government innovation subsidies can effectively improve the efficiency of technological innovation, thereby promoting regional economic development (Jiang and Tan, 2020). Nevertheless, the existing research on local government innovation support mainly focuses on its relationship with economic development. From the economic development viewpoint, due to the externalities and high risks of science and technology, high investment, uncertainty, and other characteristics (Li and Yang, 2018), government science and technology funds can address the following issues: make up for the gap of corporate innovation funds; alleviate the difficulty of insufficient research and development funds; optimize the allocation of resources for scientific and technological innovation (Ye and Liu, 2018; Sung et al., 2022; Zhang and Ayele, 2022); improve economic development efficiency.

From a societal perspective, the essence of local government innovation support is to drive social development and maintain social stability. In the process of government innovation, society gradually grows and develops due to the availability of space for activities, rights protection, resource protection, and capacity protection (He, 2013). Ma et al. (2022) concluded that economic digitization reduced CO_2 emissions in thirty Chinese provinces between 2006 and 2017. The negative impact of economic digitalization on CO_2 emissions was more profound in provinces with higher R&D investment than those with lower R&D investments. From the perspective of environmental protection, increased government support for scientific and technological innovation can effectively improve energy-utilization technology and improve environmental quality to a certain extent (Qin and Yu, 2016; Zhou and Liu, 2021), and ultimately improve energy eco-efficiency (Wang et al., 2019; Song L et al., 2021). Among other researchers, Xie et al. (2018) observed a "U-shaped" nonlinear relationship between the LGIS and GDE. Only by increasing the support of scientific and technological innovation funds and making it transition to the right end of the "U-shaped" curve can the government facilitates the role of scientific and technological innovation in promoting ecological efficiency. The green development efficiency indicator emphasizes the symbiosis and interaction mechanism of the economic, social, and environmental systems (Liu et al., 2021). Therefore, through data envelopment analysis, this paper uses the Super-SBM model to build a green development-efficiency-index evaluation system, then uses the GMM model to inquire about the relationship between local government innovation support and green development efficiency.

TABLE 1 Previous studies about government innovation support and green development efficiency.

Research topics	Research perspectives	Author	Main viewpoints
Government innovation support	• Connotations of government innovation	Kattel and Mazzucato (2018)	• The introduction of new ideas, new practices, and new models is effective for the government. Such behaviors can be judged as government innovation or policy innovation.
		Yu (2008)	• The purpose of government innovation is to promote the public interest.
	• The influencing factors of government innovation	Wu and Wu (2018)	• The central-local relationship of moderate decentralization in China, the flexible institutionalization of having skills, and the contradiction of social transformation have provided political opportunities for LGIS in China.
			• An analysis of survey data obtained by the South Korean government found that leaders' support for innovative initiatives and the development of self-taught organizations that abandoned old-fashioned mores were crucial for organizational change in government.
	• The proliferation of government innovation	Cao (2011)	• Government innovation projects can be effectively promoted and spread when there is a high degree of fit between them and local government interests.
			• The main types of diffusion of government innovation include horizontal coercion (e.g., commercial regulations and trade agreements) and vertical coercion (e.g., through grants and policies).
	• The mechanism of government innovation support	Xu (2014)	• Government policy formulation and resource allocation will significantly impact enterprise operation and further promote enterprise innovation behavior.
		Han and Gao (2018)	• The government guides industrial development and enterprises' strategic activities through policy design.
GDE	• GDE definitions	Pearce et al. (1996)	• Green development is a kind of economic development that will not cause ecological crisis and social division.
		Liu (2017)	• Green development is innovation-driven, high-level, sustainable, mutually beneficial, and harmonious.
	• Evaluation and spatial-temporal evolution of GDE	Chen et al. (2022)	• Using the super-SBM model and the malmquist index to measure the regional GDE, it is found that the GDE presents a time series characteristic of the transition from "high level, large gap" to "high level, small gap."
		Guo et al. (2022)	• Scholars constructed a GDE index evaluation system for provinces and cities in the Yellow River Basin and found that the regional gap in GDE continued to expand. During the study period, the GDE changed from "small gap with high efficiency" to "large gap with low efficiency."
	• Influence mechanism and promotion path of GDE	Guo and Zhang (2020)	• This study confirms that China's market-oriented reform has a significant positive effect on the improvement of GDE.
		Yuan et al. (2022)	• The overall GDE gap between regions in the Yangtze River Economic Belt is relatively large, and manufacturing agglomeration has a spatial spillover effect, which can improve the GDE of surrounding areas.

Note: GDE, green development efficiency; GD, green development; LGIS, local government innovation support.

3 Data sources and methods

3.1 Data sources and description

Table 2 lists the summary of the data details.

3.2 Variables

The dependent variable, green development efficiency (GDE), was estimated using the data envelopment analysis method. The green development efficiency evaluation-index system was based on the input-output model: input indicators comprised physical capital, labor, and energy input; output indicators were divided into expected output and undesired output. The expected output was represented by the gross domestic product of each region, and the CO_2 of each province was used to represent the unexpected output. Among them, the physical capital investment was measured by the capital stock, calculated by the fixed asset formation amount according to the perpetual inventory method, and the depreciation rate was taken as 9.6 percent, following Zhang et al. (2004). The GDP of each province took 2010 as the base period. The actual value was obtained after deflating according to the consumer price index of each region. Labor input represented the number of employees at the end of the year. The total energy consumption at the end of the past year was used to measure the energy input. The data on carbon dioxide emissions were compiled from the Carbon Emission Accounts and Datasets for Emerging Economies (CEADs) (Shan et al., 2016; Shan et al., 2018; Shan et al., 2020; Guan et al., 2021).

Kaoru (2001) proposed a slack-based efficiency evaluation model (Slack-Based Measure, SBM), introducing the amount of

TABLE 2 Data description, including notation and sources.

Variables	Indicators	Categories	Notation	Description	Source
Dependent variable					
Green development efficiency in provincial areas	Input	Capital input	GDE	Input-output Model	Calculated according to the super-SBM model
		Labor input			
		Energy input			
	Output	Expected output			
		Undesired output			
Independent variable					
Provincial science and technology expenditure			LGIS	100 million yuan	Statistical yearbook of China (2010–2019)
Control variables					
Provincial fixed asset investment			FAI	100 million yuan	Statistical yearbook of China (2010–2019)
Total investment in industrial pollution control			ER	10 thousand yuan	Statistical yearbook of China (2010–2019)
The proportion of the secondary and tertiary industries in the regional GDP			IS	Percentage	Statistical yearbook of China (2010–2019)
Actual use of FDI			FDI	10 thousand yuan	Statistical yearbook of China (2010–2019)

input and output slack into the objective function. When evaluating the efficiency of decision-making units in the traditional DEA method, there may be cases where the efficiency value of multiple decision-making units is 1, which cannot be further compared. Therefore, when there are multiple effective decision-making units, it cannot be considered for further comparison. Kaoru Tone Kaoru (2002) combines the advantages of the Super-DEA and SBM models. Unlike the traditional DEA model, the Super-SBM model can not only deal with the undesired output more properly, but also can make further comparisons in valid decision units. The Super-SBM model for this study was constructed as follows:

$$\rho^* = min\,\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}_{io}}{x_{io}}}{\frac{1}{s}\sum_{k=1}^{s}\frac{\bar{y}_{ko}}{y_{ko}}}$$

s.t. $\bar{x}_{io} \geq \sum_{j=1,j\neq 0}^{n}\lambda_j x_j, \forall i;$

$$\bar{y}_k \leq \Sigma_{j=1,j\neq 0}^{n}\lambda_j y_j, \forall k;$$

$$\overline{x_i} \geq x_{io}, 0 \leq \bar{y}_k \leq y_{ko}, \lambda_j \geq 0, \Sigma_{j=1,j\neq 0}^{n}\lambda_j = 1, \forall i, j, k$$

In the above equation, n = decision-making units, m = input variables, s = expected outputs, x_{ij} = input variables, y_{kj} = expected output variables, λ = weight variable, and $\rho^* > 1$ = the decision-making unit is effective. The larger the value, the higher the efficiency of the decision-making unit (Zhao and Yang, 2017).

The independent variable, local government innovation support (LGIS), was developed by taking science and technology expenditure in local government financial expenditure as a proxy variable. Science and technology expenditure can promote the technological innovation of enterprises and other regional public departments to achieve the effect of energy saving and emission reduction. Innovative technology support and energy structure transformation improve the efficiency of green development and sustainable development in the region.

For control variables, the study accumulated important factors affecting the level of regional green development, including fixed asset investment (FAI), environmental regulation (ER), industrial structure (IS), and the level of foreign direct investment Utilization (FDI) (We and Hou, 2021). In China, FAI has created favorable conditions for regional infrastructure construction and economic development, thus impacting the efficiency of green development. The level of ER reflects the cost of regional pollution control. The more the government invests in pollution control and environmental protection, the more conducive it is to reducing undesired output (Wang and Zhang, 2018). This paper uses the investment in industrial pollution control as a proxy variable for the intensity of environmental regulation. The higher the proportion of secondary and tertiary industries in IS, the higher the concentration of industries in the region, which may have a crowding effect and impact the green development efficiency. The technology spillover brought by FDI not only helps local

TABLE 3 Descriptive statistics for variables.

Variable	Mean	Sd	Min	Max
Ln GDE	−0.610	0.340	−1.350	0.0700
Ln LGIS	4.170	1.050	1.320	7.060
Ln FAI	9.200	0.720	6.960	10.76
Ln ER	11.88	0.990	8.180	14.16
Ln IS	−0.160	0.110	−0.470	0.0200
Ln FDI	14.68	1.700	8.030	18.47

Abbreviations: LGIS, local government innovation support; FAI, provincial fixed asset investment; ER, total investment in industrial pollution control; IS, the proportion of the secondary and tertiary industries in the regional GDP.

TABLE 4 Panel unit root results: augmented dickey-fuller (ADF) test.

Variable	I (0)	I (1)	Stationarity
Ln GDE	−10.7045***	−5.5847***	YES
Ln LGIS	−6.8017***	−5.1775***	YES
Ln FAI	−11.5209***	−6.7359***	YES
Ln ER	−9.5989***	−8.1646***	YES
Ln IS	−2.1922**	−1.8603**	YES
Ln FDI	−8.0796***	−6.2111***	YES

Note: *, **, and *** represents level of significance at 10%, 5% and 1%, correspondingly. Abbreviation: LGIS, local government innovation support; FAI, provincial fixed asset investment; ER, total investment in industrial pollution control; IS, the proportion of the secondary and tertiary industries in the regional GDP; FDI, actual use of foreign direct investment.

enterprises to improve the level of green production by imitating the innovation path but also stimulates the local enterprises for independent innovation, thereby contributing to the level of regional green development. It is measured by the amount of direct investment, in which the amount of foreign investment is deducted after conversion according to the annual exchange rate.

This paper used the logarithms of the dependent, independent, and control variables to control the nonlinear relationships and heteroscedasticity problems that may exist in the model test. The descriptive statistics of each variable are shown in Table 3.

Due to the long data time-span, this paper used the Augmented Dickey-Fuller (ADF) test to check the stationarity of all variables. The results in Table 4 (ADF test) supported the rejection of the null hypothesis, affirming no unit root and stationarity problems.

3.3 Model construction

Panel data helps understand the dynamic behavior of the research object. As the individual unit is small and the time is long in the dynamic long panels, the deviation of the results of the dynamic panel estimation is small. A consistent estimate can be obtained by correcting the deviation. Provided that the number of object areas studied in this paper was greater than the length of time, the dynamic difference GMM model was selected. In this model, a consistent estimate is obtained in the following steps: 1) the first-order difference is used to eliminate the individual effects of the model; 2) appropriate instrument variables are found to eliminate the endogeneity of the model. Assuming that the impact of LGIS on GDE is inconsistent, it was conjectured that the GDE in the previous period would affect the current LGIS, which in turn would affect the current period GDE, as per prior concepts (He and An, 2019). The paper introduced the lag term of GDE as an instrumental variable. According to the provincial panel data structure, the specific model settings in this paper are as follows:

$$LnGDE_{it} = \alpha + \rho_1 LnGDE_{i,t-1} + \rho_2 LnGDE_{i,t-2} + \beta_1 LnLGI_{it} + \sum_{i}^{4} w_i \, Ln\, x_1 + u_{it}$$

Where i = the specific province, t = the year; GDE_{it} = the GDE index of a certain province in a certain year, $GDE_{i,t-1}$ or $GDE_{i,t-2}$ = the GDE index of a province with a lag of one or two periods, $LGIS_{it}$ = local government innovative support by a provincial government, and x_1 = the control variable (FAI, ER, IS, and FDI), u_{it} = a random disturbance item.

4 Results and findings

4.1 GMM model output

The paper selected the dynamic panel system GMM model to test the nexus among the selected variables, GDE, LGIS, FAI, ER, IS, and FAI. In addition, since the model adds the lag term of GDE as an instrumental variable (L_1 and L_2), the GMM model can perform an over-identification test for instrumental variables (Arellano and Bond, 1991; David, 2009). As a consistent estimate, the premise of the system GMM estimate is that there is no autocorrelation in the disturbance term. This test is based on a two-step validation process: 1) the first-order autocorrelation for the first-order differences of the perturbation terms; 2) no second or higher-order autocorrelation for the differences in the perturbation terms (Arellano and Bond, 1991). The dynamic panel system GMM model results in Table 5 satisfied the pre-stated recommended criterion. Next, the Arellano–Bond test results showed that the perturbation term had first-order autocorrelation only, i.e., no second-order autocorrelation. The results of the Sargan test did not reject the null hypothesis, indicating that the instrumental variables were invalid, and the estimated results of the model were accurate.

As seen in Table 5, the effect of the GDE (previous period) on GDE (current period) was 0.72633. This result indicated that GDE improvements in the previous period contributed to

TABLE 5 Summary of the results for the dynamic panel system GMM model.

Variable	Fixed-effects	SYS_GMM
LGIS	0.27494*** (0.028)	0.04382*** (0.005)
FAI	−0.05838 (0.041)	−0.02257*** (0.004)
ER	0.01777* (0.011)	−0.00216* (0.001)
IS	1.12644*** (0.122)	0.02870** (0.013)
FDI	0.03755*** (0.014)	0.00466*** (0.001)
L_1.GDE		0.72633*** (0.062)
L_2.GDE		0.12511** (0.054)
_cons	−1.79868*** (0.349)	−0.04731 (0.051)
Observations	300	240
Arellano–bond (1)		$p = 0.002$
Arellano–bond (2)		$p = 0.284$
Sargan test		$p = 0.899$

Note: *, **, and *** represents level of significance at 10%, 5% and 1%, correspondingly. Abbreviation: LGIS, local government innovation support; FAI, provincial fixed asset investment; ER, total investment in industrial pollution control; IS, the proportion of the secondary and tertiary industries in the regional GDP; FDI, actual use of foreign direct investment.

enhancing the state of ER and technological innovation level, consequently making the impact of LGIS on economic development more evident. Also, this finding implies that continued LGIS, coupled with GDE in previous periods, has enabled improvements in current GDE in China, a view echoing previous research (Song L et al., 2021). The influence coefficient of the relationship between the second-lag GDE (L_2) and the current-lag period GDE (L_1) was 0.12511. This finding affirmed that the promotion effect of the former GDE period on the latter had begun to slow down. In line with Lin et al. (2022), this outcome supported that the GDE investment has declined recently. A possible explanation could be the volatility characteristics of ER restrictions and LGIS (Guo and Chen, 2021), which have caused slow progress in GDE and the gradual widening of the economic development gap across some regions. Under the current competitive atmosphere among local governments in China, the inferior performance of local governments lagging behind others in GDE in the second period will inhibit them from making GDE improvements in the current period. This finding contradicts preceding conclusions (He and An, 2019). As depicted in Table 5, LGIS significantly impacted GDE in local governments in China, as evidenced by the LGIS coefficient of 0.27494. Corroborating Hu and Wu's (2019) assertions, this outcome supported that green and sustainable economic development and higher returns in China would require regional governments to continue to use technology expenditures to help upgrade and progress innovative technologies, thereby enhancing the regional GDE. Scientific and technological expenditures toward technological innovation by local governments in China have played a critical role in the technological transformation and upgrading of various industries (Gao and Li, 2021; Song M et al., 2021), decreasing the discharge of environmental pollutants in the region and improving GDE.

In Table 5, the data analysis showed the following results for the role of control variables. First, the coefficient of FAI affecting GDE was −0.02257, reflecting that economic development and construction in different regions have been achieved at the cost of environmental protection, undermining a focus on green and sustainable economic development. Zhang and Ma (2022) agree that although FAI creates an excellent external environment for improving enterprise productivity, excessive underutilized investments may generate a detrimental impact. Second, the estimates showed that ER had a significant and positive impact on GDE, as evident by the ER coefficient (0.01777). This outcome affirmed that the relevant environmental protection policies formulated by regional governments have led to considerable improvements in regional GDE, supporting the work of Lin et al. (2022). Sustainable technologies can enable enterprises to strengthen the economy, protect the environment, and upgrade the efficiency of green development. Besides, some scholars (cf. Huang and Wu, 2021; Qi et al., 2022) have established ER as a critical moderator in facilitating the positive impact of trade openness on GDE. Third, due to the "threshold effect" led by environmental regulations, the impact of trade liberalization on the efficiency of urban green development exhibits a "U-shaped" characteristic of first inhibition and then promotion. In the current context, the proportion of the secondary and tertiary industries in the regional GDP (IS) had a substantial promoting effect on regional GDE in Chinese regions, with a positive IS coefficient of 1.12644. Some experts (e.g., Zhu et al., 2019) argue that industrial structure optimization and coordinated expansion, industrial market force mechanism, and transformation of development methods are beneficial for constructing mechanisms for safe pollutant discharge. Zhao et al. (2016), based on findings on the influence of the two dimensions of industrial structure adjustment (advanced industrial structure and rationalized industrial structure), concluded that the interaction between human capital and industrial structure adjustment is regarded as an essential supporting condition for improving the GDE. The second and third industry synergistic agglomeration impact on green development has a practical promotion effect. Fourth, the results confirmed the positive effect of FDI on GDE (0.03755). This outcome suggested that increased utilization of foreign investment funds has contributed to local governments' absorption of advanced green technologies. Also, it has helped in advancing production technologies and management models to promote the sustainable development and the improvement of GDE. Empirical studies have established that FDI can exert the spillover effect of technological innovation (Huang and Wu, 2021; Yue et al., 2022). Chinese regions opening up to the outside world can help them become the preferred investment

TABLE 6 Robustness test results: the dynamic panel difference GMM model.

Variable	Fixed-effects	DIF_GMM
LGIS	0.27494*** (0.028)	0.03291*** (0.003)
FAI	−0.05838 (0.041)	−0.05004*** (0.006)
ER	0.01777* (0.011)	−0.00541*** (0.001)
IS	1.12644*** (0.122)	−0.01800 (0.011)
FDI	0.03755*** (0.014)	−0.00117 (0.001)
L_1.GDE		0.72151*** (0.054)
L_2.GDE		0.17087*** (0.045)
_cons	−1.79868*** (0.349)	0.40027*** (0.060)
Observations	300	240
Arellano–bond (1)		p = 0.001
Arellano–bond (2)		p = 0.493
Sargan test		p = 0.647

Note: *, **, and *** represents level of significance at 10%, 5% and 1%, correspondingly. Abbreviation: LGIS, local government innovation support; FAI, provincial fixed asset investment; ER, total investment in industrial pollution control; IS, the proportion of the secondary and tertiary industries in the regional GDP; FDI, actual use of foreign direct investment.

destination for FDI, attract superior innovation infrastructure, resources, and high-quality human capital, and promote regional green development under the combined effect of FDI scale and quality.

4.2 Robustness check

Table 6 depicts the outputs of the dynamic panel difference GMM model adopted to test the robustness of the results. The robustness check indicated that the first-order lag term (0.72151) significantly improved the current GDE, benefiting from upsurges in LGIS, confirming prior findings (Gao and Li, 2021). With a decline in innovation input and the constraints of conditions, the GDE improvements in the second-order lag term (0.17087) began to weaken. Similarly, the fixed effects model showed that government innovation expenditures significantly contributed to the progress of GDE (0.27494). By comparing the results of the two estimators (i.e., the differential GMM model test and the system GMM model), it was concluded that no estimation bias existed, and the results of Table 5 were robust.

4.3 Heterogeneity analysis

As there are disparities among different Chinese regions and the effect of various factors (e.g., geography, humanities, and policies), comparing provinces at different levels together may lead to biased test results, i.e., varying LGIS to GDE impact across the different regions in China (Hu and Wu, 2019). Thus, this paper divided China into three regions (East, Middle, and the West) based on province location to conduct a heterogeneity analysis. The results in Table 7 showed that the GDE of the second lag period in the East (0.63684) and Middle (1.08824) regions of China had significantly influenced the GDE of the current period. In other words, the geography, resources, and economic foundations of regions have played a significant role in assisting local governments in promoting green development in the East and Middle regions of China. Song M et al. (2021) also confirmed that the interaction among regional industrial upgrading, government innovation support, and energy eco-efficiency has nonlinear characteristics, even though government innovation support could promote the optimization and upgrading of regional industrial structure. The authors stated that energy eco-efficiency has a pulling effect on government innovation support in China. In contrast, the current analysis revealed that the GDE in the first period (L_1 = 0.84392) in the West region was relatively weak in promoting GDE compared to the East and the Middle region, reflecting a more pronounced gap across regions. Yang et al. (2022) reported that capital mismatch had inhibited the further improvement of GDE in the Middle and East regions of China, while the West regions demonstrated weak progress. The results of the sub-regional tests indicated that the lagged first-order GDE in the East, Middle, and West regions have contributed to the current period.

Finally, the mean values of LGIS expenditure and GDE from 2010–2019 were taken as the sample to present the spatial distribution pattern of LGIS and GDE. The change characteristics were analyzed by combining ArcGIS mapping software. The results are shown in Figure 1. To summarise, government innovation expenditure shows an obvious distribution pattern in the East, middle, and West regions, moving from the Eastern coastal region to the interior. Benefiting from its location and solid economic foundation, the East region appears ahead of the inland region in government innovation expenditure, in which the Yangtze River Delta region has formed a clustering phenomenon. The distribution pattern of GDE resonates with the level of LGIS expenditure.

5 Conclusion and policy recommendations

This study initially attempted to explain the interaction between LGIS, GDE, and GDE, along with FAI, ER, IS, and FAI as control variables. The Super-SBM model was used to measure the provincial-level regional GDE in China, including factors such as energy consumption, capital, labor input, and undesired output. The main techniques included the dynamic

TABLE 7 Sub-regional test results: dynamic panel system GMM model.

Variable	East region	Middle region	West region
LGIS	0.09641*** (−0.033)	0.15907** (−0.066)	0.02112 (0.019)
FAI	0.41248* (−0.214)	0.38804 (−0.325)	−0.06228*** (0.020)
ER	−0.01340*** (−0.005)	−0.00186 (−0.005)	0.00651 (0.004)
IS	0.23240** (−0.101)	1,09692 (−0.766)	0.09315 (0.105)
FDI	−0.05256** (−0.021)	0.12102 (−0.105)	0.00598*** (0.002)
L_1.GDE	−0.21579 (−0.556)	−1.35756 (−0.973)	0.84392*** (0.224)
L_2.GDE	0.63684* (−0.367)	1.08824** (−0.457)	0.05308 (0.197)
_cons	−3.53119** (−1.751)	−6.84298** (−3.31)	0.32299* (0.188)
Observations	240	240	240
Arellano–bond (1)	p = 0.0147	p = 0.0801	p = 0.0895
Arellano–bond (2)	p = 0.7359	p = 0.1963	p = 0.651
Sargan test	p = 1.0000 _	p = 1.0000	p = 1.0000

Note: *, **, and *** represents level of significance at 10%, 5% and 1%, correspondingly. Abbreviation: LGIS, local government innovation support; FAI, provincial fixed asset investment; ER, total investment in industrial pollution control; IS, the proportion of the secondary and tertiary industries in the regional GDP; FDI, actual use of foreign direct investment.

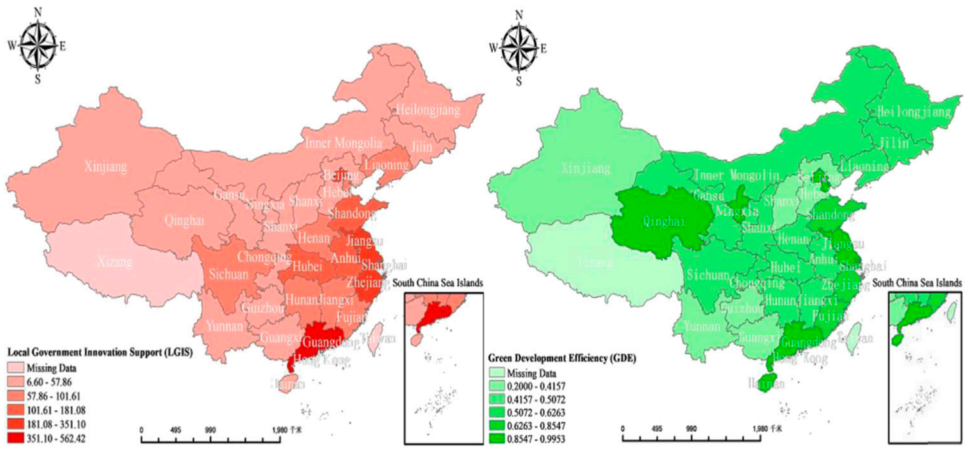

FIGURE 1
Spatial distribution pattern of LGIS expenditure and GDE.

panel system GMM model (empirical analysis), the difference GMM model (robustness check and heterogeneity analysis), and the ArcGIS mapping software for mapping LGIS and GDE patterns across the different regions in China. First, the analysis showed that LGIS had improved the efficiency of regional green development across the East, Middle, and West regions of China. The analysis confirmed that innovative technologies application (i.e., increasing science and technology expenditure) had reduced undesired outputs, thereby improving the GDE in the regions. Unlike the first-order lag period, the positive effect of LGIS on GDE was significantly low in the second-order lag period due to the instability of local government science and technology spending and policy formulation. The current findings highlight that local governments are more inclined to rapid economic development rather than improving the quality of economic development and environmental protection.

Second, the current results offer a few possible explanations for why FAI had restricted the further improvement of GDE. For instance, local governments have increased the emission of pollutants in activities, including infrastructure construction, road renovations, and large-scale investments, consequently failing to GDE. Due to the "crowding out" effect, the local governments have supported and encouraged enterprises to

invest more in energy conservation, emission reduction, and environmental protection, but inconsistent support has prompted short-term regional GDE. Enterprises cannot continue to invest more money to achieve the effect of energy conservation and emission reduction, which could inhibit regional GDE in the long run term. As factors, including ER, IS, and FDI, play a crucial role in the green development of different regions, local governments in China should pay more attention to these aspects and promote sustainable and healthy regional economic development by optimizing the policy system and enhancing institutional construction. Third, the data indicated that the effects of LGIS on GDE differ across different regions, i.e., LGIS has generated superior GDE outcomes in the economically developed East and Middle regions of China, but its effect in the economically deprived West regions is insignificant. The regional distribution pattern of LGIS level and GDE progress in China's two economically developed regions (East and the West) are highly similar, unlike the East region, which significantly differs from the rest.

The following policy suggestions are put forward based on the current conclusion. Firstly, local governments are encouraged to build a green, low-carbon, circular, and government-led technological innovation economic system while simultaneously driving green public and private sector development. They should increase investment in corporate technology incubation and research and development, create a market-oriented green technology innovation system and achieve economic development. At the same time, local governments should introduce policies, frameworks, and mechanisms to protect the ecology and improve the efficiency of green development. All regions should strive to enhance the competitiveness of green and low-carbon industries. Secondly, local governments should strengthen ER, accelerate the establishment of legal systems and policy orientations for green production and consumption, and combine formal regulations with informal regulations to jointly promote the efficiency of green development. In all regions, provincial and city governments should consistently pursue reform and innovation support. They should promote the optimization and upgrading of IS while building a green and low-carbon modern industrial system to stimulate the vitality of urban green development. The technological spillover effect brought by FDI plays a crucial role in green development. The smart utilization of FDI should focus on achieving green and sustainable economic development and strengthening local enterprises through knowledge, technology, and skills. Thirdly, regional governments should implement differentiated green development policies and green transformation strategies according to local conditions, strengthen strategic thinking of regional integration, design and coordinate development plans, and fully release the green development potential empowered by LGIS.

The chief limitation of the article is that the study findings represent local governments in China, focusing on single-country and lack comparisons with other regions or countries. Cross-country comparisons in future studies are encouraged to unwarp the complexities in the LGIS-GDE nexus. Second, LGIS is a dynamic and complex process, so its effect (promote or inhibit) on GDE may involve changes in other factors (e.g., regional GDP, regional degree of openness in economies or society, per capita income, and economic policy) not included in this study. Thus, future researchers can explore these factors in the current model. Third, the study did not capture the mechanisms or pathways through which LGIS effect GDE in each region. The article only explains the linear relationship between some selected factors, i.e., FAI, ER, IS, FDI, and GDE. Future research can use nonlinear techniques to investigate LGIS-key factors-GDE nexus.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

SK: writing. UK: proofreading. MK: supervision. TS: basic idea, conceptualization, writing initial draft, methodology, and statistical software. XW: literature review, policy recommendations, and revision. YN: introduction, conclusion, and revision.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Dynamic Role of Green Energy Efficiency and Climate Technologies in Realizing Environmental Sustainability: Fresh Insights From China

Zuoming Liu[1], *Changbo Qiu*[1]* *and Libo Zhu*[2]

[1]School of Business and Management, Jilin University, Changchun, China, [2]School of Statistics, Jilin University of Finance and Economics, Changchun, China

Amid rising industrialization and economic progress, China has shown exponential growth in energy and fossil fuel consumption; therefore, it faces great global concern and widespread criticism for energy and fuel conservation to reduce fuel-related emissions. In addition, the recent spread of COVID-19 instigates the impact of environmental pollution, exaggerates the virus intensity, and lowers people's immunity due to poor air quality. Therefore, this study explored the role of green energy efficiency and climate technologies in achieving carbon neutrality in China using an advanced quantile autoregressive distributed lag (QARDL) framework. The results indicated that green energy efficiency and climate technologies significantly reduce environmental pollution across all quantiles in the long run. In contrast, urbanization enhances environmental degradation at lower and higher emissions quantiles, while trade only promotes environmental pollution at lower quantiles. These findings suggested using alternative energy sources and carbon-reducing technologies to ensure a sustainable environment.

Keywords: green energy efficiency, renewable energy, climate technologies, environmental pollution, COVID-19

Edited by:
Asif Razzaq,
Dalian University of Technology, China

Reviewed by:
Yunpeng Sun,
Tianjin University of Commerce, China
Hafiz Waqas Kamran,
Iqra University, Pakistan

Correspondence:
Changbo Qiu
lzmhero_@126.com

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INTRODUCTION

Energy is vital for economic stability, and its demand has continuously grown worldwide (Asiedu et al., 2021). However, its ecological implication has started from its exploration and exploitation and finally from its consumption (Osiyevskyy et al., 2020). Moreover, the rapid growth of industrialization caused the excessive use of energy and increased the divestment of fossil fuels (Pata, 2018; Sun et al., 2022a). The world's major industrial countries are dependent quite heavily on inevitably depleted fossil fuels. Getting control of the climate changes invariably, governments are now seeking ways to reduce the consumption of carbon-laden fuels (Ahmad et al., 2022; Atchike et al., 2022). For instance, these issues can be valuably responded to by reducing energy consumption, developing green energy sources, and improving energy efficiency (Razzaq et al., 2021a; Irfan et al., 2021; Sun et al., 2022b; Elavarasan et al., 2022).

Since 1978 after the reforms and opening up toward the sustainable path, China's economic growth has mainly depended on the high consumption of nonrenewable energy resources (Lu et al., 2019). The ongoing accelerated pace in China's total energy consumption accounts for almost 23.6% of the complete energy depletion of the world in 2018 (K. Dong F. et al., 2018; Lei et al., 2022) and

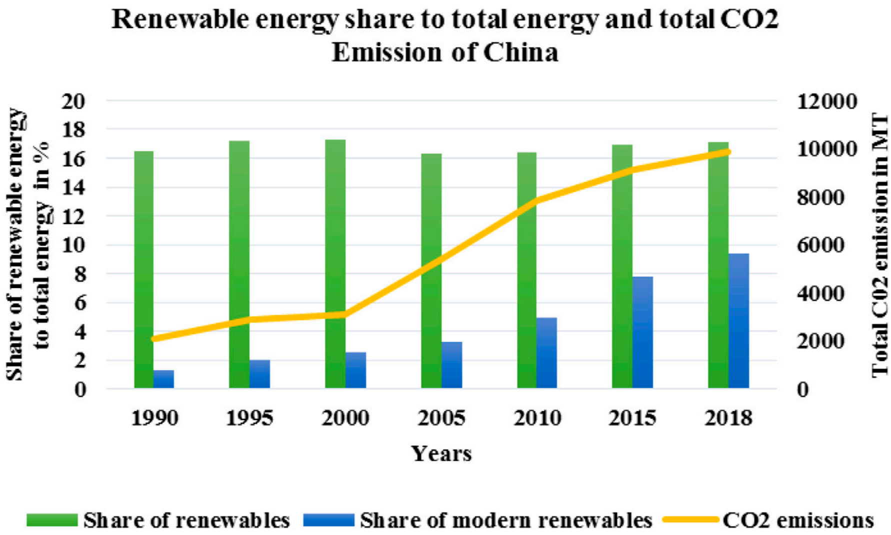

FIGURE 1 | Renewable energy share to total energy and total CO_2 emission of China. Source: IEA Sustainable Development Goal 7 https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2021.

contributed more than 34% of the net increase of global energy utilization. Moreover, the energy consumption growth rate reached 4.3% in China, which is relatively higher than the global average growth in energy consumption in 2018 (Liu et al., 2021a). Global energy growth is outpacing decarburization despite the positive progress of many countries whose economies have grown over the last decade, and their emissions have declined due to the replacement of energy-dense nonrenewable energy with green energy sources and the improvement in energy efficiency (reliance on eco-innovation) (Brown, 2021; Song et al., 2021; Fang et al., 2022; Sun and Razzaq, 2022). China is the largest energy consumer, and greenhouse gas emitter faces great global concern and widespread criticism for energy conservation and GHG emanation decline (Song et al., 2021; Yu et al., 2019; Sun et al., 2022b).

Green energy efficiency is necessary to meet the rapidly growing energy demand and the targets against climate change with sustainable development (Wu et al., 2021). In this regard, as per the Paris Agreement, China has set a target of 60–65% reduction in its emission intensity (the emission intensity is measured as the amount of GHGs released against the economic activity of per dollar) over 2005 levels in 2030 (P. Li and Ouyang, 2020; Miao et al., 2021). According to **Figure 1**, the share of renewable energy to the total energy is 17.11%, whereas the total CO_2 emission reached 9,876.5 MT in 2018. Moreover, according to the China Electric Power Yearbook for 2020, the current thermal and hydropower energy generation data state that hydropower contributes up to 68.9%; in contrast, thermal power is accounted for 17.8% of total power generation in China.

Energy efficiency refers to less consumption of energy resources while ensuring the same production level. It is the elimination of energy waste in production or any other economic activity (Liu et al., 2021b). According to the International Energy Agency (IEA), "Energy efficiency is key to ensuring a safe, reliable, affordable and sustainable energy system for the future. It is the only energy resource that every country possesses in abundance and is the quickest and least costly way of addressing energy security, environmental and economic challenges".

Improvement in green energy efficiency (GEE) ensures improved energy supply security, which is decisive for sustainable development (Murshed et al., 2020; Miao et al., 2022). Moreover, ramping up green energy efficiency by deploying green innovations, smart grids, and new green transport technologies contribute to curtailing greenhouse gas emissions, reducing the imported energy demand, and lowering the energy cost of households and the economy. Moreover, green energy efficiency has vast opportunities for each economic sector, such as manufacturing, transportation, real estate, and energy production, in terms of pollution control. China has significantly improved its industrial energy efficiency in the last couple of years by investing in technology innovations of RE resources (Irfan et al., 2020; Ling et al., 2021). However, there is still a significant demand and supply gap for which the improvement of GEE is the crucial step to reducing carbon intensity and energy protection.

Similarly, various studies have pronounced technology innovation as crucial for economic growth. However, these innovations boost not only financial actions but also spur environmental degradation (Chien et al., 2021a), whereas eco-innovation (as green innovation proxy) is a pivotal means of economic sustainability and an effective means to reduce the emanation of greenhouse gases (Ali et al., 2021). Eco-innovations (ECO) is "the adaptation of new concepts, ideas, and technologies for the procedural development of economic restructuring and optimization". The enhancement of ECO enables countries to transform the traditional economic structure into a more energy-efficient production structure (Chien et al., 2021b; Ding et al., 2021; Hu et al., 2022).

Most of the existing literature has explored the dynamic relationship between renewable energy and carbon emissions, such as Chen et al. (2019), Chien et al. (2021c), Lin and Zhu (2019), and Wang B. et al. (2018), energy efficiency (Yu et al., 2019; Wang et al., 2021; Chien et al., 2022), and eco-innovation and carbon emission (Afshan and Yaqoob, 2022; Chien et al., 2021a; Hsu et al., 2021; Jin et al., 2021) for China. However, no such study explains the role of GEE and ECO on CO_2 in China. As discussed earlier, China is a significant greenhouse gas emitter and nonrenewable and the largest energy consumer; thus, for China, the role of GEE and ECO is crucial to pursuing the environmental sustainability objective. Therefore, to respond to the gap, the current study explores the role of green energy efficiency (GEE) and eco-innovation (ECO) on environmental pollution (CO_2) in China along with two control variables such as urbanization (URB) and trade (TRD). Moreover, the study's outcomes will provide insights for establishing better policies.

Moreover, to examine the relationship between GEE, ECO, URB, and TR and CO_2 more precisely, the study employs the QARDL (quantile autoregressive distributed lag) method. This method of estimations is advantageous over the other traditional regression analysis methods in many ways; for instance, this method considers the magnitude, such as quantiles to get parameter estimates and elaborates the association among the study variables in the long run and short run. These estimates provide more reliable, accurate, and detailed relationships. Moreover, the QARDL method incorporates the potential asymmetric and nonlinear relationship between the GEE, ECO, URB, and TR and CO_2 (Cho et al., 2015; Hsu et al., 2021; Ji et al., 2021; Jin et al., 2021; Sharif et al., 2020; Song et al., 2021). Thus, based on these motivations, the study incorporated the QARDL as the most effective method for the analysis.

The study's outcomes illustrate that the GEE and ECO significantly reduce carbon emissions at all pollution levels in the long run. At the same time, URB enhances carbon emission at lower and significant pollution levels in the long run, while TRD only harms the quality of the environment at the low level of pollution in China in the long term. However, for the short-term impact, it has been observed that GEE significantly decreases CO_2 at a low pollution level while ECO drops CO_2 significantly at a high pollution level. At the same time, URB promotes CO_2 at all levels of pollution, while TRD only promotes CO_2 at the low level of pollution.

The remaining part of the study is structured as follows: section 4 discusses the relevant studies that already explored relationships among the study variables. Section 3 defines the variables data source and the QARDL model from a theoretical perspective. Moreover, **section 4** interprets the outcomes of all incorporated tests. Section 5 summarized the analysis in the form of a conclusion and suggested some policy recommendations based on that conclusion.

LITERATURE REVIEW

Recent studies have a growing concern to explore the ways to reduce environmental pollution and obtain economic and environmental sustainability. As discussed earlier in the introduction section, various recent studies have accounted for different driving factors to control environmental degradation in China, for instance, RE resource consumption (Khattak et al., 2020; Godil et al., 2021), technological innovations (Shahbaz et al., 2020), green innovation (Hu et al., 2022), industrialization (Dong K. et al., 2018; Wang and Su, 2019), globalization (Ling et al., 2021), economic growth (Liu et al., 2019), trade openness (Liu et al., 2021a), environmental regulations (Li et al., 2022), environmental taxes (Hsu et al., 2021), tourism (Razzaq et al., 2021a), FDI inflows (Shahbaz et al., 2020), and financial development (Godil et al., 2020). It has been observed that the existing literature does not provide any single study which has addressed the role of green energy efficiency on environmental degradation in China. Therefore, the current study incorporates the variable of green energy efficiency first time to investigate its impact on environmental pollution in China. Moreover, this section compiles the existing literature on the study variables.

Green Energy Efficiency and Environmental Pollution

Renewable energy implies a decrease in nonrenewable energy consumption and mitigates the detrimental effect of environmental pollution (Razmjoo et al., 2021). Similarly, energy efficiency is also decisive in controlling carbon emissions (Qin et al., 2020; Irfan et al., 2022); therefore, green energy efficiency is considered the foremost tool to mitigate the adverse effects of greenhouse gases (GHGs). There is no such study that accounts for the green or renewable energy efficiency specifically to analyze. However, few studies incorporate renewable energy and energy efficiency separately to examine their diminishing role in carbon emission (Bhadbhade et al., 2019; Chien et al., 2022; Dong F. et al., 2018; Guo and Pachauri, 2017; Huang et al., 2018; Shao et al., 2019; Wang et al., 2021; Zhang et al., 2017).

Gökgöz and Güvercin (2018) have evaluated the role of the GEE on the energy security of EU countries from 2004 to 2014. The study explored that renewable energy efficiency decreases with the increase in energy production; therefore, the emission level of GHGs is enhanced. Murshed (2020) has studied the indirect impact of ICT trade on CO_2 emission through energy efficiency in the South Asian economies. The outcomes of the panel estimation of CUP-FM suggested that the ICT trade enhances renewable energy consumption, leading to improved energy efficiency and environmental quality.

Furthermore, Akram et al. (2021) have also examined the impact of RE and energy efficiency on CO_2 for 66 underdeveloped countries. The findings of the quantile regression method are based on the panel data from 1990 to 2014 and endorse the negative impact of energy efficiency (EE) on CO_2 at high quantiles. In addition, Liu et al. (2021b) have investigated provisional policies' role in China's energy efficiency. The findings stated that the EE is the only way through which China can achieve its predefined goal of 2030 to reduce its fossil fuel consumption; therefore, by adopting low carbon technologies, China can rely more on renewable energy

TABLE 1 | Variable description.

Variable and symbol	Variable description	Variable data source
Dependent variable		
Environmental pollution—CO_2	Per capita CO_2 emission measured in metric tons per capita	World Bank (2020)
Independent variables		
Green energy efficiency—GEE	Measured as the ratio between renewable energy and GDP	British Petroleum
Eco-innovation—ECO	Measured as the number of registered green patents in the whole year	OECD
Urbanization—URB	Measured as the number of residents in the urban area or urban population	OECD
Trade—TRD	Measured as trade openness (Import + Export/GDP)	OECD

resources and improve its energy efficiency (Khan et al., 2021; Khan et al., 2022).

Another study by Li and Ouyang (2020) has explored the factors in the heavy industrial sector of china that can mitigate carbon emissions without compromising economic growth. The result of the study exhibited that clean energy consumption and the technological progress of EE can reduce the carbon intensity in China. Moreover, the studies by Bhadbhade et al. (2019), Chien et al. (2022), and Huang et al. (2018) have also found a negative association between energy efficiency and CO_2 (Irfan et al., 2019).

TABLE 2 | Results of descriptive statistics.

Variable	GEE	ECO	URB	TRD	CO_2
Mean	0.498	4.088	10.958	1.404	3.830
Minimum	0.428	3.265	3.000	1.147	2.210
Maximum	0.560	6.037	14.000	2.935	4.600
Standard deviation	0.045	0.851	3.076	0.189	0.250
Skewness	0.176	1.222	0.695	0.373	0.764
Kurtosis	0.603	0.063	0.175	0.041	0.883
Jarque–Bera	18.076	15.976	12.613	15.476	24.111
Probability	0.000	0.000	0.000	0.000	0.000

Source: author estimation

Nexus Between Eco-innovation and Environmental Pollution

The association between ECO and CO_2 has been analyzed by a vast number of studies (Khan et al., 2020; Chien et al., 2021b; Ding et al., 2021; Ji et al., 2021; Jin et al., 2021; Tao et al., 2021). ECO motivates the economies to adopt new technologies to reduce environmental pollution. It reduces traditional energy resource consumption by providing alternate solutions and controlling CO_2 (Ji et al., 2021; Hu et al., 2022). Ali et al. (2021) have analyzed the role of ECO to mitigate CO_2 in the top 10 GHG emitters of the world and found that the ECO negatively influences carbon emanation and enhances economic activities by promoting renewable energy resource consumption. Similarly, the outcomes of the study presented by Shahbaz et al. (2020) support the findings of previous studies and consider the ECO as the primary tool to control CO_2 in highly industrial economies.

Moreover, the finding of (Ji et al., 2021) study has redefined the impact of ECO on environmental quality. They explored that the highly fiscal decentralized economies experienced a significant decline in CO_2 in the long term due to ECO. Ding et al. (2021) have investigated the influence of ECO on CO_2 in G-7 countries from 1990 to 2018. The outcomes of the CS-ARDL estimator also endorse the mitigating impact of ECO on CO_2.

MATERIALS AND METHODS

Data Description

The current study attempted to explore the impact of GEE and ECO to control CO_2 in China; therefore, the study incorporates the data from 1995 to 2019 on carbon emission (CO_2) as dependent variables, green energy efficiency (GEE) and eco-innovation (ECO) as focus variables while the urbanization (URB) and trade (TRD) are taken as control variables. **Table 1** illustrates the details of the explained variables. This has been converted from annual to quarters following the match sum approach (Razzaq et al., 2021b). **Table 2** presents the detail descriptive statistics of model variables.

Theoretical Background and Methodology

The study intended to investigate the dynamic long-run correlation between green energy efficiency (GEE), eco-innovation (ECO), urbanization (URB), trade (TRD), and environmental pollution (CO_2) for China by employing the QARDL model introduced by Cho et al. (2015) which helps to test the long-run equilibrium effect of all variables on carbon emission across the different grids of quantiles. The relationship between the socioeconomic variables is not necessarily linear, as assumed by the general regression method of ordinary least squares (OLS) (Liu et al., 2021a; Razzaq et al., 2021a). Moreover, another econometric method known as ARDL (autoregressive distribution lag) considers the different order cointegration and determines only the cointegration among variables. Therefore, to alleviate the analysis's methodological deficiencies, this study incorporates the QARDL method.

QARDL method determines the nonlinear or asymmetric long-run and the short-run association between the variables over the different conditional distributions of the variables (Song et al., 2021). Moreover, for the robustness analysis and the time-varying integration, the study applied the Wald test, which allowed examining the dependency of parameters and steadiness of the integrated coefficient in each quartile (Godil et al., 2021; Song et al., 2021; Razzaq et al., 2022b). The ARDL model for this study is given as follows:

$$CO_{2t} = \alpha + \alpha_{GEE}\, GEE_t + \alpha_{ECO}\, ECO_t + \alpha_{URB}\, URB + \alpha_{TRD}\, TRD_t + \mu_t. \quad (1)$$

Equation 1 represents CO_2 as environmental pollution, GEE as the green energy efficiency, URB as the urban population or urbanization, and TRD as trade openness of China, whereas t represents the time dimension and the coefficients of variables illustrated as $\alpha_{GEE} = \frac{CO_{2t}}{GEE_t}$, $\alpha_{ECO} = \frac{CO_{2t}}{ECO_t}$, $\alpha_{URB} = \frac{CO_{2t}}{URB_t}$, $and\ \alpha_{TRD} = \frac{CO_{2t}}{TRD_t}$, while μ_t is defined as an error term in the model. Renewable energy implies a decrease in nonrenewable energy consumption and mitigates the detrimental effect of CO2 (Razmjoo et al., 2021). Similarly; energy efficiency is also decisive in controlling carbon emission (Qin et al., 2020); therefore, the GEE is expected to have a negative coefficient $\alpha_{GEE} = \frac{CO_{2t}}{GEE_t} < 0$ to describe the relationship with environmental pollution.

According to Su et al. (2021) and Sharif et al. (2020), technological innovations accelerate fossil fuel consumption, improve economic growth, and enhance environmental degradation. However, eco-innovation reduces the traditional energy resource consumption by providing alternate solutions and controlling CO_2 (Ji et al., 2021; Hu et al., 2022); therefore, the ECO is expected to reduce CO_2, such as $\alpha_{ECO} = \frac{CO_{2t}}{ECO_t} < 0$. Similarly, trade openness enhances production activities, leading to more energy consumption and becoming the reason for more carbon emissions (Lv and Xu, 2019). However, being an emerging country in China, trade attracts FDI inflows, enhancing investment opportunities in energy efficiency projects and reducing carbon emissions (Q. Wang and Zhang, 2021). Therefore, the TRD is expected to have a positive $\alpha_{TRD} = \frac{CO_{2t}}{TRD} > 0$ or a negative $\alpha_{TRD} = \frac{CO_{2t}}{TRD_t} < 0$ coefficient link with CO_2. On the contrary, China has currently transformed into a high-quality urbanization mode (Qi et al., 2020) where the services and free-market boost the economic growth and lead to high carbon emissions. Hence, the expected outcome is the positive $\alpha_{URB} = \frac{CO_{2t}}{URB_t} > 0$ coefficient of urbanization, with regards to carbon emission or environmental pollution (Afridi et al., 2019).

RESULTS AND DISCUSSION

Table 1 illustrates the outcomes of the descriptive analysis of environmental pollution (CO2), green energy efficiency (GEE), eco-innovation (ECO), urbanization (URB), and trade (TRD). It has been observed that GEE has the lowest mean value of 0.498 between the range of 0.428–0.560. In comparison, URB has the highest mean value of 10.958, which lies between 3.00 and 14.00. Similarly, the highest standard deviation value is also demonstrated by URB, which is 3.076, while the least standard deviation of 0.045 is observed for GEE. Moreover, the Jarque–Bera statistic evaluates the normality among the variables. The results illustrated that all the variables meet the significance level of 1% and endorse that the data distribution is not normal. Therefore, this study is allowed to apply the QARDL method to obtain the regression estimates of the selected data (Sharif et al., 2020; Razzaq et al., 2021b; Chien et al., 2021c; Godil et al., 2021; Song et al., 2021).

TABLE 3 | Results of the unit root test.

Variable	GEE	ECO	URB	TRD	CO_2
ADF (level)	0.375	−1.275	−2.094**	−0.995	−1.739*
ADF (Δ)	−3.572***	−4.048***	−3.668***	−4.583***	−6.583***
ZA (level)	−1.048	−2.586	−0.587	−2.409	1.436
Year	2012 Q1	1999 Q4	2006 Q1	2015 Q1	2010 Q2
ZA (Δ)	−6.707***	−5.996***	−5.281**	−7.021***	−11.584***
Year	2016 Q4	2016 Q4	2008 Q3	2015 Q4	1997 Q1
Source: author estimation					

*Notes: For stationarity, the values are specified in the matrix of the ADF and ZA. ***, **, and * indicate a level of significance at 1, 5, and 10%, respectively.*

In the time-series data, it is crucial to ensure the integration order of the series before applying the QARDL model for estimations (Razzaq et al., 2021c; Song et al., 2021). Therefore, this study conducted the ZA (Zivot–Andrew) and ADF (Augmented Dickey–Fuller test) unit root tests to determine whether the time series data are stationary. However, the ZA test has more importance because it considers the structural break. **Table 3** presents the estimates of the ADF and ZA test, which affirm the non-stationarity of variables at the level. However, ZA and ADF test results reject the null hypothesis and endorse all variables' stationarity at the first difference at 1 and 5% significance levels. Based on these results, it has been assumed that the QARDL is the most appropriate method for estimations that account for the structural break, nonlinearity, and dynamic trend in the data (Sharif et al., 2020; Godil et al., 2021).

Table 4 illustrates the estimates of the QARDL methods. The test outcomes revealed the interaction between the GEE, ECO, URB, TRD, and CO_2. Moreover, the parameter of ECM or the value of ρ^*, also known as the parameter of the speed of adjustment, is negative and significant at the low, middle quantile (0.05–0.50), and high quantile (0.80–0.95) and proves the presence of the reversal toward the equilibrium in the long run between the selected variables. The nexus between GEE-CO2 is supposed to be negative in China because the green energy efficiency reduces carbon emission. In the last couple of years, China has heavily invested and subsidized various green energy projects such as FIT schemes and the subsidies for Solar PV installation, which has enhanced the green energy efficiency to work as a catalyst to reduce CO2. In the long run, the coefficient value of GEE is negative and significant across all quantiles, which proves that energy efficiency is used as the appropriate tool to curb environmental pollution. The finding is supported by the recent studies (Chien et al., 2022; Gökgöz and Güvercin, 2018; Li et al., 2022; Xu et al., 2021; Zhou et al., 2018).

Similarly, the results from **Table 4** revealed that the ECO has a significantly negative association with CO_2 at all quantiles in the long run which has proven that ECO is the adaptation of advanced technology to prevent the waste of energy resources, promote a green economy, and ultimately control carbon emission. Eco-innovation is considered the main component of policy formulation related to environmental sustainability. It reduces the pollution of the

TABLE 4 | Long-short run estimates of quantile ARDL estimations.

Quantile (τ)	Constant	ECM	Long-run estimates				Short-run estimates						
	$\alpha_*(\tau)$	$\rho_*(\tau)$	$\alpha_{GEE}(\tau)$	$\alpha_{ECO}(\tau)$	$\alpha_{URB}(\tau)$	$\alpha_{TRD}(\tau)$	$\phi_1(\tau)$	$\omega_0^{GEE}(\tau)$	$\omega_1^{GEE}(\tau)$	$\gamma_0^{ECO}(\tau)$	$\gamma_1^{ECO}(\tau)$	$\theta_0^{URB}(\tau)$	$\delta_0^{TRD}(\tau)$
0.05	0.109	−0.084***	−0.510***	−0.103***	0.355*	0.669**	0.449***	−0.039***	−0.036	−0.111	−0.044	0.007*	0.249***
	(0.073)	(0.017)	(0.021)	(0.019)	(0.203)	(0.281)	(0.081)	(0.010)	(0.298)	(0.149)	(0.794)	(0.004)	(0.075)
0.10	0.277***	−0.220***	−0.461***	−0.125***	0.355	0.610**	0.404***	−0.039***	−0.025	−0.178	−0.052	0.007***	0.124***
	(0.055)	(0.044)	(0.038)	(0.037)	(0.222)	(0.270)	(0.050)	(0.010)	(0.299)	(0.288)	(0.496)	(0.002)	(0.040)
0.20	0.087**	−0.258***	−0.383***	−0.129***	0.532**	0.771**	0.486***	−0.039***	−0.002	−0.207	−0.022	0.007***	0.124***
	(0.037)	(0.029)	(0.041)	(0.025)	(0.250)	(0.270)	(0.045)	(0.012)	(0.259)	(0.139)	(0.430)	(0.002)	(0.041)
0.30	0.095**	−0.294***	−0.352***	−0.144***	0.177	0.357**	0.505***	−0.039**	−0.002	−0.178	−0.044	0.007**	0.198***
	(0.036)	(0.028)	(0.051)	(0.025)	(0.261)	(0.160)	(0.060)	(0.020)	(0.199)	(0.139)	(0.397)	(0.003)	(0.042)
0.40	0.139***	−0.112***	−0.302***	−0.141***	0.355	0.119	0.515***	−0.313	−0.003	−0.170	−0.022	0.015***	0.171***
	(0.039)	(0.031)	(0.045)	(0.023)	(0.301)	(0.171)	(0.041)	(0.260)	(0.298)	(0.139)	(0.340)	(0.003)	(0.043)
0.50	0.152***	−0.122***	−0.250***	−0.217***	0.355	0.119	0.522***	−0.106	−0.006	−0.155	−0.022	0.044***	0.373
	(0.041)	(0.033)	(0.031)	(0.021)	(0.312)	(0.201)	(0.052)	(0.301)	(0.199)	(0.189)	(0.304)	(0.003)	(0.282)
0.60	0.033	−0.033	−0.166***	−0.198***	0.355**	0.139	0.445***	−0.159	−0.009	−0.052	−0.015	0.067***	0.124
	(0.039)	(0.031)	(0.023)	(0.025)	(0.151)	(0.192)	(0.059)	(0.321)	(0.130)	(0.199)	(0.250)	(0.004)	(0.320)
0.70	−0.022	-0.016	−0.129***	−0.202***	2.128***	0.219	0.423***	−0.200	−0.002	−0.007	−0.007	0.007*	0.124
	(0.039)	(0.031)	(0.011)	(0.035)	(0.172)	(0.190)	(0.059)	(0.360)	(0.110)	(0.158)	(0.204)	(0.004)	(0.353)
0.80	−0.044	-0.413***	−0.113***	−0.194***	1.125***	0.278	0.404***	−0.225	−0.005	−0.159*	−0.022	0.015***	0.124
	(0.042)	(0.033)	(0.015)	(0.046)	(0.195)	(0.190)	(0.061)	(0.415)	(0.099)	(0.088)	(0.197)	(0.004)	(0.393)
0.90	−0.076	−0.465***	−0.160***	−0.160***	0.801***	0.297	0.392***	−0.290	−0.006	−0.196**	−0.163	0.037***	0.498
	(0.047)	(0.038)	(0.018)	(0.030)	(0.208)	(0.172)	(0.053)	(0.420)	(0.091)	(0.081)	(0.160)	(0.005)	(0.430)
0.95	0.041	−0.522***	-0.240***	−0.175***	0.700***	0.233	0.402***	−0.303	−0.003	−0.226***	−0.252	0.022***	0.373
	(0.046)	(0.037)	(0.023)	(0.032)	(0.212)	(0.188)	(0.059)	(0.443)	(0.089)	(0.041)	(0.156)	(0.005)	(0.470)

Note: The table shows coefficient and standard error in brackets. Moreover, ***, **, and * indicate a level of significance at 1, 5, and 10%, respectively.
Source: author estimation.

environment with the mutual influence of the other economic variables, for instance, energy efficiency, renewable energy resources, and the development of infrastructure and production mechanisms to reduce the dependency on traditional energy recourse. The result is aligned with previous study results (Hu et al., 2022; Ji et al., 2021; Khattak et al., 2020; Shao et al., 2021).

Moreover, in the long run, the coefficient of URB shows a positively significant impact on CO_2 at the lowest quartile (0.05) at a 10% level of significance. In contrast, at a low quantile (0.2), the effect is positive but significant at 5% significance, while at the medium to high quartile (0.60–0.95), the influence is positive and highly significant, indicating that urbanization puts environmental pressure on the economy at a high pollution level. The increase in urbanization drives industrial production accelerating energy demand and infrastructure development, increasing the consumption of nonrenewable energy resources, and enhancing carbon emissions. The findings are supported by recent studies (Afridi et al., 2019; Huang et al., 2021; Wang and Su, 2019; Wang S. et al., 2018; Yao et al., 2021).

Similarly, the outcome for the nexus between TRD and CO_2 revealed that TRD has a positive impact on environmental pollution across all quantiles. However, it is significant only at a lower quantile (0.05–0.30) at the 5% level of significance, which exhibits that the increase in trade activities accelerates the carbon emission at the low pollution level in China. Trade has an essential role in enhancing production activities and economic development, leading to more energy consumption and becoming the reason for more carbon emissions in the long run. This result is in line with the existing studies (Du et al., 2019; Lv and Xu, 2019; Wang and Zhang, 2021), whereas the findings are contrary to the results of Wang and Zhang (2021).

On the other hand, to evaluate the short-run dynamics of analysis (**Table 4**), the study's findings revealed that variation in the present CO_2 is significantly enhanced by their previous level in China at all quantiles at a 1% level of significance. The accumulated variation of past and present GEEs negatively and greatly influenced the current CO_2 level at the lowest to low quantiles (0.05–0.20) at the 1% significance level. In comparison, at the middle quantile (0.30), the impact remains significantly opposite at 5% significance, indicating that green energy efficiency combats the carbon emission at a low pollution level in China in the short run. Similarly, the combined variation of previous and current ECO significantly reduces the current level of CO_2. However, this negative impact remains significant only at high to the highest quantile of (0.80) at 10%, (0.90) at 5%, and (0.95) at 1% level of significance, which has exhibited that the ECO can only help reduce the carbon emission at a high pollution level in the short run.

Moreover, in the short run, the past and present changes in URB significantly promote the current changes in CO_2 across all quantiles. In contrast, the cumulative variations in the current and previous TRD enhance the current level of CO_2 at the lowest to middle quantiles (0.05–0.40), representing that the TRD only increases the carbon emission at a low level of environmental pollution. Hence, the overall outcomes of the

TABLE 5 | Results of the Wald Test for the constancy of parameters.

Variable	Wald statistics [*p*-value]
ρ	3.978*** [0.000]
α_{GEE}	5.381*** [0.000]
α_{ECO}	4.004*** [0.000]
α_{URB}	7.481* [0.000]
α_{TRD}	5.559** [0.000]
φ1	6.039*** [0.000]
ω0	2.685** [0.048]
ω1	0.381 [0.931]
γ 0	7.904*** [0.000]
γ 1	0.478 [0.853]
θ0	3.094*** [0.001]
δ0	4.113*** [0.000]
Short-term cumulative effect	
ω^*	0.105 [0.999]
γ_*	1.094 [0.251]

Source: author estimation

QARDL model revealed that for China, the GEE and ECO have a negative influence, whereas URB and TRD have a positive influence on CO_2 in the long run and the short run at different pollution levels.

The Wald test results presented in **Table 5** confirm the long-run and short-run asymmetric associations of the GEE, ECO, URB, and TRD with CO_2. The outcomes to check the consistency or stability of the parameter revealed that the null hypothesis of the linearity of the speed of adjustment parameter has been rejected. Similarly, the hypothesis of long-run parameters consistency has also been rejected by the coefficients of α_{GEE}, α_{ECO}, α_{URB}, and α_{TRD}. These outcomes endorse that GEE, ECO, URB, and TRD have a high correlation with CO_2 in the long run. Moreover, in short-run dynamics, the collective effects of the past level of CO_2 on the current level of CO_2 are positive and significant, which also rejects the null hypothesis. The same results of the nonlinear and significant collective influences of GEE, ECO, URB, and TRD on CO_2 have been observed in the short run. Additionally, **Table 5** also demonstrated that the Wald test failed to reject the null hypothesis of parameter consistency for the cumulative effect of the GEE and ECO on CO_2 at lag 1.

CONCLUSION AND POLICY RECOMMENDATIONS

The current study investigated the relationship between GEE, ECO, URB, TRD, and CO_2 in China. The study employed the quarterly time-series data from 1995 to 2019 and applied the most appropriate and advanced quantile autoregressive distributed lag (QARDL) method to get detailed, reliable, and accurate estimates. The study's empirical finding reveals that green energy efficiency and eco-innovation significantly reduced environmental pollution in the long run. China has heavily invested in and subsidized various green energy projects such as FIT schemes and the subsidies for solar PV installation, which has enhanced the green energy efficiency to work as a catalyst to reduce environmental degradation. The negative association of the GEE with CO_2 proves that energy efficiency can be used as the appropriate tool to curb environmental pollution (Chien et al., 2022; Xu et al., 2021; Zhou et al., 2018).

Similarly, the negative correlation between ECO and CO_2 also endorses that the ECO is considered the main component of policy formulation related to environmental sustainability. It enhances the efficiency of renewable energy resources, prevents energy waste, and promotes a green economy by reducing carbon emissions (Khattak et al., 2020; Ji et al., 2021; Tao et al., 2021; Hu et al., 2022). At the same time, urbanization enhances environmental degradation at low and high quantiles. The increase in urbanization drives industrial production and accelerates energy demand and infrastructure development, leading to the increased consumption of nonrenewable energy resources and carbon emissions (Afridi et al., 2019; Huang et al., 2021). When trade or trade openness only promotes environmental pollution in low quantiles, an increase in trade activities accelerates and causes environmental degradation (Du et al., 2019; Wang and Zhang, 2021). However, the findings remain the same in the short run except for the green energy efficiency, which decreases CO_2 at a low quantile, and eco-innovation, which reduces CO_2 at a high quantile. Moreover, the study found bidirectional causality among all variables at all quantiles. Thus, it has been concluded that GEE and ECO are the most reliable ways to control CO_2 in China.

Based on the study's conclusion, the government of China should develop policies to promote green energy efficiency and eco-innovation for each sector of the economy. China has additional green energy efficiency potential, which has not yet been quantified due to the obstacles and barriers hampering the cost-effective technologies to improve green energy efficiency. By providing more incentives, the government of China can attract more private investors to boost the investment in green energy efficiency projects. Similarly, eco-innovation effectively promotes economic and environmental sustainability by breaking down the resources and environmental constraints. Therefore, implementing the environmental regulations enhances green energy efficiency, saves energy, and reduces carbon emission. Government and policymakers need to add green energy efficiency and eco-innovations in the planning of smart cities; they can construct green buildings and infrastructure to promote innovative heating, ventilation, and cooling system in urban areas to make more resilient cities. Similarly, optimal renewable energy resources and integrated energy services will make the production sector more intelligent and competitive.

Moreover, for the production sector, the authorities should also promote the investment in private venture capital in R&D related to improving green energy efficiency and eco-innovation by reducing the corporate taxes on energy-saving and energy management projects. Furthermore, the private venture capital will also support the startups to

improve green energy efficiency sector-wise. Despite the investment, there is also a need to create awareness and strong skills by knowledge sharing to obtain the maximum benefit of green energy efficiency in terms of business case investment and green energy efficiency business measures. In addition, the inclusion of green energy efficiency standards in the municipal regulations will help the local government adopt the energy efficiency measures to consider environmental sustainability in the city's expansion plans and new building construction.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary materials; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZL presented the research's idea and design, and CQ applied the model and drafted the manuscript.

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University of Agriculture, Peshawar,
Pakistan
Mahejabin Sayyad,
Agasti Arts, Commerce And Dadasaheb
Rupwate Science College, India

*CORRESPONDENCE
Muhammad Anees Khan,
lookanees123@gmail.com

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Applying artificial intelligence techniques for predicting the environment, social, and governance (ESG) pillar score based on balance sheet and income statement data: A case of non-financial companies of USA, UK, and Germany

Hassan Raza[1], Muhammad Anees Khan[1]*, M. S. Mazliham[2], Muhammad Mansoor Alam[2], Nida Aman[1] and Kumail Abbas[2]

[1]Bahria Business School, Bahria University, Islamabad, Pakistan, [2]Faculty of Computing and Informatics, Multimedia University, Cyberjaya, Malaysia

Due to globalization, environment, social, and governance (ESG) issues have gained importance over the last few decades. ESG is a worldwide issue, which clarifies that organizations throughout the world are lacking in contribution to the environment, society, and corporate governance characteristics for sustainable development. The problem of ESG spread over all stakeholders needs to be addressed. In this regard, rating agencies also have a close eye on ESG issues and have developed the methodology of score that aims to provide disclosure on ESG metrics which, in return, help investors and asset managers better differentiate between responsible and irresponsible companies. The ESG score has become an important tool among asset managers but is highly questioned in terms of reliability. The study objective was to develop machine learning algorithms to assess how balance sheet and income statement data impact the Thomson Reuters ESG score for non-financial public companies of USA, UK, and Germany from 2008 to 2020. In addition, the study also has an objective to assess which machine learning (ML) algorithm better predicts the ESG score using structural data, that is, return on assets (ROA), return on equity (ROE), earning per share (EPS), earnings before interest and taxes (EBIT), dividend yield, and net sales. The results concluded that balance sheet and income statement data are critical in explaining the ESG score, and the ANN algorithm outperforms with minimum RMSE and MAE values. All in all, the results of the study, based on the concept of artificial intelligence, bring suggestion for improvement to regulatory bodies, researchers, academia, practitioners, publicly listed companies around the globe, and last but not the least to the US, UK, and Germany markets. Moreover, it also provides suggestions for up-to-date compliance of ESG-relevant activities for boosting the firm performance.

KEYWORDS
ESG score, machine learning, prediction, sustainability, balance sheet

Introduction

Over the last two decades, ESG has significantly influenced businesses, stakeholders, and shareholders around the world and caused damage, including a decline in the worldwide reputations of companies, auditors, security analysts, regulators, and financial markets based on ESG compliance (Ball, 2009). Despite the effort made for minimizing the issue of ESG, they have not stopped (Vladu & Cuzdriorean, 2013). Moreover, due to lack of overall compliance with ESG issues, corporate frauds have been on the increase across the world in the form of false ESG reporting, environmental ignorance, and social embezzlement (MingChia, 2012). Ultimately, these accounting frauds and violations have created ripples in the corporate world. As a result, investors and other stakeholders have lost their trust and confidence in the ESG reporting processes and management teams (Hamid, Hashim, & Salleh, 2012). The previously discussed ESG issues have led to the global collapse of many high-profile businesses (Moncarz, Moncarz, Cabello, & Moncarz, 2006). In this regard, researchers used machine learning techniques to predict the firm performance and success based on ESG scores (Ahmed & Hamdan, 2015), which involves the automatic deduction of patterns in data. It is described as a program that learns to automatically accomplish a task rather than programmed explicitly. It has the ability to process a vast volume of data and extract meaningful information through different programming techniques. They are widely used nowadays for predicting or forecasting the stock market, commodity market, and foreign exchange market. The digital transformation journey is at the heart of the fourth industrial revolution, and analysts and decision-makers aim to make daily processes simpler and more efficient. The process of data gathering, analysis, planning, implementation, tracking and automation, and reporting can be overwhelming. Artificial intelligence is a major technological breakthrough that everyone is talking about its exciting potential. Artificial intelligence is described as a machine's ability to make intellectual human-like decisions and continue to improve. John McCarthy came up with the term "artificial intelligence" in 1956. Deep learning, natural language processing (NLP), machine learning, image recognition, sound recognition, cognitive computing, and enhanced intelligence are all terms used to explain artificial intelligence (Yaninen, 2017). Machine learning comprises the creation of models, especially statistical models that can be developed and predict outcomes. According to a recent Bank of America Corporation study, ESG investments based in the United States will grow the size of the US stock market over the next two to three decades. Data are becoming more readily available and of higher quality, which provide useful tools for analyzing sustainable investing. Artificial intelligence can swiftly reveal hidden risks and possibilities that traditional analysis may oversee. In a comparison of conventional techniques that are quickly becoming obsolete, artificial intelligence techniques may offer significant benefits to the world of finance, by automating certain tasks and boosting analytical capability. Artificial intelligence is a critical part of modern finance because it makes it cheaper, quicker, bigger, more available, profitable, and competitive in a variety of ways.

The benefit of this research is that the non-linearity and complexity of historical data require adoption of new technologies which better analyze the data because traditional statistical methodologies have various flaws that might put financial organizations at risk and negatively impact their performance (Chen Y. et al., 2021). The benefit of this research is that the ML technique predicts the future, while the old regression techniques estimate the data rather than predicting it.

On the other hand, the benefit of this research will contribute to minimizing the bad practices of ESG. As it is reported by the previous authors that sometimes ESG reports are unethical and executed to mislead the stakeholders and investors. Thus, it can be added that current research will for sure improve the services committed by companies to the stakeholders and will also improve the overall treatment and process based on the stakeholder's theory concept, which in turn will help in future research, thus developing the smart system. This research will for sure help in developing a new and latest idea with certain data diagnosis, treatments, and processes that could eventually help one in industry, academia, and scholar in the future.

This study will fill the exhibited gap of these variables (ESG and FFP), in the limited and incongruent literature on ESG and FFP by extending the previous conventional model to the novel artificial intelligence model. The problem statement and literature review sections, respectively, identify the literature gaps of the study. Moreover, as discussed previously in the problem statement, the ESG score and FFP in developing and emerging economies are in their infancy stage and have no exception for developed countries, that is, why working on the ESG score for development became very important. Although many previous academic researchers have contributed to knowledge of the ESG and FFP, however, through traditional methodology but in this study, we worked on ESG based on the latest novel methodology, that is, artificial intelligence based on machine learning techniques. The aim of the study was to sum up the gaps in the study depicted on the basis of the inclusive–exclusive theory with a wide range of different datasets for the latent period based on the machine learning technique for the ignored non-financial sectors. Therefore, the previously discussed gaps create a problem in understanding that rationalizes the need to continue research

using the latest data available in concerned company's annual reports.

Environment, social, and governance (ESG)

Environmental, social, and governance (ESG) are three key aspects in determining a company's long-term viability and ethical influence (Zheng et al., 2021a; Zheng et al., 2021b; Zheng et al., 2021c). An ESG score has become a popular phrase used by investors and in capital markets to assess a firm's behavior and determine a company's financial performance. ESG is an umbrella concept for firms and businesses that aim to generate favorable returns while simultaneously having a long-term influence on society, the environment, and the company's governance referred to as "sustainable investing" (Lei et al., 2021; He et al., 2022; Yao et al., 2022). It is based on the growing belief that environmental and social factors are increasingly impacting the financial performance of organizations. In other words, so-called "non-financial" risk becomes financial risk (Antoncic, 2020). Following the guidelines for responsible investments (PRI) in 2006, a collection of principles for incorporating sustainability aspects, ESG investing has formally entered mainstream investment discourse (Cantele et al., 2020). A variety of causes may be attributed to the increase in ESG investments. The business sector is growing more aware of social, labor, and human rights issues as supply chains become more complicated. The ESG score is determined by considering several factors for an environmental pillar, social pillar, and governance pillar (Choi et al., 2021; Yang et al., 2022; Zhao and Wang 2022). Greenhouse gas emissions, deforestation, waste material and pollution, climate change, and resource depletion are all factors that impact a company's environmental pillar. Equal treatment of all corporate employees, including gender concerns, health and safety, job security, and human rights is a prevalent topic related to the social side of sustainability (Cardillo and Longo, 2020). Tax planning, executive remuneration, board diversity, political donations, corruption, lobbying, and bribery are among the topics that focus on the governance side of sustainability. The fundamental question is whether AI technology can tell the difference between responsible and irresponsible businesses. For the years 2008–2020, the study observed the role of structural variables including balance sheet and income statement data as predictors of ESG scores of public corporations in the United Kingdom, the United States, and Germany using machine learning techniques. KNN, polynomial regression, naive Bayes, random forest, decision tree, support vector machine (linear), support vector machine (Rbf), and artificial neural networks are examples of supervised machine learning techniques used in the study. These algorithms were created using Thomson Reuters Refinitiv ESG scores to forecast the ESG score. A total of 300 non-financial enterprises from the technology and communication, chemical, fertilizer, pharmaceutical, power generation and distribution, textile, and cement industries were chosen for the study. After the initial data preprocessing stage, the dataset was partitioned into two subsets: a training set (3,120) for training the models and a testing set (780) for testing the models, totaling 3,900 rows. Testing data are used to evaluate the training algorithm progress. Although investing in environmental, social, and governance (ESG)-driven portfolios account for a sizable and rising share of global assets under management, quantitative methodologies for improving and standardizing ESG rating and portfolio creation remain neglected (Sokolov et al., 2021). Internal approaches and practices are currently being used to incorporate ESG concerns into institutions' business strategy, procedures, and risk management. Inconsistency and data scarcity, described as "a scarcity of relevant, comparable, reliable, and user-friendly data," threaten the validity of ESG risk measurements (EBA, 2020a). The major risk-based approaches depend on historical data and are analyzed with traditional statistical techniques. According to the EBA (2020b), traditional models do not integrate ESG aspects, and the majority of ESG risks are non-linear. The non-linearity and complexity of historical data require adoption of new technologies which better analyze the data. Traditional statistical methodologies have various flaws that might put financial organizations at risk and negatively impact their performance (Chen Y. et al., 2021).

Methodology of the study

Theory, sample, and data

The study used the computational learning theory, with the purpose to identify that which machine learning technique best predicts the ESG score. The computational learning theory refers to a formal mathematical framework that aims to quantify learning tasks and algorithms. It is also called "statistical learning theory." The basic purpose of the computational learning theory is to learn the machine learning algorithm and determine what is understandable. It will help us to know the required data sufficient for the training of a specific algorithm. This theory is related to the design and analysis of machine learning algorithms (association for computational learning). Thus, the study's overall concept is based on the computational learning theory, which is an area of theoretical computing that discusses the design of computer programs and their ability to learn, as well as the identification of computing limitations with machines (Chen et al., 2021a; Lei et al., 2021; Wu and Zhu 2021). The computational learning theory aids in posing and answering concerns about the performance of learning algorithms. Data were collected for non-financial public companies of USA, UK, and Germany for the period of

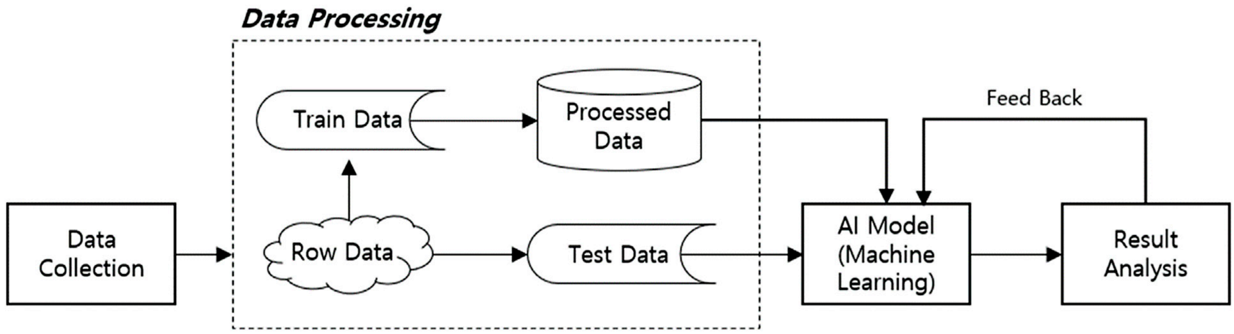

FIGURE 1
Proposed approach employed in the study as a block diagram (Arora and Kaur, 2020).

13 years from 2008 to 2020. Data were collected from Thomson Reuter's data stream. The population for the research study includes all non-financial companies listed on the New York Stock Exchange (NYSE), London Stock Exchange (LSE), and Frankfurt Stock Exchange. Moreover, we used a sample of 300 companies (100 from each country) from the non-financial sector in the United States, the United Kingdom, and Germany to establish the accuracy of ESG score prediction.

Variables used

Following accounting, market and sales performance was used for the prediction of the ESG pillar score:

ML technique and algorithms used

In this study, we used the supervised machine learning techniques like K-nearest neighbor (KNN), polynomial regression, naïve Bayes, random forest, artificial neural networks (ANNs), support vector machine (linear), and support vector machine (Rbf) algorithms to predict ESG score for non-financial companies of UK, USA, and Germany. The dataset for all six predictor features as shown in Table 1 were divided into train set and a test set for processing into the algorithm. The training set for the training model and a testing set for testing models has a ratio of 80:20, respectively. The whole dataset consisted of 3,900 rows, of which 3,120 rows (80%) were used for training and 780 rows (20%) were used for testing. Moreover, Python version 3.9.2 was used to assess values for ESG score prediction. Based on these prediction results, the criteria for selection of algorithms are based on the value of error terms; the less the error term, the higher the accuracy of the algorithm. Figure 1 depicts the proposed approach employed in the study as a block diagram (Arora and Kaur, 2020).

Performance evaluation of ML techniques

The performance of different supervised technique models used in this study was examined using two evaluation metrics, that is, root mean square error (RMSE) and mean absolute error. These measurements demonstrate how accurate our projections are and how much they differ from the actual data.

Root mean square error

RMSE is used for measuring the error rate of the regression models. It is an effective metric to compare the forecasting errors and is calculated as follows:

$$RMSE = \sqrt{\sum_{i-1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}},$$

where n is the number of test samples, y_i is the true target value of the *i*th sample, and y_i_cap is the forecasted value by the regressor.

TABLE 1 Variables used as predictor features for the ESG score.

Variable	Formula
Return of asset (ROA)	Net income/total assets
Return on equity (ROE)	Net income/total equity
Earnings before interest and taxes (EBIT)	Revenue – cost of goods sold – operating expenses
Earnings per share (EPS)	Net income/outstanding number of shares
Dividend yield (DY)	Annual dividend per share/current share price
Net sales	Gross sales – (sales discounts + sales allowance + sale returns)

10.3389/fenvs.2022.975487

Mean absolute error

MAE is a performance metric used to evaluate the performance of a regressor. It is calculated as follows:

$$\text{MAE} = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n},$$

where n is the number of test samples, y_i is the true target value of the *i*th sample and x_i is the forecasted value by the regressor and |.| represents the absolute value.

Analysis and results: ESG pillar score

Model evaluation based on RMSE and MAE using artificial intelligence models

Table 2 reports the results of different artificial intelligence models like *KNN*, *naive Bayes*, *SVM linear*, and *SVM RBF* that are based on the final evaluation of RMSE and MAE for selecting the best model. The relationship is built on the basis of the computational learning theory, which states that which machine learning technique best predicts the ESG score. Thus, we used four different techniques of machine learning as cited in Table 2. We run RMSE and MAE measurements on all the four models in order to select the best model out of these four based on the figures of error measurement for the variable ESG pillar score. The objective of the analysis was to select one of these four techniques, which will be the best and most accurate predictor of the ESG pillar score with less error value. We applied two types of SVM kernel functions for the prediction of the ESG pillar score. Considering the aforementioned phenomena, the result in Table 2 indicates that the values of RMSE are less in SVM RBF which is 0.1247 than SVM linear which is 0.4589, while the value of MAE is also less in SVM RBF, that is, 0.01882 than SVM linear which is 0.0598. If the prediction is based on RMSE and MAE, we can say that SVM RBF performs better than SVM linear. Similarly, subject to Table 2, the result obtained from the naive Bayes technique shows the value of 0.25266 for RMSE and the value of 0.7913 for MAE. In line with previous results, if we compare these results with SVM techniques, we can see that naïve Bayes is better than SVM linear based on less error values for RMSE; however, if we compare the values of naïve Bayes with SVM RBF, we can conclude that SVM RBF outperforms the naïve Bayes, and if the prediction is performed on MAE value, then SVM RBF is also better than naïve Bayes based on the value comparisons in Table 2. Likewise, the results of RMSE obtained from the KNN technique show the least values among the other three techniques. The RMSE value obtained from KNN is 0.1243 which is less than the RMSE value of naïve Bayes (that is, 0.25266), SVM linear (i.e., 0.4589), and SVM RBF (that is,

TABLE 3 Result of ESG pillar score error measurement using the ANN Technique.

Technique	RMSE	MAE
ESG pillar score ANN 1-2	0.2745	0.0117
ESG pillar score ANN 1-4	0.2894	0.0871
ESG pillar score ANN 1-8	0.9852	0.1122
ESG pillar score ANN 1-16	0.1444	0.2255
ESG pillar score ANN 1-32	0.1942	0.2356
ESG pillar score ANN 1-64	0.3245	0.6667
ESG pillar score ANN 1-128	0.3257	0.1013
ESG pillar score ANN 2-2	0.3985	0.2315
ESG pillar score ANN 2-4	0.2345	0.6419
ESG pillar score ANN 2-8	0.5713	0.9874
ESG pillar score ANN 2-16	0.3197	0.0253
ESG pillar score ANN 2-32	0.1285	0.0125
ESG pillar score ANN 2-64	0.1456	0.0127
ESG pillar score ANN 2-128	0.1287	0.0275
ESG pillar score ANN 3-2	0.1124	0.2369
ESG pillar score ANN 3-4	0.1245	0.1236
ESG pillar score ANN 3-8	0.1265	0.1235
ESG pillar score ANN 3-16	0.1258	0.1297
ESG pillar score ANN 3-32	0.1284	0.3975
ESG pillar score ANN 3-64	0.1278	0.1245
ESG pillar score ANN 3-128	0.1945	0.2356
ESG pillar score ANN 4-2	0.7536	0.3641
ESG pillar score ANN 4-4	0.2314	0.2314
ESG pillar score ANN 4-8	0.8974	0.9746
ESG pillar score ANN 4-16	0.1235	0.0485
ESG pillar score ANN 4-32	0.1244	0.0214
ESG pillar score ANN 4-64	0.0149	0.0124
ESG pillar score ANN 4-128	0.1865	0.0974
ESG pillar score ANN 5-2	0.1973	0.1975
ESG pillar score ANN 5-4	0.1973	0.0971
ESG pillar score ANN 5-8	0.6713	0.2451
ESG pillar score ANN 5-16	0.4597	0.0966
ESG pillar score ANN 5-32	0.0974	0.0971
ESG pillar score ANN 5-64	0.0931	0.0235
ESG pillar score ANN 5-128	0.5491	0.1245

TABLE 2 Result of error measurement using KNN, SVM linear, SVM RBF, and naïve Bayes.

Technique	RMSE	MAE
KNN	0.1243	0.1456
Naive Bayes	0.2526	0.7913
SVM linear	0.4589	0.0598
SVM RBF	0.1247	0.0188

TABLE 4 Result of ESG pillar score error measurement using hidden layer 1 with 2, 4, 8, 16, 32, 64, and 128 neurons.

Technique	RMSE	MAE
ESG pillar score ANN 1-2	0.2333	0.0117
ESG pillar score ANN 1-4	0.2223	0.0871
ESG pillar score ANN 1-8	0.8738	0.1122
ESG pillar score ANN 1-16	0.1444	0.2255
ESG pillar score ANN 1-32	0.1872	0.2356
ESG pillar score ANN 1-64	0.2244	0.6667
ESG pillar score ANN 1-128	0.6661	0.1013

TABLE 5 Result of ESG pillar score error measurement using hidden layer 2 with 2, 4, 8, 16, 32, 64, and 128 neurons.

Technique	RMSE	MAE
ESG pillar score ANN 2-2	0.3985	0.2315
ESG pillar score ANN 2-4	0.2345	0.6419
ESG pillar score ANN 2-8	0.5713	0.9874
ESG pillar score ANN 2-16	0.3197	0.0253
ESG pillar score ANN 2-32	0.1285	0.0125
ESG pillar score ANN 2-64	0.1456	0.0125
ESG pillar score ANN 2-128	0.1287	0.0275

0.1247). Similarly, the MAE value obtained by applying the KNN technique is 0.1456 which outperforms the results of naïve Bayes (that is, 0.7913). So, overall, we can say that from the aforementioned techniques in the table, the KNN technique outperforms the rest of the three techniques (naïve Bayes, SVM linear, and SVM RBF) based on RMSE, whereas SVM RBF outperforms the rest of the three techniques, that is, naïve Bayes, SVM linear and KNN based on MAE.

Model evaluation based on RMSE and MAE using artificial neural networks (ANNs)

Table 3 shows the results of ESG pillar score error measurement using the ANN Technique. The results are in the form of ANN, illustrated as ANN w-z means, where w represents the hidden layers and each layer comprises z neurons. Each neuron in the hidden layer receives input from all neurons of previous layers. We found prediction errors in every hidden layer with the help of these neurons. In our study, we predicted the results of the ANN technique by using five hidden layers and neurons up to 128. Here, we first discussed the results of each hidden layer individually with their multiple numbers of neurons and determined prediction results based on the number of neurons in the respective hidden layer. After that, the comparison will be made based on the hidden layer that which layer gives fewer error values.

Model evaluation based on RMSE and MAE using hidden layer 1

We have summarized the results of hidden layer 1 in Table 4. According to our error measurement criteria, hidden layer 1 with 16 neurons shows less prediction error than the other neurons within hidden layer 1. As illustrated in the aforementioned Table 4, the results show that RMSE and MAE values are less in hidden layer 1 with 16 and 2 neurons, that is, 0.1444 and 0.01177, respectively, than hidden layer 1 with 4, 8, 32, 64, and 128 neurons.

TABLE 6 Result of ESG pillar score error measurement using hidden layer 3 with 2, 4, 8, 16, 32, 64, and 128 neurons.

Technique	RMSE	MAE
ESG pillar score ANN 3-2	0.1945	0.2369
ESG pillar score ANN 3-4	0.1245	0.1245
ESG pillar score ANN 3-8	0.1265	0.1235
ESG pillar score ANN 3-16	0.1258	0.1297
ESG pillar score ANN 3-32	0.1284	0.3975
ESG pillar score ANN 3-64	0.1278	0.1236
ESG pillar score ANN 3-128	0.1124	0.2356

Model evaluation based on RMSE and MAE using hidden layer 2

Evaluation based on RMSE and MAE using hidden layer 2 is summarized in Table 5. According to our error measurement criteria, hidden layer 2 with 32 neurons shows less prediction error than the other neurons within hidden layer 2. As illustrated in the aforementioned Table 5, the results show that RMSE and MAE values are less in hidden layer 2 with 32 neurons, that is, 0.1285 and 0.0125, respectively, than hidden layer 2 with 2, 4, 8, 16, 64, and 128 neurons.

Model evaluation based on RMSE and MAE using hidden layer 3

The results of hidden layer 3, based on RMSE and MAE, are shown in Table 6 alongside the AI techniques and figures. According to our error measurement criteria, hidden layer 3 with 128 neurons shows less prediction error for RMSE value than the other neurons within hidden layer 3. As illustrated in aforementioned Table 6, the

TABLE 7 Result of ESG pillar score error measurement using hidden layer 4 with 2, 4, 8, 16, 32, 64, and 128 neurons.

Technique	RMSE	MAE
ESG pillar score ANN 4-2	0.7536	0.3641
ESG pillar score ANN 4-4	0.2314	0.2314
ESG pillar score ANN 4-8	0.8974	0.9746
ESG pillar score ANN 4-16	0.1235	0.0485
ESG pillar score ANN 4-32	0.1244	0.0214
ESG pillar score ANN 4-64	0.0149	0.0124
ESG pillar score ANN 4-128	0.1865	0.0974

TABLE 8 Result of ESG pillar score error measurement using hidden layer 5 with 2, 4, 8, 16, 32, 64, and 128 neurons.

Technique	RMSE	MAE
ESG pillar score ANN 5-2	0.1973	0.1975
ESG pillar score ANN 5-4	0.1973	0.0971
ESG pillar score ANN 5-8	0.6713	0.2451
ESG pillar score ANN 5-16	0.4597	0.0966
ESG pillar score ANN 5-32	0.0974	0.0971
ESG pillar score ANN 5-64	0.0931	0.0235
ESG pillar score ANN 5-128	0.5491	0.1245

results show that the RMSE value is less in hidden layer 3 with 128 neurons, i.e., 0.1124 as compared to hidden layer 3 with 2, 4, 8, 16, 32, and 64 neurons. But if we look at the MAE value, then we can see that it is less in hidden layer 3 with 64 neurons, i.e., 0.1236 as compared to hidden layer 3 with 2, 4, 8,16, 32, and 128 neurons.

Model evaluation based on RMSE and MAE using hidden layer 4

We have summarized the results of hidden layer 4 in Table 7. Therefore, according to our error measurement criteria, hidden layer 4 with 64 neurons shows less prediction error than the other neurons within hidden layer 4. As illustrated in aforementioned Table 7, the results show that RMSE and MAE values are less in hidden layer 4 with 64 neurons, that is, 0.01497 and 0.01249, respectively, than hidden layer 4 with 2, 4, 8, 16, 32, and 128 neurons.

Model evaluation based on RMSE and MAE using hidden layer 5

Table 6 reports the results of hidden layer 5. According to our error measurement criteria, hidden layer 5 with 64 neurons shows less prediction error than the other neurons within hidden layer 5. As illustrated in aforementioned Table 8, the results show that RMSE and MAE values are less in hidden layer 5 with 64 neurons, that is, 0.09312 and 0.0235, respectively, than hidden layer 5 with 2, 4, 8, 16, 32, and 128 neurons.

TABLE 9 Result of ESG pillar score error measurement using polynomial regression.

Technique	RMSE	MAE
ESG pillar score Poly 1	0.2455	0.3412
ESG pillar score Poly 2	0.7845	0.1249
ESG pillar score Poly 3	0.8974	0.9713
ESG pillar score Poly 4	0.2314	0.7849
ESG pillar score Poly 5	0.1593	0.1786

Model evaluation based on RMSE and MAE using polynomial regression

In Table 9, the results of polynomial regression up to degree 5 have been shown which are applied to our dataset for accurate prediction of the ESG pillar score using RMSE and MAE as evaluation matrices. We can see that polynomial regression with degree 5 has the least value for RMSE, that is, 0.1593 as compared to RMSE values for polynomial regression with degrees 1, 2, 3, and 4, i.e., 0.2455, 0.7845, 0.8974, and 0.2314, respectively. Likewise, for MAE, polynomial regression with degree 2 outperforms as it has the least value, i.e., 0.1249 among MAE values for polynomial regression with degrees 1, 3, 4, and 5, that is, 0.3412, 0.9713, 0.7849, and 0.17849, respectively. So, for both evaluation parameters, polynomial regression with degrees 5 and 2 outperforms. Therefore, polynomial degree 2 is the best for predicting the ESG pillar score because it has the minimum prediction error during the test.

Models' evaluations based on RMSE and MAE using decision tree and random forest

In Table 10, the results of two techniques of machine learning, that is, decision tree (individual) and random forests with 2, 3, 5, 7, 10, and 15 decision trees have been shown which are applied to our dataset for accurate prediction of the ESG pillar score using RMSE and MAE as evaluation matrices. We can see that the decision tree model has RMSE and MAE values of 0.6976 and 0.7591, respectively. But the random forest technique with different numbers of decision trees gives relatively lower values of RMSE and MAE than the single decision tree model. If we make predictions based on the RMSE parameter, the random forest technique with 15 decision trees gives the lowest value of RMSE, that is, 0.2245 among the single decision tree and random

TABLE 10 ESG pillar score error measurement using the decision tree and random forest technique.

Technique	RMSE	MAE
ESG pillar score decision tree	0.6976	0.7591
ESG pillar score random forest 2	0.3649	0.3713
ESG pillar score random forest 3	0.2550	0.4923
ESG pillar score random forest 5	0.3599	0.3316
ESG pillar score random forest 7	0.2255	0.3311
ESG pillar score random forest 10	0.5467	0.2915
ESG pillar score random forest 15	0.2245	0.3018

TABLE 11 Comparison of results based on RMSE and MAE of all the techniques used for predicting ESG pillar score.

Technique	RMSE	MAE
ESG pillar score KNN	0.1243	0.1456
ESG pillar score naive Bayes	0.2526	0.7913
ESG pillar score SVM linear	0.4589	0.0598
ESG pillar score SVM RBF	0.1247	0.0188
ESG pillar score decision tree	0.6976	0.7591
ESG pillar score ANN	0.0149	0.0117
ESG pillar score poly	0.1593	0.1249
ESG pillar score random forest	0.2245	0.2915

forest with 2, 3, 5, 7, and 10 decision trees. If we make predictions based on the MAE parameter, the random forest technique with 10 decision trees gives the lowest value of MAE, that is, 0.2915 as compared to a single decision tree and random forest with 2, 3, 5, 7, and 15 decision trees. Therefore, a random forest with a greater number of decision trees gives more accurate results, and the reason for this technique to perform better than a single decision tree is that it has the power of numerous decision trees combined in it and it does not rely on a single decision tree's feature relevance. We can say collectively that for both evaluation parameters, the random forest technique outperforms with the least values of RMSE and MAE.

TABLE 12 Comparison of the order of all the techniques used for predicting ESG pillar score.

ESG pillar score using RMSE parameter
ANN > KNN > SVM RBF > POLY regression > random forest > naïve Bayes > SVM linear > decision tree
ESG pillar score MAE parameter
ANN > SVM RBF > SVM linear > naïve Bayes > POLY regression > KNN > random forest > naïve Bayes

Comparison of all techniques

As we have discussed the results of all the techniques with their different degrees, nodes, and hidden layers within the same technique and then compared their results with the result of other relevant techniques, now we determine which technique is overall the best fit for accurate prediction of the ESG pillar score among all the techniques used.

From Table 11, we can see that ANN, KNN, and SVM RBF techniques outperform compared to the rest of the techniques as these give the least values of RMSE and MAE. The ANN technique is the best fit for accurate prediction of the ESG pillar score as it is giving the minimum error values, and the reason this technique performs better than other techniques is that it has the power of numerous hidden layers and number of neurons, i.e., 2, 4, 8, 16, 32, 64, and 128. The more the number of hidden layers is added, the more accurate the results with minimum error values are achieved. Finally, the order of accuracy of ESG pillar score prediction using different machine learning techniques is as follows in Table 12.

Contribution

This study investigates the relationship between ESG and FFP based on artificial intelligence-supervised techniques. Hence, by adopting this latest advancement and convergence of traditional to artificial intelligence techniques, this study is of immense value to investors, academia, regulatory bodies, policymakers, the accounting, and auditing profession, and other relevant stakeholders. In addition, the results of this study will reveal evidence on whether FFP can be enhanced through ESG score and compliance. Apart from these, the results of the study are significantly beneficial for establishing rules pertaining to board of directors' attributes, particularly those in developing capital markets. Importantly, the obtained results will be of utmost help to both developed and developing countries and can be a benchmark for planning and formulating ESG scores and compliance policies in the future.

Conclusion and recommendations

In the current study, we have used artificial intelligence techniques based on different machine learning algorithms, including random forest, decision tree, artificial neural networks (ANN), K-nearest neighbor (KNN), naive Bayes, support vector machine (linear), support vector machine (radial basis function), and various degrees of polynomial regression. These machine learning algorithms were used to predict future ESG scores using balance sheet and income statement items, that is, return on asset (ROA), return on equity (ROE), and earnings before interest and taxes (EBIT), earnings per share (EPS), net sales (NS),

and dividend yield (DY). The target features in the study are ESG pillar score; the values of these three features are predicted using the balance sheet and income statement items. The findings of this study will help in developing the newly proposed ESG score code following the aforementioned methods, and this study will contribute to the ongoing debate about ESG compliance, issues, and its incorporations into the companies' reporting standards. All in all, the results of this study have significance for regulatory bodies, researchers, academic researchers, practitioners, industries, publicly listed companies, and the security commission to uplift their ESG performance and curb the issues pertinent to ESG. Therefore, consideration should be given to this study to help the stakeholders and improve the overall performance of the organizations of the world. In short, our findings will be of interest to academics and practitioners interested in sustainable finance and sustainable investing. Moreover, talking about the limitation of the study, due to time constraints, this study could not include other developed countries like France, Norway, Denmark, Italy, Canada, Australia, and Holland, This research might be conducted on other countries with similar potential to further authenticate its findings or to identify changes in results about different markets and comprehend this variation about them, to widen its reach and verify its findings. Furthermore, two assessment parameters are used in this work to make predictions. To further evaluate the results, additional assessment factors such as accuracy, f1 score, and confusion matrix might be included. In this current study, only ML algorithms were analyzed, discussed, and compared. In the future, researchers might use both ML approaches and econometric forecasting models to get more exact findings and might be able to determine whether the hybrid of both methods outperforms or which of the individual methods is the best. Future researchers might consider a comparison of ML techniques using examples of developed and developing countries, whereas in this study, we have taken examples of UK, USA, and Germany. Future researchers might compare these findings by taking examples of developing countries like India, China, and Malaysia.

Study limits and prospective research areas

Apart from several contributions, this study has some limitations. First, as discussed previously, the scope of the study is limited by its population, which included only three developed countries. For this reason, the sample should be expanded to developing countries, and the results should be compared with the developed main market countries. Second, due to data availability and time constraints, this study reports only the selected years for this study; however, future studies could be extended to the proceeding years of future years subject to the availability of data. Last but not the least, future studies should include a purposive sampling procedure for small, medium, and large countries for better insight, understanding, and comparison. Moreover, this study is limited to the machine learning-supervised models which may restrict the generalizability of the findings; therefore, future researchers should utilize unsupervised machine learning techniques. In addition to previous findings, future researchers can take different years, samples, and sectors for examining the impact of ECG mechanisms on FFP based on machine learning and other techniques.

Data availability statement

Publicly available datasets were analyzed in this study. The data can be found at REFINITIV DATASTREAM.

Author contributions

MK performed the analysis and data collection. HR contributed to writing the abstract and introduction. MM contributed to the literature, and MA worked on the methodology and final draft of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Vishal Dagar,
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Council for Agricultural and Economics Research (CREA), Italy
Mahejabin Sayyad,
Agasti Arts, Commerce and Dadasaheb Rupwate Science College, India

*CORRESPONDENCE
Muhammad Anees Khan,
lookanees123@gmail.com

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An empirical mediation analysis of technological innovation based on artificial intelligence in the relationship between economic development and corporate governance mechanism

Muhammad Anees Khan[1]*, M. S. Mazliham[2], Muhammad Mansoor Alam[3], Nida Aman[1], Sakshi Malik[3], Syeda Faiza Urooj[4] and Tanveer Taj[1]

[1]Bahria Business School, Bahria University, Islamabad, Pakistan, [2]Faculty of Computing and Informatics, Multimedia University, Cyberjaya, Malaysia, [3]Jindal Global Business School, O.P. Jindal Global University, Sonipat, Haryana, India, [4]Department of Commerce, Federal Urdu University of Arts Science and Technology, Islamabad, Pakistan

Although strong recommendations and steps have been developed and taken to adopt the latest technological trend through corporate governance reforms for improving the economic development, however, the trend toward adopting the latest technology has not been adopted and thus has remained a big issue in the non-financial sector for the last two decades around the globe. The study used GLS (random effect) regression estimator to a sample composed of 1600 firm-year observations from 2017 to 2021. The findings indicated that the majority of the firms were involved in an income-decreasing economic situation. Moreover, the findings evidenced that compliance with some specific CG attributes welcomed the technological innovation and significantly had an impact on the economic development. However, some CG attributes of the models did not play any significant role in technological innovation and economic development which needs improvement. Moreover, this study also evidenced that the impact of CG attributes is not directly affecting economic development but is mediated by the technological innovation, which is of importance to managers of a firm, who hold responsibility for investing and financing activities. In addition, this study revealed a fully significant mediating role of technological innovation in the relationship of BOD meetings, audit committee size, managerial ownership, and foreign ownership with economic development. However, no significant mediating role of technological innovation was observed in the relationship of independent BOD and economic development. All in all, the results of this study have significance for regulatory bodies, researchers, academic researchers, practitioners, publicly listed companies in Malaysia, the Bursa

Malaysia and the security commission to uplift their financial performance and curb EM activities through the effective use of CG mechanisms.

KEYWORDS

AI, economic, corporate governance, random effect regression, fintech

1 Introduction

Over the last two decades, technological innovation (artificial intelligence), economic development, and corporate governance (CG) mechanisms have significantly influenced businesses, stakeholders, and shareholders around the world. In this regard, due to lack of technological innovation (artificial intelligence), the late 1990s and early 21st century witnessed the series of different accounting scandals (e.g., Enron, HealthSouth, Parmalat, Tyco, WorldCom, and Xerox) appeared across the United States and Europe which have changed the climate of business and trust (Petrick and Scherer, 2003). In addition, companies did not focus on environmental, social, and governance issues, which in return create issues for different business organizations around the globe. After witnessing these scandals, security agencies, stock markets, and other stakeholders felt the need for technological innovation that will control these scandals and will lead to economic development. These scandals caused damage, including a decline in the worldwide reputations of companies, auditors, security analysts, regulators, and financial markets (Ball, 2009). Moreover, it was also noted by the authors that the adoptability issue of technological innovation has always been a concern for the stakeholders and auditors which can lead to economic development. Empirical evidence from the academic literature has shown that the good corporate governance practices have always had an impact on the economic and financial performance of the organization by minimizing the economic development issues by adopting the latest technological advancement (Barth and Lang, 2008). Ban et al. (2022); Chen et al. (2021); Lei et al. (2021) demonstrated that technological development is one of the successful instruments of the executives, which attract the stakeholders for investment, and thus helps in boosting the economic development in the shape of return on assets, return on equity and earning per share. It also helps in minimizing the time and improves the efficiency of the organization. So, in this regard, installing and using technology in the shape of artificial intelligence is considered as core business decisions of the firm. Overall, it can be noted that the essential goal of the firm was to boost the investor's wealth by choosing an appropriate advancement in technology to have a positive impact on the relationship between corporate governance mechanism and economic/financial growth (Lei et al., 2021; Pan et al., 2021; Lu et al., 2022). In this regard, numerous specialists have conducted their examinations to recognize corporate governance, technological advancement, and economic performance to center around whether what are its qualities and how these attributes affect the performance of the firm Shen et al., 2022; Wu and Zhu 2021; Xu et al., 2022). Studies found numerous answers identified with analysts' questions through giving a reasonable meaning of good corporate governance, their morals and techniques utilized so as to perform, oversee, and screen a business. The greater part of these examinations was to look at the connection between corporate governance components and performance measures (Shen et al., 2022). In the previous two decades, consideration about problems identified with corporate governance, technological advancement, and economic development is expanding because of progression of money-related and financial occasions occurring in the world over. In such a manner, prominent budgetary outrages, monetary emergencies, and startling corporate disappointment come across nations to reinforce the corporate rules so as to building the trust in money-related markets.

The study is further structured with the corporate governance mechanism literature together with technological innovation based on the AI technique. In addition, econometrics models will be run based on theory discussed with methodology, results, and mediation interpretation.

2 Corporate governance mechanism

Corporate governance (CG) is defined as a system by which companies are directed and controlled (O'Sullivan, 1999). Agency theory suggests that the CG system is of the utmost importance for effective monitoring and development of an organization (Farber, 2005; Murthy, 2006). Thus, the CG mechanism is similar to a monitoring system which helps in improving the overall performance of the firm (Fama, 1980; Murphy and Zimmerman, 1993; Gul and Leung, 2004; Ali Shah et al., 2009). Therefore, it is widely accepted that an effective compliance of CG also increases a manager's ability to constrain EM practices and maximize shareholders wealth (Peasnell et al., 2005; Ali Shah et al., 2009; Jaggi et al., 2009; Lo et al., 2010). CG broadly refers to the mechanisms, processes, and relations by which corporations are controlled and directed (Gul et al., 2003). A CG mechanism is the combination of internal directors of the board, internal audit committee, structure of ownership, and the external auditor (Hillman and Keim, 2001). A CG mechanism is the process of directing and monitoring the overall FFP and reducing the EM (Farber, 2005). Moreover, CG practices increase a manager's ability to work for the maximization of shareholder wealth (Peasnell et al., 2005; Jaggi et al., 2009; Lo et al., 2010). Although the CG mechanism is differently defined by authors, CG is a system that minimizes the earnings manipulation ability

of managers (Lo et al., 2010). Following this, many firms significantly improvised and executed the CG mechanism to reduce the practices of EM to improve their firm's financial performance.

3 Technological innovation based on artificial intelligence

We measure the technological innovation based on the latest artificial intelligence (AI) techniques that is used in finance. Artificial intelligence relates to technological advances which allow machines to become "intelligent." In 1956, John McCarthy coined the word artificial intelligence. The objective of artificial intelligence was to develop a system that is intellectual and self-contained. Machine learning comes under the heading of artificial intelligence which allows a system to adapt and develop its own understanding without having to program it explicitly. AI works in two ways: one is data-driven, and the other is symbolic. For the data-based side called ML, a large amount of data is needed to be fed into the machine before it is capable of learning. Machines are capable of learning in a much wider range of dimensions. Reasoning, information representation, NLP, scheduling, deep learning, interpretation, and the ability of transferring and controlling them are all domains of the AI study. One of AI's aims was to achieve general intelligence. ANN can be used for forecasting because of their ability of pattern recognition and machine learning (Zaidi and Ofori-Abebrese, 2016). The procedures which are needed to achieve the objective comprise traditional symbolic AI, artificial intelligence, and statistical methods. AI is rapidly developing in a variety of fields and has an excess of features. The technology has the prospective to be used in a variety of industries and sectors. Artificial intelligence is applied in finance to recognize and track financial and banking activities. All of these processes are conducted through machine learning. Machine learning systems are categorized based on how much and what kind of supervision they receive during training. Machine learning is broadly divided into the following three categories.

3.1 Supervised

Based on the training dataset, supervised learning develops a function that translates inputs to outputs. The purpose of supervised learning was to predict a known outcome. To train a model, a dataset with features and labels is used. The technique generates a function that maps features to labels and then utilizes it to forecast the labels of unlabeled data. The accuracy of supervised learning models in forecasting outcome across one or more sets of data not included in the growth process is typically measured.

3.2 Un-supervised

In unsupervised learning, the training data are unlabeled. The system tries to realize this without the assistance of a teacher. Unsupervised learning uncovers hidden patterns in unlabeled data and makes conclusions from it. It is not anticipation of a precise outcome. Instead, the program looks for patterns or groups of data to identify. This is a difficult task to review, and the value of groups learned through unsupervised learning is frequently assessed by performance in a successive supervised learning assignment, which determines if these groupings are beneficial.

3.3 Reinforcement technique

The reinforcement technique is relatively a new type of learning that combines supervised and unsupervised learning. It is a completely distinct beast. The algorithm in it maximizes accuracy through trial and error. The model is shaped through feedback from the training set's outcomes of real and simulated decisions. In this context, the learning system is referred to as an agent since it can check the environment, select, and carry out actions, and receive rewards or penalties. It must, then, figure out for itself what the ideal technique, known as a policy, is for maximizing reward over time. In each case, a policy specifies what action the agent should take.

4 Economic/financial development

We measure the economic development based on the financial performance of the firm that will collectively contribute to the GDP as an economic growth. So, in this regard, economic development of a firm is defined as "how well a firm generates the maximum revenue by using the available resources to satisfy the stockholders and investors." Economic/financial development is the output of a successful business operation in the shape of a higher return on assets or return on equity. In simple words, economic/financial development increases the earning, dividends, and overall price of the share (Stout, 2013). According to shareholder primacy theory, every owner of a firm wants to increase the share price which, in turn, positively affects the shareholder value and overall firm performance (Hillman and Keim, 2001). The core objective of the management of any firm is to increase the economic/financial development, which will increase the goodwill of the firm in the market (Shen and Chih, 2007). Moreover, economic/financial development is seen as a major concern by investors, shareholders, and stakeholders (Pfeffer, 1973; Lang and Stulz, 1993).

International strategy research and behavioral finance theories state that economic/financial development is one of the most important characteristics of the firm in that it creates a helpful scale for deciding upon an investment in a firm (Tong et al., 2008). Hence, investors and creditors observe economic/financial development on regular basis before making the investment or lending credit to the concerned firm (Ittner and Larcker, 2001; Lin and Chen, 2005; Bird and Casavecchia, 2007; Kantudu and Samaila, 2015; Shittu et al., 2016).

5 Theories of the study

5.1 Agency theory

Agency theory strength is subject to the existence of CG mechanisms by which firm owners are able to monitor the performance of managers (Fama, 1980). Therefore, strict monitoring of managers is undertaken by the firms boards (principals or their representatives), for constraining the managerial opportunistic behavior and reducing the agency costs (Fama, 1980; McKnight and Weir, 2009). The aforementioned argument is strongly supported by the Malaysian Codes of Corporate Governance (MCCG, 2017), that the role of CG is continuous monitoring of managers and thus protecting the shareholders. Therefore, researchers who examine the association between EM and CG relied upon agency theory (Watts & Zimmerman, 1986; Dellaportas et al., 2012; González and García-Meca, 2014). Hence, the relationship between CG, technological innovation, and economic development is developed based on the agency theory concept.

5.2 Stakeholder theory

Mary Parker Follett brought the idea of stakeholder theory about 60 years ago (Schilling, 2000). The origins of stakeholder theory draw on four key academic fields, that is , sociology, economics, politics, and ethics (Freeman, 2004). The modern utilization of stakeholder theory developed back in 1963, when Stanford Research Institute generalized and expanded the notion of the shareholders (Benneworth and Jongbloed, 2010). A stakeholder is defined as any group or individual who can influence or is influenced by the achievement of the organization's objectives (Freeman, 2004). Thus, stakeholders are persons or groups with legitimate interests in procedural aspects of corporate activity (Friedman and Miles, 2002).

6 Question/objective

The main question/objective of this study was to examine the mediating impact of technological innovation (artificial intelligence) on the relationship between the corporate governance mechanism (BODSIZE, INDEPBOD, BODMEET, AUDTCOMMSZE, AUDTCOMMEET, MANGEROWNR, and FORGNOWNR) and economic/financial development in Malaysian public listed companies."

7 Conceptual framework

The following conceptual framework is developed based on the aforementioned discussion to examine the relationship between the CG mechanism (BODSIZE, INDEPBOD, BODMEET, AUDTCOMMSZE, AUDTCOMMEET, MANGEROWNR, and FORGNOWNR) and economic/financial development with a mediation of technological innovation (artificial intelligence) in Malaysian public listed companies. The mediation links between the CG mechanism technological innovation and economic/financial development.

8 Model specification and tests

Previously, the study developed and discussed the theories of this study; however, the next section discusses the econometric models with their respective conceptual models for testing the hypotheses developed for the current study. To investigate the effects of specific CG attributes on techno innovation and economic development with a mediating impact of techno innovation on the relationship between CG attributes and economic development, the study was separated into four models. Thus, the study develops four models for testing the 22 hypotheses. This research utilizes the following four models to test the research hypotheses.

8.1 Regression model 1 (A to B)

In model A to B as shown in the Figure 1, this study regressed TechnoInnovat (AI) on specific CG attributes selected from MCCG-2017. Seven of 19 hypotheses were developed for model A to B. The econometric equation model with its respective conceptual model of A to B is given as below:

$$
\begin{aligned}
\text{TechnoInnovat}(AI) = {} & \beta_0 + \beta_1 \text{BODSZE}_{\text{it}} + \beta_2 \text{INDEPBOD}_{\text{it}} \\
& + \beta_3 \text{BODMEETG}_{\text{it}} + \beta_4 \text{AUDTSZE}_{\text{it}} \\
& + \beta_5 \text{AUDTCOMMETG}_{\text{it}} \\
& + \beta_6 \text{MANOWN}_{\text{it}} \\
& + \beta_7 \text{FOROWN}_{\text{it}}\, \beta_8 \text{LOGTASST}_{\text{it}} \\
& + \beta_9 \text{SHAREMKTPRICE}_{\text{it}} \\
& + \beta_{10} \text{MKTTOBV}_{\text{it}} + \beta_{11} \text{LEVERAGE}_{\text{it}} \\
& + \beta_{12} \text{IFRS}_{\text{it}} + \varepsilon.
\end{aligned}
$$

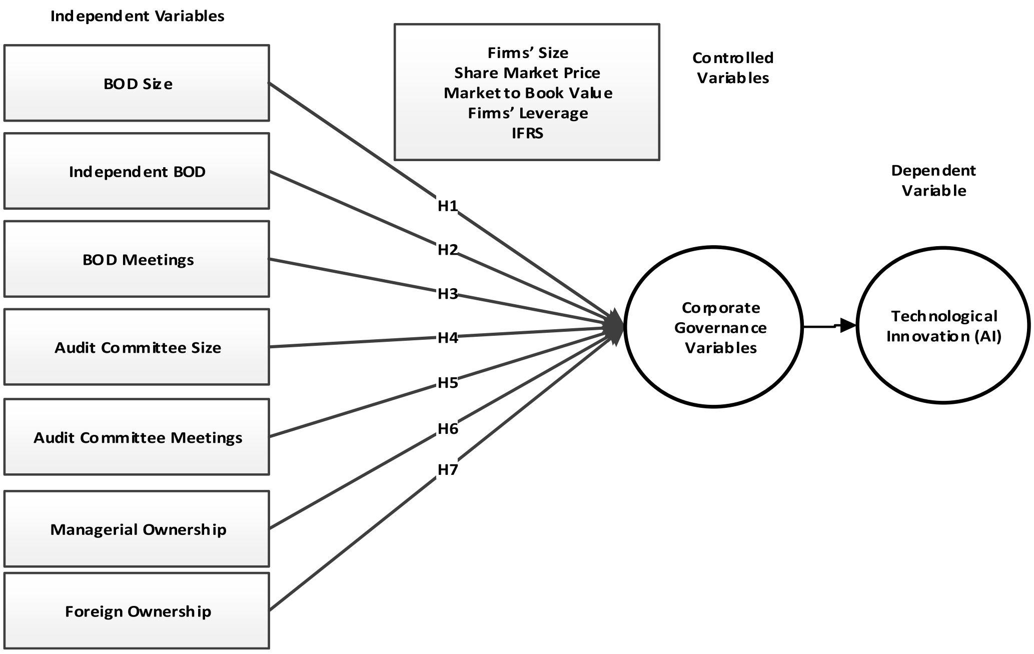

FIGURE 1
Conceptual model of A to B.

8.2 Regression model 2 (B to C)

In model B to C, as shown in the Figure 2 economic/financial development was regressed on technological innovation. Economic/financial development was measured by ROA, ROE, and EPS, while technological innovation was measured by dummy variables based on Malaysia country data. However, only one hypothesis was developed for model B to C. Following is the econometric equation model with its respective conceptual model of model B to C:

$$\frac{\text{Econoic}}{\text{FinancialDevp}} = \beta_0 + \beta 1\text{TechnoInnovatnit} + \beta_2\text{LOGTASST}_{\text{it}} + \beta_3\text{SHAREMKTPRICE}_{\text{it}} + \beta_4\text{MKTTOBV}_{\text{it}} + \beta_5\text{LEVERAGE}_{\text{it}} + \beta_6\text{IFRS}_{\text{it}} + \varepsilon.$$

8.3 Regression model 3 (A to C)

In Model A to C as shown in the Figure 3, this study replaces technological innovation with economic/financial development and then regressed it on specific CG attributes selected from MCCG-2017. Moreover, seven hypotheses were developed for model A to C as well. The econometric presentation of model four with its respective conceptual model is given as follows: economic/financial development was measured by ROA, ROE, and EPS, while technological innovation was measured by dummy variables based on Malaysia country data.

$$\frac{\text{Econoic}}{\text{FinancialDevp}} = \beta_0 + \beta_1\text{BODSZ}_{\text{it}} + \beta_2\text{INDBOD}_{\text{it}} + \beta_3\text{BODMTG}_{\text{it}} + \beta_4\text{ACSZ}_{\text{it}} + \beta_5\text{ACMTG}_{\text{it}} + \beta_6\text{MANOWN}_{\text{it}} + \beta_7\text{FOROWN}_{\text{it}} + \beta_8\text{LOGTASST}_{\text{it}} + \beta_9\text{SHAREMKTPRICE}_{\text{it}} + \beta_{10}\text{MKTTOBV}_{\text{it}} + \beta_{11}\text{LEVERAGE}_{\text{it}} + \beta_{12}\text{IFRS}_{\text{it}} + \varepsilon.$$

Following the aforementioned econometric models, from models 1 to 4, this study used the generalized least square

FIGURE 2
Conceptual model of B to C.

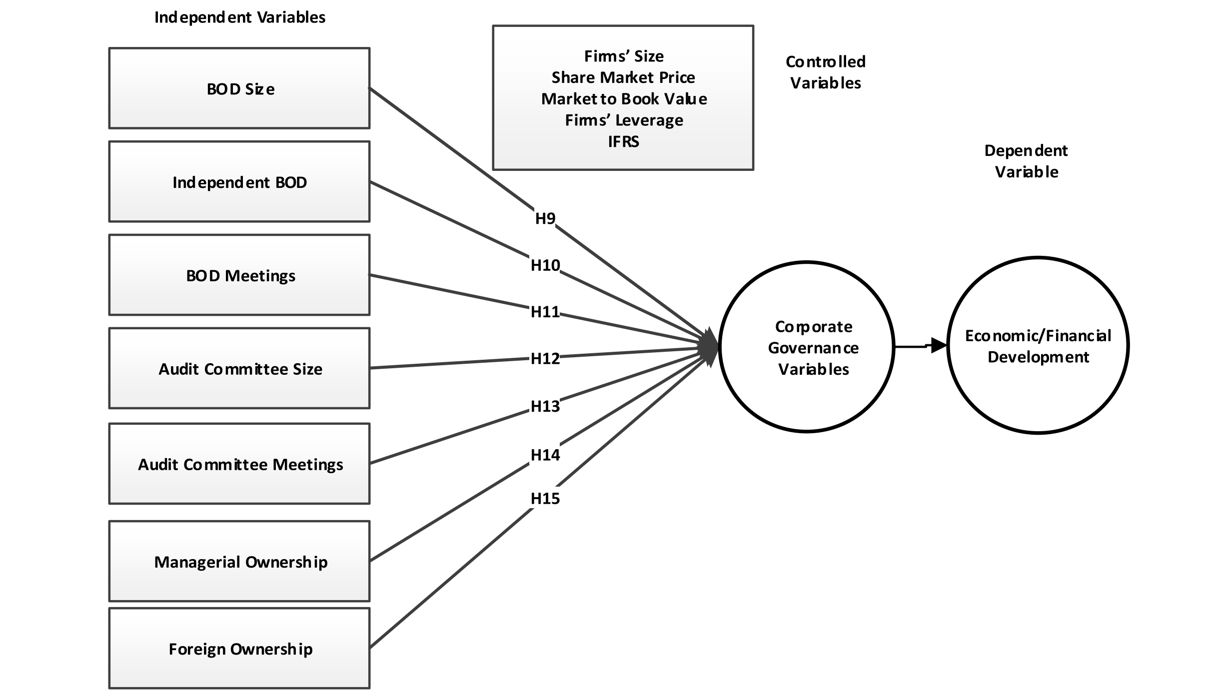

FIGURE 3
Conceptual model of A to C.

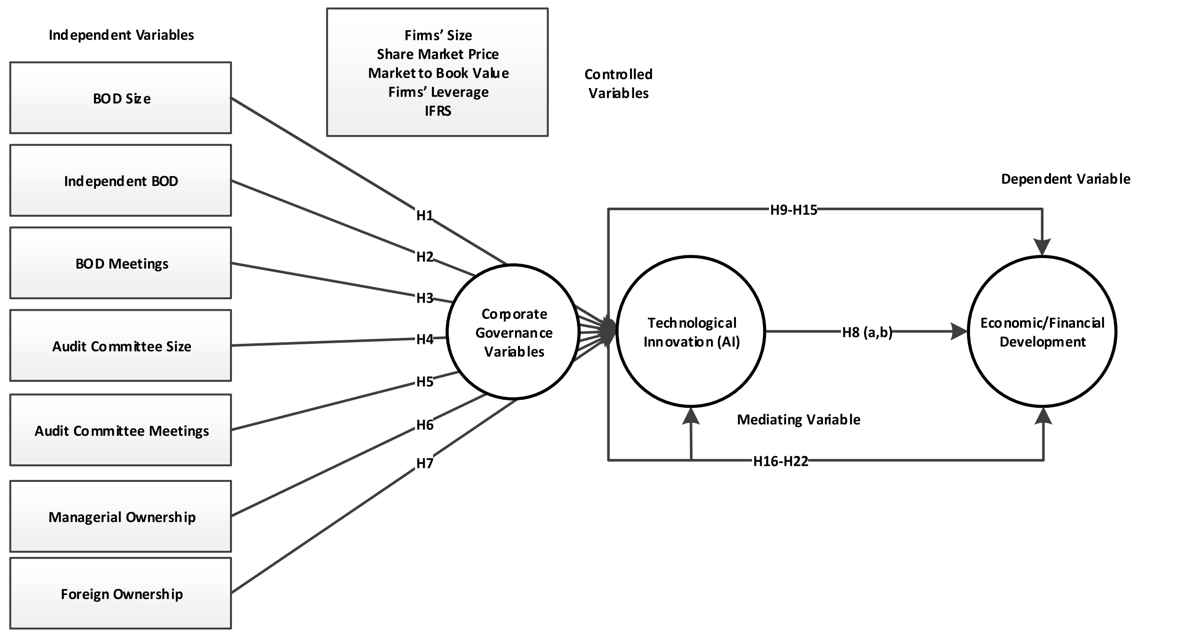

FIGURE 4
Conceptual models A to B and B to C and ABC.

(GLS) random effect regression estimator, which was selected based on Hausman specification test in STATA 15.0.

8.4 Regression mediating model 4 (A to B, B to C, and A to C and ABC)

The last and the fourth model (A to B, B to C, A to C, and ABC) as shown in Figure 4 was the novel model of mediation wherein FFP was taken a mediating variable in the relationship of specific CG attributes and EM practices in Malaysian public listed companies for the years 2010–14. Therefore, the empirical models with the econometric equation of main variables of this study tests are as follows.where

Economic/Financial Dep: economic/financial development
TechnoInnovatn: technological innovation (AI)
β_0: constant
BODSZ: board of director's size
INDBOD: board of director's independence
BODMTG: board of directors' meeting
ACSZ: audit committee size
ACMTG: audit committee meeting
MANOWN: managerial ownership
FOROWN: foreign ownership
LOGTASST: log total assets.
SHAREMKTPRICE: share market price
MKTTOBV: market to book value
LEVERAGE: leverage
IFRS: International Financial Reporting System
e: residual error

9 Methodology

This study used balanced panel data because it is a more sensitive measurement of the changes that could take place between points in time (Cavana et al., 2001).The sample size of this study comprises 320 firms listed on Bursa Malaysia, during the period 2017–2021. Financial institutions, insurance, and mining firms are excluded, as is common in this type of studies because of their particular accounting practices (González and García-Meca, 2014). We assumed technological innovation (artificial intelligence) data a dummy and collected 1 as if the company use latest financial innovation, that is, AI while 0 for not using the AI. The financial data for economic development are secondary in nature and obtained from the DataStream database, while data of the CG mechanism (board of director size, audit committee meetings, and external auditor) extracted directly from company's annual reports, which are available on firms' websites or through the Bursa Malaysia website. The data will be analyzed through descriptive statistics, correlation, multiple regression, and mediation analysis for results interpretation. Data run through the statistical package for social science (SPSS), Version 21 and STATA, Version 15. For making the result more robust, constant, and stable, we run some initial steps for cleaning and screening the data, which will imply that the samples are more representative and the results are meaningful (Sekaran and Bougie, 2003).

TABLE 1 Descriptive statistics of the study.

Variable	Obs	Min	Max	Mean	Std. Dev
ECODEVELOPEMENT	1600	−1.77	0.636	0.409	0.86
TECHINNOVAT (AI)	1600	0	1	0.6	0.49
BODSIZE	1600	3	14	7.23	1.72
AUDCOMTSIZE	1600	0.21	0.79	46.87	12.4
AUDTCOMMTMEET	1600	2	18	5.36	1.68
AUDTCOMSZE	1600	2	7	3.21	0.49
AUDTCOMMET	1600	2	14	4.83	0.99
MANGEOWN	1600	0	74	12.27	17.0
FORGNOWN	1600	0	86	5.53	15.0
LOGTASSET	1600	4.07	7.35	5.59	0.58
SHAEMKET	1600	0.009	47.3	1.83	3.78
LEVERAGE	1600	0	2.83	0.45	0.14
IFRS	1600	0	1	0.6	0.49

Note: Economic development, ECODEVELOPEMENT proxy; technological innovation, AI; BODSIZE, board of director size; INDEPBOD, independent board of director; BODMEET, board of directors' meeting; AUDTCOMSZE, audit committee size; AUDTCOMMET, audit committee meeting; MANGEOWN, managerial ownership; FORGNOWN, foreign ownership; LOGTASSET, log of total assets; SHAEMKET, share market price; LEVERAGE, leverage; IFRS, International Financial Reporting System.

10 Results and discussion

10.1 Descriptive statistics

Table 1 shows the descriptive statistics for dependent, mediating, independent, and control variables of the study in Malaysian public listed companies for the 9 years from 2017 to 2021. The results in Table 1 for dependent variable ECODEVELOPEMENT shows that the mean value of 0.409 ranged from a minimum of -1.77 to a maximum of 0.636. Similarly, TECHINNOVAT (AI) was measured by earnings multiples and taken as a mediating variable in the study. The finding presented in Table 1 for TECHINNOVAT (AI) shows a mean of 0.6, ranging from 0 to 1. Moreover, all the descriptive results of other variables are also shown in the table.

10.2 Correlation analysis

This section presents the summary of Pearson's correlations between the mediating, dependent, independent, and control variables. The purpose of checking correlation among variables

TABLE 2 Pearson's correlation matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
TECHINNOVAT (AI) (1)	1													
ECODEVELOPEMENT (2)	**0.100	1												
BODSIZE (3)	**0.026	**−0.04	1											
INDEPBOD (4)	0.0240	−0.033	**0.089	1										
BODMEET (5)	**0.0920	**0.175	−0.003	**-0.22	1									
AUDCOMTSZE (6)	**0.1390	**0.150	**0.123	0.041	**0.223	1								
AUDTCOMMET (7)	−0.0370	0.047	**0.432	0.021	**0.102	**0.075	1							
MANGEOWN (8)	**−0.073	**-0.15	−0.040	0.022	**−0.12	**−0.16	−0.025	1						
FORGNOWN (9)	**0.1820	**−0.10	*−0.056	*−0.064	0.033	**0.096	**−0.11	**−0.15	1					
LOGTASSET (10)	**0.1810	**0.548	0.041	**−0.06	**0.337	**0.203	**0.121	**−0.28	**0.121	1				
SHAEMKET (11)	**.4830	**0.263	−0.013	−0.015	**0.157	**0.234	−0.042	**−0.18	**0.244	**0.414	1			
MKTTOBV (12)	**0.1270	**0.110	0.003	−0.022	0.015	**0.071	0.025	−0.035	**0.100	**0.092	0.022	1		
LEVERAGE (13)	**-0.0840	**0.084	**0.083	0.001	0.014	0.049	0.037	−0.009	0.001	*0.051	−0.040	0.042	1	
IFRS (14)	***0.005	−0.001	0.037	**0.104	−0.009	0.020	0.043	−0.016	0.021	*0.049	*0.060	0.010	0.044	1

Notes: ** correlation is significant at the 0.01 level (2-tailed), * correlation is significant at the 0.05 level (2-tailed).

was to investigate the correlations of study variables as well as to know about any multicollinearity issue among the independent variables. A multicollinearity problem exists in the data if the Pearson's correlation coefficient is greater than 0.80 (Hooper et al., 2008). Due to the continuous nature of the variables, this study provided only Pearson's correlation. Table 2 presents the Pearson's correlations matrix for the model of this study, which clearly demonstrates no multicollinearity issue is present among the independent variables as none of the coefficients are greater than 0.80 (Hooper et al., 2008). Table 2 shows the statistics for Pearson's correlation matrix of the sampled firms for the dependent, independent, and control variables. The correlation statistics reported for model 1 (A to B) in Table 2 show that ECODEVELOPEMENT had a significant positive correlation with the board of director size (BODSIZE). These findings are consistent with previous studies such as Salihi (2015), Germain et al. (2014), and Cheng and Warfield (2005), who stated that there is a positive impact of board size on ECODEVELOPEMENT. However, the proportion of independent board of director (INDEPBOD) showed an insignificant and positive correlation with ECODEVELOPEMENT.

10.3 Multivariate analysis of models 1, 2, and 3 with a mediation analysis is given as follows

10.3.1 Results and discussion of the first (1) model, that is, (A to B)

The results of random effect (GLS) regression for the first model of the study are summarized in Table 3. The regression estimator for model 1 examined the impact of CG attributes (BODSIZE, INDEPBOD, BODMEET, AUDTCOMMSZE, AUDTCOMMEET, MANGEROWNR, and FORGNOWNR) on TECHINNOVAT (AI). In addition, Table 3, also explains the impact of control variables (LOGTASSETS, SHAREMKETPRC, MKTTOBV, LEVERGE, and IFRS) on the relationship of CG attributes and TECHINNOVAT (AI). According the study of Baltagi and Kao (2001), a goodness-of-fit test should be conducted to examine the robustness of the model and data. Therefore, for confirming the goodness-of-fit of the model, this study used Wald Chi2 (1) and Prob > Chi2 test. The statistics of Wald Chi2 (1) = 67.48, with Prob > Chi2 = 0.000 are shown in Table 3. The significance of the result (Prob > Chi2 = 0.000) confirms the goodness-of-fit for the first model of the study. Similarly, for making the model more robust and error free, this study also used Durbin–Watson statistic for autocorrelation. The results of Durbin–Watson statistics test = 2.07 shows no issues of autocorrelation as the threshold value of Durbin–Watson statistics is either equal to two (2) or near to two (2) (Johnson and Wichern, 2014). Moreover, the statistics of Durbin (score) Chi2 (1) and Wu–Hausman F (1589) in Table 3, also show no endogeneity issue in the first model of the study by revealing the results as Durbin (score) Chi2 (1) = 1.23 with p = 0.110, and the results for Wu–Hausman F (1589) = 1.54 with p = 0.134. The rule of thumb for the aforementioned tests is, if the probability value is greater than 0.05, no endogeneity is present in the model. Therefore, in this case; the p-value is greater than 0.05 and indicates no issue of endogeneity in the model. Similarly, R-square (49.22) in Table 3 suggests the amount of change in a dependent variable

TABLE 3 Random effect (GLS) model 1 (A to B).

TECHINNOVAT (AI)	Coef.	Std. Err.	P
BODSIZE	0.015918	0.0238615	0.0505
INDEPBOD	0.006267	0.0034157	0.067
BODMEET	−0.020221	0.0260399	0.437
AUDTCOMMSZE	0.077853	0.0541406	0.015
AUDTCOMMEET	0.053702	0.0611343	0.380
MANGEOWNR	0.066329	0.0654212	0.081
FORGNOWNR	0.144147	0.0704879	0.041
LOGTASSETS	0.037894	0.0745221	0.411
SHAREMKETPRC	0.734122	0.0657167	0.000
MKTTOBV	0.197979	0.0499443	0.000
LEVERGE	−0.000439	0.0001797	0.014
IFRS	−0.111207	0.0820342	0.175
Cons	0.0227741	0.3119759	0.942
GLS			Random effect
Observations (320*5)			1600
R-Square			49.22
Years			Dummy
Industry			Dummy
Wald Chi(2)			67.48
Prob > Chi2			0.000
DW-statistics			2.070
Durbin (score) Chi2(1)		1.23	0.110
Wu–Hausman F(1589)		1.54	0.134

Significant at 10%, ** significant at 5%, and *** significant at 1%.

(FFP) caused by independent variables, CG attributes in Malaysian public listed companies for the years 2017–2021.

$$\begin{aligned}\text{TechnoInnovat}(AI) = \beta_0 &+ \beta_1\text{BODSZE}_{it} \\ &+ \beta_2\text{INDEPBOD}_{it}\beta_3\text{BODMEETG}_{it} \\ &+ \beta_4\text{AUDTSZE}_{it} \\ &+ \beta_5\text{AUDTCOMMETG}_{it} \\ &+ \beta_6\text{MANOWN}_{it} + \beta_7\text{FOROWN}_{it} \\ &+ \beta_8\text{LOGTASST}_{it} \\ &+ \beta_9\text{SHAREMKTPRICE}_{it} \\ &+ \beta_{10}\text{MKTTOBV}_{it} + \beta_{11}\text{LEVERAGE}_{it} \\ &+ \beta_{12}\text{IFRS}_{it} + \varepsilon.\end{aligned}$$

10.3.2 Results and discussion of the second (2) model, that is, (B to C model)

Regression results based on the random effect (GLS) technique for the second model of the study sample are summarized in Table 4. The model examined the impact of TECHINNOVAT (AI) on ECODEVELOPEMENT. In addition to the regression findings of model two for dependent, independent, and control variables, Table 4 also reports the results of Wald Chi2(1) for goodness-of-

TABLE 4 Random effect (GLS) model 2 (B to C).

ECODEVELOPEMENT	Coef.	Std. Err.	P
TECHINNOVAT (AI)	−0.006112	0.0131101	0.064
LOGTASSETS	0.650011	0.0365648	0.000
SHAREMKETPRC	−0.075010	0.03422	0.028
MKTTOBV	−0.040390	0.0251046	0.010
LEVERGE	0.000269	0.0000931	0.004
IFRS	−0.152105	0.0418539	0.000
Cons	0.0766206	0.0325573	0.019
GLS			Random effect
Observations (320*5)			1600
R-Square			33.08
Years			Dummy
Industry			Dummy
Wald Chi(2)			56.48
Prob > Chi2			0.000
DW-statistics			1.95
Durbin (score) & Chi2(1)		1.490	0.157
Wu–Hausman F(1590)		1.210	0.247

*Significant at 10%, ** significant at 5%, and *** significant at 1%.

TABLE 5 Random effect (GLS) model 3 (A to C).

ECODEVELOPEMENT	Coef.	Std. Err.	p
BODSIZE	−0.0084774	0.012305	0.0491
INDEPBOD	−0.0004046	0.0017614	0.0818
BODMEET	0.033297	0.0134284	0.130
AUDTCOMMSZE	−0.086368	0.0279195	0.002
AUDTCOMMEET	−0.1022286	0.031526	0.001
MANGEOWNR	0.0668606	0.0337367	0.047
FORGNOWNR	−0.0512255	0.0363495	0.0159
LOGTASSETS	0.5985634	0.0384299	0.000
SHAREMKETPRC	−0.0674793	0.0338891	0.046
MKTTOBV	−0.034536	0.0257555	0.18
LEVERGE	0.0002477	0.0000927	0.008
IFRS	−0.1373727	0.0423038	0.001
Cons	−0.0084774	0.012305	0.0491
GLS			Random effect
Observations (320*5)			1600
R-square			34.24
Years			Dummy
Industry			Dummy
Wald Chi(2)			50.26
Prob > Chi2			0.000
DW-statistics			1.90
Durbin (score) Chi2(1)		1.32	0.129
Wu–Hausman F(1595)		1.75	0.145

*Significant at 10%, ** significant at 5%, and *** significant at 1%.

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TABLE 6 CG, FFP, and EM.

Independent variable	Mediating variable	Dependent variable	Step 1 A–B (a)		Step 2 B–C (b)		Step 3 A–C (c)		Step 4 path (c') A–B–C		Type of mediation
			Beta	R^2	Beta	R^2	Beta	R^2	Beta	R^2	
BODSIZE	TECHINNOVAT (AI)	ECODEVELOPEMENT	0.0133	0.0070	***0.0907	0.0131	**0.0252	0.0131	***0.0240	0.0027	Partial mediation
			0.3025		0.000		0.0277		0.0369		
INDEPBOD			0.0019	0.0007	***0.0879	0.01014	-0.0017	0.01014	-0.0016	0.0006	No mediation
			0.2878		0.0001		0.2675		0.3171		
BODMEET			***0.0469	0.0086	***0.0727	0.0374	***0.0756	0.0374	***0.0791	0.0308	Full mediation
			0.002		0.000		0.001		0.000		
AUDTCOMMEET			-0.0308	0.0013	***0.0912	0.0128	**0.0406	0.0128	**0.0378	0.0024	Partial mediation
			0.1533		0.000		0.0345		0.0500		
AUDTCOMMSZE			***0.2456	0.0195	***0.0708	0.0324	***0.2373	0.0324	***0.2547	0.0262	Full mediation
			0.000		0.0015		0.000		0.000		
MANGEOWNR			***0.0037	0.0025	***0.0792	0.0332	***0.0070	0.0332	***0.0073	0.0254	Full mediation
			0.0035		0.003		0.000		0.000		
FORGNOWNR			***0.105	0.0332	***0.0744	0.0178	***0.0047	0.00178	***0.0054	0.0111	Full mediation
			0.000		0.0010		0.000		0.0000		

Note: Four step mediation process of Baron and Kenny (1986).

fit, Prob > Chi2 for confirming the goodness-of-fitness of the model, Durbin–Watson statistics for autocorrelation, Breusch–Pagan/ Cook–Weisberg test of Chi2(1) for heteroscedasticity, while both the Durban (score) test and Wu–Hausman F(1589) test for confirming the endogeneity (Gujarati, 2009; Greene, 2012; Wooldridge, 2013; Babones, 2016). Following the previous discussion, the statistics of Wald Chi2 (1) = 56.48, with Prob > Chi2 = 0.000 for model 2 are shown in Table 4. The significance of the result (Prob > Chi2 = 0.000)confirms the goodness-of-fit for the second model of the study. Similarly, the issue of autocorrelation was identified through the Durbin–Watson test. The results of Durbin–Watson test were 1.95, showing that no issues of autocorrelation are present, as the result lies under the threshold value of Durbin–Watson, which is 2.

$$\frac{\text{Econoic}}{\text{Financial}}\text{Devp} = \beta_0 + \beta 1\text{TechnoInnovatn it} + \beta_2\text{LOGTASST}_{it} + \beta_3\text{SHAREMKTPRICE}_{it} + \beta_4\text{MKTTOBV}_{it} + \beta_5\text{LEVERAGE}_{it} + \beta_6\text{IFRS}_{it} + \varepsilon.$$

10.3.3 Results and discussion of model 3 (A to C models)

The regression results based on the random effect (GLS) technique for the third model of the study are summarized in Table 5. The findings examined the impact of specific CG attributes (BOD size, independent BOD, BOD meeting, audit committee size, audit committee meetings, managerial ownership, and foreign ownership) on ECODEVELOPEMENT. Moreover, Table 5 also explains the impact of control variables (firm size, share market price, market to book value, and leverage) on ECODEVELOPEMENT. It is worth noting that before running the regression estimator, some specific tests such as(Wald Chi2, DW-statistics, Breusch–Pagan/ Cook–Weisberg test, Durban (score) test, and Wu–Hausman) should be run to examine the reliability of the model 3 (Gujarati, 2009; Greene, 2012; Wooldridge, 2013; Babones, 2016). Following the aforementioned discussion, Table 5 reports the findings of Wald Chi2 (1) for goodness-of-fit, Prob > Chi2 for confirming the goodness-of-fit of the model, DW-statistics for autocorrelation, the Breusch–Pagan/Cook–Weisberg test of Chi2 (1) for heteroscedasticity, and both the Durban (score) test and Wu–Hausman F (1589) test for confirming the endogeneity in the third model of the study.

$$\frac{\text{Econoic}}{\text{Financial}}\text{Devp} = \beta_0 + \beta_1\text{BODSZ}_{it} + \beta_2\text{INDBOD}_{it}\,\beta_3\text{BODMTG}_{it} + \beta_4\text{ACSZ}_{it} + \beta_5\text{ACMTG}_{it} + \beta_6\text{MANOWN}_{it} + \beta_7\text{FOROWN}_{it} + \beta_8\text{LOGTASST}_{it} + \beta_9\text{SHAREMKTPRICE}_{it} + \beta_{10}\text{MKTTOBV}_{it} + \beta_{11}\text{LEVERAGE}_{it} + \beta_{12}\text{IFRS}_{it} + \varepsilon.$$

10.3.4 Results and discussion of model 4 (the mediation of FFP in the relationship between CG attributes and EM)

Table 6 shows the mediational models that are concerned with explaining the mechanism by which an independent variable exerts its impact on a dependent variable through a mediating variable. Mediation is said to occur when the causal effect of an independent variable (x) on a dependent variable (y) is transmitted by a mediator (M). This section empirically investigates model 4 of this study concerning the mediating impact of TECHINNOVAT (AI) on the relationship between specific CG attributes (BODSIZE, INDEPBOD, BODMEET, AUDTCOMMSZE, AUDTCOMMEET, MANGEROWNR, and FORGNOWNR) and ECODEVELOPEMENT.

11 Conclusion and recommendations

This study is the evidence that the effective use of the corporate governance mechanism has a differential effect on the economic development with a perfect blend of technological innovation, which clarifies the important contribution of corporate governance attributes toward the maximization of firm wealth and improvement of the overall performance of the firm that contributes to the GDP. This research provides key insights for market participants including investors, analysts, accounting, and auditing professionals. These insights relate to the role of the corporate governance mechanism in relation to technological innovation and economic development. The result also improves general awareness of the extent of technological innovation and corporate governance effectiveness in improving the economic development of the country. Similarly, the empirical result will contribute to help in recommendation and improvement of technological innovation and its adoption, economic development for the development of the Malaysian code of corporate governance (MCCG-2017). Moreover, the results of this study will help the board of directors, policy makers, government, Security Commission of Malaysia, and Bursa Malaysia for further improvements of the relevant policies and regulations in future. This study also provides theoretical contributions to prove the essence of agency theory in Malaysia, that firms should play its role in management through corporate governance practices. The empirical results also contributed to the latest knowledge of the study and extended the literature on the corporate governance mechanism and its impact on the shareholder value. Overall, although not all corporate governance variables support the stated hypotheses; but this study has

achieved its objective by identifying the attributes that answer the research question. Because the sample companies reviewed in this study suggest that earning management in Malaysian listed companies averagely increased even after the introduction of MCCG-2017. This study investigated that how a good corporate governance structure can influence earning management practices in the firm. After this empirical study, it is clear that reform in MCCG-2017 is important and new effective corporate governance compliance practices should be developed in order to minimize the practices of earning management. Apart from several contributions, this study has some limitations. First, as discussed earlier, the scope of the study is limited by its population, which included only non-financial companies listed on Bursa Malaysia under the main market rather than the ACE market. For this reason, the sample should be expanded to ACE market companies and the results should be compared with the main market companies in Bursa Malaysia. Moreover, with different years, samples, populations, and use of moderation analysis are also suggested for future researchers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Ethics statement

The patients/participants provided their written informed consent to participate in this study.

Author contributions

Idea and literature was first drafted by MK. Data were collected by MM. Analysis was performed by MA and MK, while SM helped in overview.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Cem Işık,
Anadolu University, Turkey

REVIEWED BY
Umer Shahzad,
Anhui University of Finance and Economics, China
Sufyan Ullah Khan,
University of Stavanger, Norway
Syed Hussain Gillani,
National Textile University, Pakistan

*CORRESPONDENCE
Shah Fahad,
shah.fahad@mail.xjtu.edu.cn

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The impact of digital technology use on farmers' low-carbon production behavior under the background of carbon emission peak and carbon neutrality goals

Xiaohui Huang[1], Fei Yang[1] and Shah Fahad[2,3]*

[1]Business School, Jiangsu Normal University, Xuzhou, China, [2]School of Management, Hainan University, Haikou, China, [3]School of Economics and Management, Leshan Normal University, Leshan, China

In the digital economy era, as a new production factor, digital technology can break through the information blocking constraints on farmers' behavior, become an important driving force affecting farmers' low-carbon production behavior, and provide new opportunities for agricultural green low-carbon transformation and the realization of carbon emission peak and carbon neutrality goals. Based on the field survey data of 571 farm households in Jiangsu Province, China, this paper employs the Ordered Probit model and the mediating effect test method, and takes risk cognition as the mediating variable to empirically analyze the impact of digital technology use on farmers' low-carbon production behavior and its path. The study results show that environmental risk cognition, health risk cognition, agricultural product safety risk cognition, and pesticide residue risk cognition have a significant positive impact on farmers' low-carbon production behavior. Study findings also reveal that, on one side, the use of digital technology has a direct effect on the farmers' low-carbon production behavior, on the other side, it indirectly affects the farmers' low-carbon production behavior by affecting their risk cognition, that is, risk cognition plays a partial mediation role in this relationship. Furthermore, the results indicate that among the control variables, joint cooperative membership, food security knowledge, agricultural income, technical guidance, and following instructions have a significant and positive impact on farmers' low-carbon production behavior. Based on study findings, the variable "number of the labor force" has a negative and significant impact on farmers' low-carbon production behavior. Based on study findings, to effectively realize carbon emission peak and carbon neutrality goals and promote sustainable and high-quality agriculture development, agricultural policy makers should pay attention to the role of digital technology to actively promote low-carbon production behavior.

KEYWORDS

digital technology use, farmers' low-carbon production behavior, carbon emission peak, carbon neutrality, risk cognition, mediating effect

1 Introduction

In recent years, with the rapid development of the global economy, extreme climate problems caused by dioxide emissions and other greenhouse gas emissions have become increasingly serious, which seriously threaten the economic development, ecological balance and sustainable development of human society (Chen et al., 2020; Su et al., 2021a; Song et al., 2022a; Isik et al., 2022). According to the report issued by the World Meteorological Organization, the debate on global greenhouse gases is expected to increase and the global temperature is observed to be 1.2°C higher than before industrialization. Therefore, implementing carbon emission reduction to cope with climate change has become a global consensus. Around 175 countries signed the Paris Agreement to regulate global temperature within 2 C. As the world's largest emitter of greenhouse gases, China plays a key role in carbon emission reduction. In 2020, President Xi solemnly announced at the seventy-fifth UN General Assembly that "China will augment the state's independent involvement and adopt more effective strategies and measures, by 2030, CO_2 emissions will reach the highest, while by 2060, the goal of carbon neutrality will be achieved" (Fahad et al., 2022a; Yu et al., 2021; Yang et al., 2021).

Agriculture is an important source of greenhouse gas emissions. China is the country with the highest agricultural carbon emissions in the world (Alvarado et al., 2021; Zhang et al., 2019; Zhang and Wang 2020; Fatima et al., 2022). Over the past 40 years of reform and opening up, China's grain production has achieved "eighteen consecutive harvests", which has made great contributions to world food security (Fahad et al., 2022b; Fahad et al., 2022c; Wang et al., 2020). However, this achievement mainly depend on the excessive use of chemical fertilizers, pesticides, and other relevant factors. This traditional mode of extensive agricultural production has produced a large amount of carbon emissions, resulting in serious ecological and environmental problems (Li et al., 2011; Hu and Wang, 2022; Su et al., 2021b; Song et al., 2022b), which directly threatens China's food security and agricultural sustainable development (Xu et al., 2016; Chen et al., 2017; Yang et al., 2022). Therefore, under the background of carbon emission peak and carbon neutrality goals, it is urgent to change the mode of agricultural production, promote low carbon agriculture transformation and accelerate the pace of agricultural carbon emission reduction. This will be not only a specific action to implement the new development concept but also an inevitable choice to realize ecological civilization and promote agriculture high-quality and sustainable development (Yu 2018; Jin et al., 2020; Isik et al., 2021; Han and Yuan, 2022). In order to better explore the green and low-carbon transformation of agriculture, more and more scholars have begun to devote themselves to the research of agricultural carbon emissions and other related environmental issues. At the macro level, domestic and foreign scholars have mainly carried out systematic discussions on the measurement, characteristics, and influencing factors of agricultural carbon emissions (Johnson et al., 2007). Research shows that agricultural mechanization, operation scale, agricultural support policy, technology diffusion, industrial agglomeration, and other factors affect agricultural carbon emissions (Ali et al., 2021; Ismael et al., 2018).

Currently, there are 260 million farmers in China, of which 230 million are contracted farmers (Yang et al., 2021). For a long time, the concept of "large country and small farmers" has been the basic pattern of Chinese agricultural. China's national conditions determine that ordinary farmers will remain the basic subject of agricultural production for a long time in the future (Han 2018; Hossain et al., 2022; Wang et al., 2022). Taking into account their importance, farmers are the basic subject of low-carbon agricultural production. Agriculture green transformation depends on the active participation of farmers, and promoting farmers to actively implement low carbon production behavior is of great significance to cope with climate change, improving the ecological environment, and promoting sustainable and high-quality development. The government has taken a series of effective measures to encourage farmers to reduce the input of production factors. However, in reality, farmers' agricultural production mode is still extensive, the input of chemical fertilizers, pesticides, and other production factors is still high, which makes the effect of agricultural carbon emission reduction not ideal and threatens agriculture sustainable and high-quality development. In recent years, scholars at home and abroad have conducted a lot of research on the factors that influence farmers' low-carbon production behavior. According to the existing research, farmers' low-carbon production behavior is mainly affected by their own endowment characteristics, family endowment characteristics, production and management characteristics, psychological cognition and external environment (Tian et al., 2015; Fan et al., 2017; Jiang et al., 2018; Tian 2019; Pata and Isik 2021). According to the planned behavior theory, farmers' behavior logic follows the influence path of "cognition→willingness→behavior". Farmers' cognition and behavior decision-making are constrained by information blocking, which makes farmers' behavior insufficient, and makes agriculture green and low-carbon transformation in a dilemma.

At present, China is moving toward the digital economy era. Various new technologies, new products, and new business formats are constantly emerging. The digital economy has been advancing steadily in various fields and has become an important instrument for driving economic growth and a new way to drive industrial transformation. Digital empowerment has become a common feature of the new round of scientific and technological revolution that attracted extensive attention of the society (Zhang et al., 2021; Khan et al., 2022a; Su et al., 2022). Promoting the deep integration of digital technology and

agricultural economy can further improve resource allocation efficiency and accelerate green and low carbon development, which is generally conducive to reducing carbon emissions (Ding 2020). With the establishment of China's "digital village strategy", the scale of rural Internet users is expanding. In June 2021, according to the 48th statistical report on China's Internet Development announced by the China Internet Network Information Center, the internet users in rural China were 297 million, and the Internet penetration rate in rural areas was 59.2%. It can be seen that with the rapid development of the digital economy, digital technologies such as mobile phone and the internet have generally penetrated the daily life and agricultural production of farmers. At the same time, the digital technology represented by mobile phones has broadened the farmers' access to information. It also effectively reduced information costs, facilitated rural farmers to obtain effective agricultural production information in time, strengthened farmers' risk cognition, and promoted farmers' pro-environmental behavior (Fahad and Wang, 2018; Fahad and Wang, 2019; Shi et al., 2018; Khan et al., 2022b). Digital technology can break through the restriction of information blocking on farmers' behavior decisions, inject new power into the behavior logic of "cognition→willingness→behavior", become an important driving force affecting farmers' low-carbon production behavior, and provide new opportunities for agricultural green and low-carbon transformation.

Throughout the existing studies, the following questions have not been answered.1) Under the background of carbon emission peak and carbon neutrality goals, how does digital technology use affect farmers' low carbon production behavior? 2) Does the use of digital technology affect farmers' low-carbon production behavior through risk cognition? 3) What policies and measures should be designed to promote farmers' low-carbon production behavior? In order to answer these questions, this paper builds a theoretical framework of the relationship between digital technology use and farmers' low-carbon production behavior. Based on the field survey data of 571 farm households in Jiangsu Province, China, this paper employs the ordered Probit model and the mediating effect test method, and takes risk cognition as the mediating variable to empirically analyze the impact of digital technology use on farmers' low-carbon production behavior and its path. This research is unique and contributes to academia by answering the above questions. The innovation and contribution of this paper are as follows: 1) Bring the use of digital technology and farmers' low-carbon production behavior into the same analysis framework for empirical analysis and reveal its impact on farmers' low-carbon production behavior and its mechanism; 2) Test the use of digital technology affects farmers' low-carbon production behavior through the impact mechanism of risk cognition, that is, to test the mediating effect of risk cognition; 3) From the perspective of digital technology, put forward policy suggestions to promote farmers' low-carbon production behavior. This research fills the existing research and entices academic attention to this unique issue. This paper studies the impact and mechanism of digital technology use on farmers' low-carbon production behavior from both theoretical and empirical perspectives, which has important theoretical and practical significance. It can supplement the research content of farmer behavior theory. It can provide a path choice for realizing the green and low-carbon transformation of agriculture under the background of carbon emission peak and carbon neutrality goals. It can provide practical guidance for rural digital transformation under the background of digital economy.

The remainder of this study is ordered as follows: The relevant theoretical framework is discussed in Section 2. Section 3 specifies the methodology and model specification, while Section 4 provides empirical results and discussion. Section 5 provides concludes the study and discusses limitations and propose the policy implications.

2 Theoretical framework and research hypothesis

2.1 Impact of digital technology use on farm households' low carbon production behavior

Digital technology has the advantages of high growth, wide coverage, strong permeability, cross-border integration, and intelligent sharing. It plays an important role in spreading rural ecological civilization and affecting farmers' environmental behavior (Jin and Bian 2015). Agricultural digitization can guide the rational allocation and flow of fertilizer and effectively reduce the environmental pollution caused by the use of nitrogen fertilizer (Mei 2001). The Internet provides an information platform for farmers' production activities. Farmers can timely obtain information about crops, seeds, chemical fertilizers, pesticides, disease prevention and control through mobile phone apps/software, which can help farmers reasonably plan their agricultural production activities, optimize factor input, and reduce excessive use of pesticides (Mittal and Tripathi 2009; Zhang and Zhang 2020). By watching the video of agricultural production activities on mobile phones, farmers will learn the operation specifications of pesticide reduction, guide farmers to standardize the application behavior, and achieve the purpose of pesticide reduction (Suchiradipta and Raj 2018; Wyckhuys et al., 2018). Farmers who can effectively use Internet resources have stronger safety production capacity and are more likely to reduce pesticide application (Goncalves et al., 2018). It can be noticed that the use of digital technology can change the behavior of farmers, reduce pesticide application, promote farmers' low carbon production behavior and reduce agricultural carbon emissions. Through digital technology, farmers can know the

country's carbon emission peak and carbon neutrality goals and believe that they have the responsibility to adopt low-carbon production behavior and reduce agricultural carbon emissions. Based on the above, the following research hypothesis is constructed:

Hypothesis (H1): the use of digital technology has a significant positive impact on farmers' low-carbon production behavior.

2.2 Impact of the use of digital technology on farmers' risk cognition

In general, digital technology has the characteristics of universality, permeability, and innovation. It can spread information about the ecological environment to all farmers and constantly change the cognition of farmers about the ecological environment. With the use of the Internet, farmers not only improve their cognition of relevant agricultural information, but also change their conventional ideas, formulate farming strategies, and form a modern agricultural production literacy (Cole and Fernando 2012). Information on agricultural pollution and food safety through Internet sources will encourage farmers' emotional reverberation and catastrophe consciousness, animate farmers' green production sense of responsibility, shape green production consciousness, and improve their risk cognition (Monica et al., 2019; Peng et al., 2019). It can also be noticed that digital technology not only broadens farmers' information acquisition channels but also improves farmers' information acquisition ability, so that they have more scientific knowledge and risk cognition. Through digital technology, farmers can watch videos of disasters caused by climate change. Farmers can intuitively feel the harm of carbon emissions, which will encourage farmers to adopt low-carbon production behavior and reduce agricultural carbon emissions. Based on the above following hypothesis is proposed:

Hypothesis (H2): The use of digital technology has a significant positive impact on farmers' risk cognition.

2.3 Impact of risk cognition on farmers' low-carbon production behavior

Risk cognition includes environmental risk cognition, health risk cognition, agricultural product safety risk cognition, and pesticide residue cognition. Farmers who do not know the harm of pesticide residues will unreasonable application of pesticides and random treatment of pesticide packaging (Jetiyanon and Wittaya-areekul 2009). Farmers who are conscious about food safety pay proper attention to their production behavior and avoid using pesticides with high toxicity and high residue (Zhou and Xu, 2008). Psychological cognition has a significant impact on farmers' rational application of pesticides. Farmers who understand the harm of carbon emissions can increase their risk cognition level and promote them to adopt low-carbon production behavior. The following research hypothesis is constructed accordingly:

Hypothesis (H3): Risk cognition and its different dimensions have a significant positive impact on farmers' low-carbon agricultural production behavior.

2.4 Mediating effect of the risk cognition

Farmers will obtain a large amount of carbon emission reduction information through the Internet, which will increase farmers' knowledge and thus promote farmers to reduce pesticide application (Zhao 2021). Farmers' cognition has a partial mediating effect in the impact of information utilization on farmers' adoption of Integrated Pest Management (IPM) technology (Yan et al., 2020). Based on the above analysis and from the perspective of causal logic, the use of digital technology can affect farmers' low-carbon production behavior by affecting farmers' risk cognition. Farmers can obtain a large amount of carbon emission information through digital technology, which can improve farmers' risk cognition level, and then promote farmers' low-carbon production behavior. Therefore, the following hypothesis is proposed:

Hypothesis (H4): Risk cognition and its different dimensions play a mediating effect in the relationship between the use of digital technology and farmers' low-carbon production behavior.

Consequently, this paper constructs a model including the impact of digital technology use and risk cognition on farmers' low-carbon production behavior (as shown in Figure 1).

3 Materials and methods

3.1 Data sources

A household survey was conducted during September to November 2021 in rural villages in Xuzhou and Yangzhou Jiangsu province. Primary data farmers were collected using the stratified random sampling method, for which a structured questionnaire was used. In the first phase, Xuzhou and Yangzhou were purposely chosen, and in the second phase, 2-4 districts were randomly selected from each city. In the third phase, 1-2 towns randomly chosen from each county (district), and in the fourth phase, 4-5 villages were selected from each town, and finally 12–16 farmers were targeted for a households survey from each village. A total of 580 questionnaires were distributed, and after sorting of missing questionnaires, 571 valid questionnaires were obtained with an effective rate of 98.45% (as shown in Figure 2). The questionnaire consisted of questions

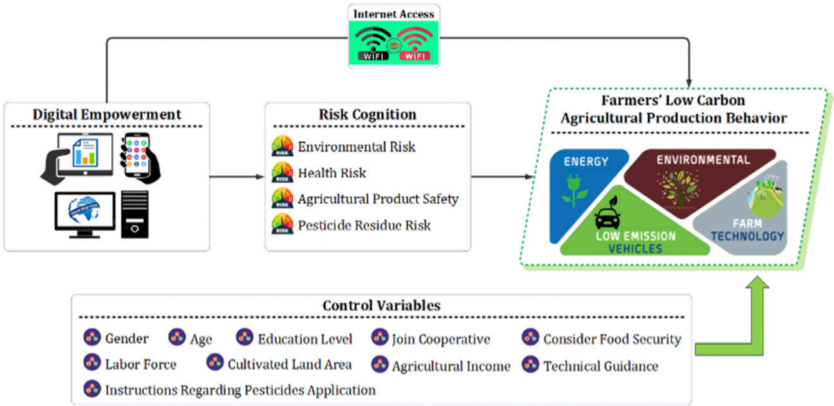

FIGURE 1
Impact mechanism of digital technology use and risk cognition on farmers' low-carbon production behavior.

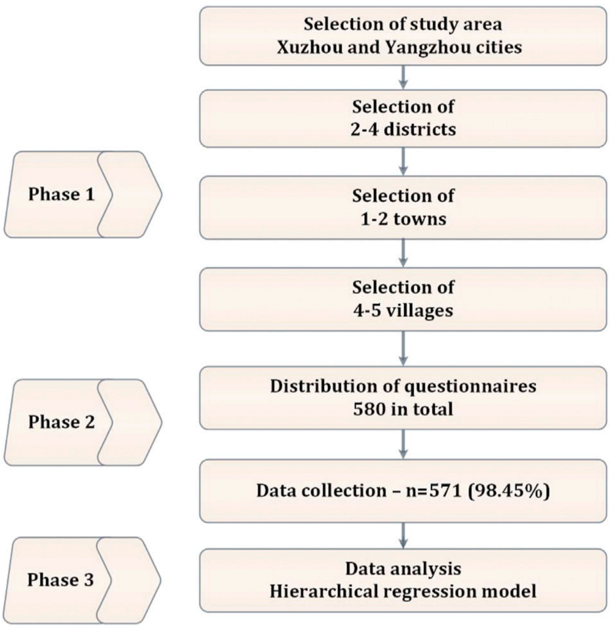

FIGURE 2
Sampling pathway.

regarding the basic characteristics of farmers and their families, farmers' risk cognition, low-carbon production behavior, and the use of digital technology. The socioeconomic characteristics of the respondents are presented in Table 1 and Figure 3. According to the household survey, 73.91% of the farmers sampled were over 50 years old, which shows that the aging of the farmers involved in agricultural production is obvious. The education level of the surveyed farmers is generally low, 86.51% of the sampled farmers had junior middle school, and below education. Men accounted for 55.87% of the total sampled farmers. Families with a total income of 20000–50000 accounted for 40.63% of the total sample. The research sample basically conforms to the current rural reality.

The main grain producing areas are important agricultural areas in China, which play the most important supporting role for the national food security. Agricultural carbon emissions in the main grain producing areas are relatively high. Therefore, the main grain producing areas have great potential for carbon emission reduction. It is of great significance to study farmers' low-carbon production behavior in main grain producing areas. Jiangsu is an important grain production province in China, and its agricultural production value and agricultural modernization level are in the forefront of the country. Therefore, Jiangsu province is selected as the research area; Xuzhou and Yangzhou cities are accelerating the construction of digital villages. They are key demonstration areas for agricultural green development and pilot areas for digital village construction. It is of practical significance to study the impact of digital technology use on farmers' low-carbon production behavior in this area. Therefore, Xuzhou City and Yangzhou city are selected as the research sites, which are representative.

3.2 Variables selection

Dependent variable: In this paper, the low carbon agricultural production behavior of farmers is used as a dependent variable. China is the largest producer and consumer of pesticides in the world. The pesticide is overused, and the effective utilization rate is less than 35%. The excessive application of pesticides is an important source of agricultural carbon emissions. Therefore,

TABLE 1 Socioeconomics characteristics of sampled farmers.

Variables	Description	Frequency	Percentage
Gender of farmers	Male	319	55.87
	Female	252	44.13
Age group of farmers	21–30 years	5	0.88
	31–40 years	25	4.38
	41–50 years	119	20.84
	51–65 years	298	52.19
	66 years and above	124	21.72
Educational level of farmers	No education	77	13.49
	Primary school	156	27.32
	Junior middle school	261	45.71
	High school	70	12.26
	Graduation or above	7	1.23
Family income	10 thousands and below	61	10.68
	10–20 thousands	60	10.51
	20–50 thousands	232	40.63
	50 thousands and above	218	38.18

Source: Households Survey 2021

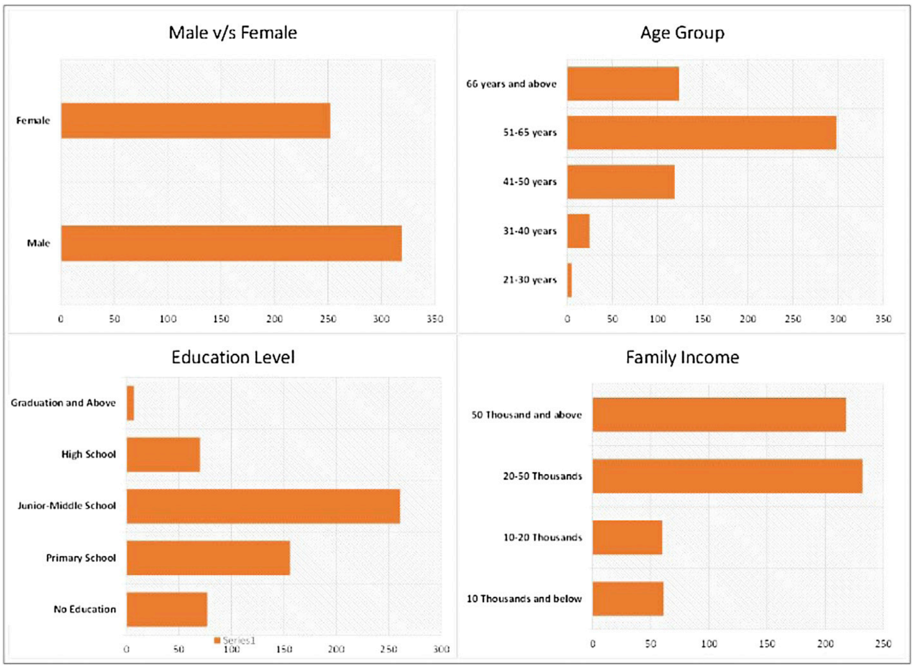

FIGURE 3
Socioeconomics characteristics.

this paper takes pesticide reduction application as an example to study farmers' low-carbon production behavior. The question is: In recent years, the amount of pesticide application per hectare in your family is decreasing?

Core explanatory variables: Digital technology use is used as core explanatory variable. The question is: whether farmers obtain agricultural related information through digital technologies such as mobile phones, such as WeChat group, app or web browsing.

TABLE 2 Variable definitions and statistical descriptions.

Variable	Description	Mean	SD	Min	Max
Dependent variable					
Farmers' pesticide reduction behavior	"The amount of pesticide application per hectare in your family is decreasing?" 1 = strongly disagree; 2 = not quite agree; 3 = general; 4 = relatively agree; 5 = strongly agree	3.10	1.33	1	5
Core explanatory variables					
Digital technology use	"Whether farmers obtain agricultural information through digital technologies such as mobile phones"	0.37	0.48	0	1
	1 = Yes; 0 = No				
Mediation variable					
Environmental risk cognition	Do you think excessive pesticide spraying has any impact on the environment?	0.64	0.48	0	1
	1 = Yes; 0 = No				
Health risk cognition	Do you think excessive pesticide spraying is harmful to your own health?	0.78	0.41	0	1
	1 = Yes; 0 = No				
Agricultural product safety risk cognition	Do you think excessive pesticide spraying has an impact on the safety of agricultural products?	0.69	0.47	0	1
	1 = Yes; 0 = No				
Pesticide residue risk cognition	Do you know what the pesticide residues are? 1 = don't know at all, 2 = know a little, 3 = know generally, 4 = know more, 5 = know very much	1.96	1.03	1	5
Control variables					
Gender	1 = Male; 0 = Female	0.56	0.49	0	1
Age	Age of the household head	57.67	10.08	25	85
Education level	Education level of the household head	2.60	0.91	1	5
	Illiterate = 1, Primary school = 2, Junior middle school = 3, High school = 4 and College graduate or above = 5				
Join cooperative	Whether to join cooperative	0.12	0.33	0	1
	1 = Yes; 0 = No				
Consider food security	Whether to consider food security	0.36	0.48	0	1
	1 = Yes; 0 = No				
Labor force	Number of the labor force	4.95	1.69	1	11
Cultivated land area	Cultivated land area of family (*mu*)	4.86	2.68	0	20
Agricultural income	Household agricultural income (10 thousand)	0.76	0.77	0	6
Technical guidance	Have you received any guidance from agricultural technicians on pesticides?	0.19	0.39	0	1
	1 = Yes; 0 = No				
Follow the instructions	Do you follow the instructions when applying the pesticides? 1 = Yes; 0 = No	0.69	0.46	0	1

Source: Households Survey 2021.

When farmers use one of the platforms to obtain agricultural related information, the value is 1, otherwise it is 0.

Mediation variables (risk cognition): Excessive use of pesticides can cause serious damage to the environment (soil, water, atmosphere, ecological balance, etc.), produce a lot of carbon emissions, damage to farmers' own health, lead to excessive residues of agricultural products, and seriously threaten the quality and safety of agricultural products. This paper comprehensively focused on the farmers' risk cognition (e.g., farmers' environmental risk cognition, health risk cognition, agricultural product safety risk cognition, and pesticide residue risk cognition) as a mediator variable.

Control variables: Following the existing relevant literature, gender, age, level of education, joint cooperative membership, food security cognition, number of the labor force, agricultural income, cultivated land area, technical guidance were used as control variables in this study. Table 2 shows the descriptive statistics of the variables used in this study.

3.3 Model specification

3.3.1 Benchmark regression model

The hierarchical five-likert scale technique was used to evaluate farmers' pesticide reduction application behavior. Farmers' pesticide reduction application behavior was ranked from 1 to 5, where 1 = strongly disagree, 2 = not quite agree,3 = general, 4 = relatively agree,5 = strongly agree. For this kind of discrete variable, probability model is usually used for estimation. As the discrete variable of farmers' pesticide reduction

application behavior has exceeded two categories and is in an orderly state, so, ordered Probit model approach was used to estimate farmers' pesticide reduction application behavior. The basic form of the Ordered Probit model is as follows:

$$y^* = X^{'}\beta + \varepsilon \tag{1}$$

The selection rule is:

$$y = \begin{cases} 1, & \text{if } y* \le r_1 \\ 2 & \text{if } r_1 < y* \le r_2 \\ 3 & \text{if } r_2 < y* \le r_3 \\ 4 & \text{if } r_3 < y* \le r_4 \\ 5 & \text{if } r_4 < y^* \end{cases} \tag{2}$$

Assuming $\varepsilon \sim N(0,1)$,then:

$$\begin{aligned} P(y=1|x) &= P(y^* \le r_1|x) = P(x'\beta + \varepsilon \le r_1|x) \\ &= P(\varepsilon \le r_1 - x'\beta|x) = \Phi(r_1 - x'\beta) \\ P(y=2|x) &= P(r_1 < y^* \le r_2|x) = P(y^* \le r_2|x) - P(y^* < r_1|x) \\ &= P(x'\beta + \varepsilon \le r_2|x) - \Phi(r_1 - x'\beta) \\ &= P(\varepsilon \le r_2 - x'\beta|x) - \Phi(r_1 - x'\beta) \\ &= \Phi(r_2 - x'\beta) - \Phi(r_1 - x'\beta) \\ P(y=3|x) &= \Phi(r_3 - x'\beta) - \Phi(r_2 - x'\beta) \\ P(y=4|x) &= \Phi(r_4 - x'\beta) - \Phi(r_3 - x'\beta) \\ P(y=5|x) &= 1 - \Phi(r_4 - x'\beta) \end{aligned} \tag{3}$$

In Eq. 1, y^* is an unobservable potential variable and X are independent variables, representing the factors affecting farmers' pesticide reduction application behavior, namely risk cognition and control variables.β represents the parameters to be estimated, $\varepsilon_i \sim N(0, \sigma^2 2I)$, $r_1 < r_2 < r_3 < r_4$ is the cut-off point.

3.3.2 Mediating effect model

In the field of psychology and other social sciences, a large number of empirical articles have established mediating effect models to analyze the influence process and mechanism of independent variables on dependent variables. Among them, the most representative is the mediating effect test proposed by Wen et al. (2004). This paper uses this method to verify that risk cognition plays an intermediary role in the relationship between digital technology use and farmers' low-carbon production behavior. The details are as follows:

$$Y_i = cX + e_1 \tag{4}$$

$$M_i = a_1X + e_2 \tag{5}$$

$$Y_i = c'X + bM_i + e_3 \tag{6}$$

In the above equations, X represents digital technology use; Y_i represents farmers' pesticide reduction application behavior; M_i represents the risk cognition of farmers. a_1、b、c、c' are regression coefficients, e_1、e_2、e_3 are the random error terms. In this paper, Eq. 4 is used to test the direct impact of digital technology use on farmers' pesticide reduction application behavior. Eq. 5 and Eq. 6 are used to test whether the use of digital technology can indirectly affect farmers' pesticide reduction application behavior by influencing farmers' risk cognition.

4 Results and discussion

4.1 Impact of digital technology use

In Table 3, the results of Model 1 and 2 revealed that the use of digital technology has a positive and significant impact on farmers' low-carbon production behavior. This indicates that with the rapid development of digitization and the popularization of the Internet networks, digital networks have become the main information sources of farmers. Through the digital network platform, farmers will receive more and more professional pesticide-related information and understand that excessive application of pesticides leads to increased carbon emissions and climatic and environmental problems. In this regard, farmers will carry out agricultural low-carbon production and reduce the usage of pesticides and hence it verifies the *Hypothesis (H1)*. In Table 3, the use of digital technology has a significant and positive impact (at a 1% significance level) on the environmental risk cognition of farmers, agricultural product safety risk cognition, pesticide residue risk cognition, the use of digital technology has a significant and positive impact (at a 5% significance level) on health risk cognition, which verifies *Hypothesis H2*. The dissemination and education function of digital technology can increase the knowledge level of farmers, improve risk cognition.

4.2 Impact of risk cognition

The results show that environmental risk cognition has a positive and significant impact on farmers' low-carbon production behavior. If farmers assume that excessive pesticide use has an adverse effect on the environment, they are more likely to reduce the amount of pesticide use, consequently reducing agricultural carbon emissions. According to the findings, health risk cognition also showed a positive and significant relationship with farmers' pesticide reduction behavior (at 5% significance level), indicating that when farmers think excessive spraying of pesticides has adverse impacts on their health, they are more likely to reduce pesticide use of pesticides. Likewise, agricultural product safety risk cognition showed a positive and significant association with farmers' pesticide reduction behavior, when farmers assume that excessive pesticide use has an adverse impact on the safety of their agricultural product income and pesticide residues in agricultural products, they are more likely to avoid pesticide use. Similarly, risk cognition of pesticide residues also revealed a positive and significant relationship with farmers' pesticide reduction behavior, indicating that When farmers are worried that the pesticide residues in agricultural products are

TABLE 3 Impact of digital technology use and risk cognition on farmers' pesticide reduction behavior.

Variable	Model 1		Model 2	
	Coefficient	Standard error	Coefficient	Standard error
Digital technology use	0.933***	0.174	0.725**	0.177
Risk cognition				
Environmental risk cognition			0.336***	0.106
Health risk cognition			0.661**	0.259
Agricultural product safety risk cognition			0.882***	0.236
Pesticide residue risk cognition			0.254***	0.087
Control variables				
Gender	0.122	0.165	0.353	0.172
Age	−0.000	0.165	0.083	0.105
Educational level	−0.007	0.014	−0.029	0.096
Joint cooperative membership	1.948***	0.282	1.864***	0.286
Consider food security issues	0.566***	0.168	0.458**	0.177
Agricultural income	0.239*	0.125	0.224*	0.123
Cultivated land area	0.031	0.035	0.003	0.036
Number of labor force	−0.121	0.077	−0.166**	0.079
Technical guidance	1.581***	0.223	1.629***	0.229
Follow the instructions	1.102***	0.181	0.923***	0.184
Log likelihood	−764.24539		−714.3369	
LR chi2	239.42		339.23	
Prob > chi2	0.0000		0.0000	
Pseudo R2	0.1354		0.1919	

Note: *, ** and *** represent significant tests at 10%, 5%, and 1% levels, respectively.

TABLE 4 Impact of digital technology use on farmers' risk cognition.

	Environmental risk cognition	Health risk cognition	Agricultural product safety risk cognition	Pesticide residue risk cognition
Digital technology use	0.575***	0.917***	0.669***	0.322*
Other variables	Controlled	Controlled	Controlled	Controlled
Log likelihood	−356.82906	−284.45538	−338.80757	−710.94263
Prob > chi2	0.0002	0.0010	0.0010	0.0000

Note: *, ** and *** represent significant tests at 10%, 5%, and 1% levels, respectively.

too high and affect their income, they are more likely to reduce pesticide usage, so that hypothesis (*H3*) is verified here.

4.3 Mediating effect of risk cognition in the relationship between the use of digital technology and farmers' low-carbon agricultural production behavior

According to the results of model 1 in Table 3, the impact of digital technology use on farmers' low-carbon agricultural production behavior shows significant at a level of 1% with coefficient 0.933. It can be seen from the results in Tables 3, 4, that the use of digital technology has a significant and positive impact on risk cognition. According to the results of model 2 in Table 3, after the introduction of risk cognition, the impact of risk cognition on the pesticide reduction behavior of farmers showed a significantly positive relationship. At the same time, the impact of digital technology use on farmers' pesticide reduction behavior still shows a significantly positive association, but the coefficient is reduced to 0.725. Therefore, risk cognition plays the role of a mediator in the relationship between digital technology use and farmers' pesticide reduction behavior, which verifies *hypothesis* (*H4*).

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With the popularity of the Internet, the Internet has become one of the main channels for farmers to obtain relevant agricultural information and knowledge. This led farmers to understand that the excessive use of pesticides will increase carbon emissions and cause climatic and environmental problems. Farm households will also realize that the excessive application of pesticides will lead to pesticide residues, affect the safety of agricultural products, affect their health, and increase the levels of farmers' risk cognition. This will promote farmers' low-carbon production behavior.

4.4 Impact of control variable

Among control variables, joint cooperative membership has a positive and significant effect on farmers' low-carbon agricultural production behavior. In practice, cooperatives provide standardized technical guidance and training services to their members through technical service teams, invited agricultural experts, and agricultural technology extension personnel, which promote farmers' pesticide reduction behavior (Cai et al., 2019). Farmers considering food security showed a positive and significant association with farmers' pesticide reduction behavior, indicating that farmers who are more aware about their food security are more likely to reduce the use of pesticide. Based on the findings of the study, agricultural income has shown a positive relationship with farmers' pesticide reduction behavior at a significance level of 1%. This indicates that the higher the agricultural income, the more farmers rely on agricultural production and the more they can realize the losses due to the excessive use of pesticides. Therefore, farmers are more likely to reduce the use of pesticides. Likewise, the variable number of labor force has revealed a negative but significant impact on the farmers' pesticide reduction behavior, pointing that the higher the number of labor force, the more they rely on non-agricultural income and pay less attention to the agricultural production activities. Therefore, farmers are unlikely to reduce pesticide application. Technical guidance from extension services has shown a positive and significant impact on farmers' pesticide reduction behavior, showing that farmers with more access to extension sources obtained guidance from agricultural extension services are more likely to receive a reduction in pesticide reduction behavior. The more they know about pesticide residues, the more they know about pesticide usage norms, and the more likely they are to reduce pesticide usage. Farmers who have received training on pesticide usage are more likely to choose environmentally friendly pesticide application behavior (Li and Guan, 2013). This also reflects the importance of training in pesticide use in rational application. Results further showed a positive and significant association with farmers' pesticide reduction behavior, indicating that the instructions regarding the use of pesticides through scientific sources led farmers to more likely reduce the use of pesticides. Relevant research shows that the size of the farm has a very important influence on the adoption of eco-friendly fertilization technology adoption. However, the regression results of this paper show that the land scale did not pass the significance test. The possible explanation is that the sample farmers' land management scale is small, they may rely more on non-agricultural employment income, pay little attention to agricultural production, and adopt low-carbon production behavior which has no scale economy effect, which inhibits farmers' low-carbon production behavior.

5 Conclusions and policy implications

5.1 Conclusions

Based on the field survey data of 571 farm households in China, and employs the Ordered Probit model and the mediating effect test method, this study empirically analyzes the impact of digital technology use on farmers' pesticide reduction behavior by taking risk cognition as mediating variable. Based on the findings of the study, the following are the concluding points. Environmental risk cognition, health risk cognition, agricultural product safety risk cognition, and pesticide residue risk cognition have shown a significant and positive affect on farmers' pesticide reduction behavior. The use of digital technology has a direct impact on farmers' pesticide reduction behavior, while it indirectly affects farmers' pesticide reduction behavior by influencing farmers' risk cognition, which indicates that risk cognition plays a part of the mediating effect in this influence relationship. Among the control variables, joining cooperatives, considering food security, agricultural income, technical guidance, and following the instructions have shown positive and significant impact on the farmers' pesticide reduction behavior. Furthermore, the number of labor force showed a negative and significant impact on farmers' pesticide reduction behavior.

5.2 Policy implications

Based on the results of our study and the above conclusion, the following policy recommendations are proposed.

a. Governments and other authorities should formulate relevant policies to support digital development in rural areas, accelerate the construction of digital technology infrastructure, improve the level of rural digitization, and improve the availability of digital infrastructure for farm households. Improve the digital literacy of farmers and promote the development of low-carbon agriculture through digitization. Promote the rapid transformation of

the mode of agricultural development by means of digital technology, in order to further promote the green and low carbon transformation and sustainable development of agriculture.

b. In the promotion of the current rural digital strategy, it is necessary to pay attention to the role of digital technology in the education of farmers' ecological knowledge, make full use of the education and communication function of digital technology to disseminate ecological knowledge to farmers, improve farmers' awareness of environmental protection and ecological risk cognition, enhance farmers' pesticide residue hazards cognition, and enhance farmers' skills in scientific and safe use of pesticides, so as to promote farmers' pesticide reduction behavior.
c. Governments and responsible authorities should provide farmers with pesticide guidance and technical training about pesticide usage, which will improve their cognitive level, prevent excessive pesticide application, reduce uncertain behavior in pesticide usage, and fundamentally reduce agricultural carbon emissions.
d. We should explore and build a sound policy system to support the development of cooperatives, guide the healthy development of cooperatives, promote cooperatives to strengthen service guidance and training for farmers, and drive farmers' low-carbon production behavior.

This study has few limitations as follows: First, due to limited time and funds, we only selected 571 farm households in Jiangsu province as the research object, which could not reflect the general situation of low-carbon agricultural production behavior in China. Due to the limited objective conditions, we used only 1 year data, that is, cross-sectional data of the peasant household survey, which cannot reflect the dynamic change process of the peasant household's low-carbon agricultural production behavior. Therefore, future research should focus on expanding the research area and research objects and enhance the representativeness and persuasion of research conclusions. We should also use the tracking survey data for many years to investigate the dynamic change trend of farmers' low-carbon production behavior.

Second, digital technology use can be affected by the personal characteristics of farmers, and it is a kind of self-selection behavior. Therefore, there may be endogenous problems. However, there is no appropriate tool variable in the questionnaire, so this problem is not well solved, which is also a defect of the paper. It will be improved in future research. With the continuous development of digital services, the digital literacy and digital skills of farmers are constantly improving, and the participation of farmers in digital production, digital logistics, digital marketing, digital finance, digital life and digital rural governance is getting higher and higher. Therefore, in the future, we should measure digital technology with a diversified indicator system. Low carbon production behaviors include chemical fertilizer reduction application, pesticide reduction application, conservation tillage technology, soil testing formula fertilizer technology, green pest prevention and control technology, water-saving irrigation technology, straw returning to the field, agricultural film recycling and so on. In this paper, the low-carbon production behavior expressed by pesticide reduction application has certain limitations. In the future, the low-carbon production behavior of farmers should be investigated from multiple dimensions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

XH: Writing—original draft. FY Conceptualization, Supervision. SF Writing—review and editing and Data curation, Visualization, Investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Cem Işık,
Anadolu University, Turkey

REVIEWED BY
Mohamed Chakroun,
German University of Technology in Oman, Oman
Minhaj Ali,
Islamia University of Bahawalpur, Pakistan

*CORRESPONDENCE
Jun Zhou,
304696@whut.edu.cn
Qamaruddin Maitlo,
qamar.maitlo@iba-suk.edu.pk

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Effect of green technology innovation on the upgrading of the manufacturing value chain: Evidence from China

Xiuting Wang[1], Jun Zhou[1]* and Qamaruddin Maitlo[2]*

[1]School of Management, Wuhan University of Technology, Wuhan, China, [2]Department of Business Administration, Sukkur IBA University, Sukkur, Pakistan

Green technology innovation is an important driving force for the upgrading of the manufacturing value chain. The purpose of this study is to explore the effect of green technology innovation on the upgrading of the manufacturing value chain under institutional environments. To this aim, the panel data of 28 provinces in China from 2010 to 2019 and panel threshold regression model are applied. Empirical results show that the effect of green technology innovation on the upgrading of the manufacturing value chain is nonlinear under institutional environments. The effect of formal and informal institutional environments on the relationship between green technology innovation and the upgrading of the manufacturing value chain is also different. The positive effect of green technology innovation on the upgrading of the manufacturing value chain is best when the level of formal institutional environment is high and informal institutional environment is moderate. In addition, when we divide the sample into three regions (Eastern, Central, Western), the effect of green technology innovation on the upgrading of the manufacturing value chain under institutional environments shows regional heterogeneity. Hence, with this calculated optimal interval of institutional environments, the government can adjust and improve institutional environments so as to provide the most favorable institutional conditions for green technology innovation to promote the upgrading of the manufacturing value chain. This research is helpful for the government to make rational decisions according to the situation.

KEYWORDS

green technology innovation, the upgrading of the manufacturing value chain, formal institutional environment, threshold effect, informal institutional environment

1 Introduction

Constructing a powerful manufacturing country, promoting green transformation and upgrading the manufacturing industry are important development strategies of China at present. Under economic globalization, the key to strengthening the manufacturing industry is to promote the position of the manufacturing industry in the global value chain. However, developed countries have firmly occupied the high end of the global value

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chain with their advanced technology, abundant market resources and strong independent innovation ability, and China is facing the dilemma of "low-end locking" in the global value chain (Chen et al., 2019). Production and manufacturing links at the low end of the global value chain tend to consume a lot of energy and emit a lot of carbon dioxide (Ren et al., 2014; Kan et al., 2019), China's resource and environmental carrying capacity is close to its limit, and it is unsustainable to sacrifice the environment for the development of manufacturing (Qu et al., 2020).

Green technology innovation can promote the industrial green transformation (Kemp and Never, 2017) and achieve "win-win" state between economic development and ecological protection (Sun et al., 2008; Schiederig et al., 2012). In this context, China has launched "Made in China 2025″ strategy and "Industrial Green Development Plan (2016–2020)", and the report of the 19th National Congress of the Communist Party of China also clearly proposed to "build a market-oriented green technology innovation system and strengthen the main position of green technology innovation in enterprises", which aimed at driving the upgrading of the manufacturing value chain through green technology innovation and realizing the coordinated development of society, economy and ecology. However, green technology innovation has the positive externality of knowledge and technology spillover and the negative externality of production pollution. Society can benefit from the reduction of environmental pollution while enterprises bear the high risk and high investment of green technology innovation, so it is difficult to drive enterprises to carry out green technology innovation only by market mechanism (Wu et al., 2021). Some studies showed that policies can effectively promote green technology innovation, especially environmental regulations (Yang and Yang, 2015); social trust can reduce the occurrence of infringement or "free riding" to a certain extent, and alleviate the externality of green technology innovation (Yang et al., 2021); the media can guide the public to understand and evaluate the green innovation behavior of enterprises, which will exert public pressure on enterprises, and then force enterprises to pay attention to green innovation (Sun et al., 2021), all of which imply that we can improve formal institutions such as environmental regulation and informal institutions such as social trust and media attention to promote enterprises to carry out green innovation activities and then promote the upgrading of the manufacturing value chain. However, most of the researches on the relationship between green technology innovation, institutional environments and the upgrading of the manufacturing value chain focus on the exploration of the relationship between the two rather than bring institutional environments into the research framework of green technology innovation and the upgrading of the manufacturing value chain and explore the relationship between the three. For example, Yuan and Chen (2019) used GMM estimation to test the impact of environmental regulation on technological innovation and the impact of green technology innovation on the transformation and upgrading of manufacturing, and concluded that strict environmental regulation would promote pollution-intensive enterprises to engage in green technology innovation, and that the relationship between green technology innovation and the transformation and upgrading of manufacturing was U-shaped; Du et al. (2021) measured the heterogeneous effects of environmental regulation on green technology innovation and the industrial structure in 105 environmental monitoring cities in China, and concluded that when the level of economic development is low, environmental regulation will inhibit the development of green technology innovation. In addition, the advantage of the threshold model is that it can find the structural break points through real data simulation and perform statistical tests on it, which overcomes the subjectivity of selecting the threshold through group regression and cross model (Yang and Song, 2019).

Based on existing research results, this study attempts to fill the gap in the existing literature by incorporating the institutional environments into the research framework of green technology innovation and the upgrading of the manufacturing value chain, and further testing the effect of institutional environments on the relationship between green technology innovation and the upgrading of the manufacturing value chain. Specifically, based on the panel data of 28 provinces in China from 2010 to 2019, this study empirically investigate the driving effect of green technology innovation on the upgrading of the manufacturing value chain, and the effect of institutional environments on the relationship between green technology innovation and the upgrading of the manufacturing value chain. This study answers the following two questions: 1) Can green technology innovation effectively promote the upgrading of the manufacturing value chain? 2) How to adjust and improve the institutional environments to make green technology innovation better promote the upgrading of the manufacturing value chain? Does formal and informal institutional environments play different roles? Is there regional heterogeneity? This study can make the following contributions: firstly, because of the externalities of green technology innovation, it is difficult to promote enterprise to carry out green technology innovation only by the market mechanism. This study believes that the institutional environments plays an important role in the process of green technology innovation promoting the upgrading of the manufacturing value chain, and brings it into the research framework. Secondly, this study brings formal and informal institutional environments into the research framework at the same time, and compares the differences of their roles. Thirdly, it further divides the sample into three regions to explore the regional heterogeneity of effcet of green technology innovation on the upgrading of the manufacturing value chain under

different institutional environments, aiming at providing the government with a rational basis for making decisions on regional green technology innovation policies and improving institutional environments. The rest of the study is organized as follows: Section 2 reviews relevant literature, Section 3 provides theoretical background and research hypothesis, Section 4 provides model settings and variable descriptions, Section 5 provides results and discussion, Section 6 provides conclusions and policy recommendations, and Section 7 is the limitations and future research directions.

2 Literature review

With the development of green environmental protection and low-carbon life concepts, the effect of green technology innovation and institutional environments on the upgrading of the manufacturing value chain has gradually attracted the attention of scholars. Regarding the relationship between green technology innovation, institutional environments and the upgrading of the manufacturing value chain, scholars have mostly explored the effect of green technology innovation on the upgrading of the manufacturing value chain, the effect of institutional environments on green technology innovation and the effect of institutional environments on the upgrading of the manufacturing value chain.

2.1 Green technology innovation and the upgrading of the manufacturing value chain

Regarding the relationship between green technology innovation and the upgrading of the manufacturing value chain, there are two more representative views at home and abroad: one view is that green technology innovation can effectively promote the upgrading of the manufacturing value chain, stimulate changes in demand and play a decisive role in the upgrading of the industrial structure (Kaplinsky and Morris, 2000). This positive effect is mainly reflected in two aspects: the innovative compensation effect and the energy saving and emission reduction effect. The innovative compensation effect is mainly because green technology innovation can promote the upgrading of enterprise processes, products and functions by increasing production efficiency, improving or creating brand new products, and promoting the fame of brands (Yuan and Dai, 2017). The energy saving and emission reduction effect is mainly the improvement of enterprise's green technology innovation ability that can promote the development and the use of various cleaner production processes, emission reduction technologies and green products, which can reduce energy consumption and pollution emissions, save environmental costs, thus improving enterprise profitability and promoting the upgrading of the value chain (Hua, 2011). Another view is that green technology innovation has a certain inhibitory effect on the upgrading of the manufacturing value chain, which is mainly embodied in the lock-in effect and crowding-out effect. The lock-in effect is mainly because in international competition, the developed countries, with their advantages in mastering core technology and resources and their position in the "high end" of the global value chain, threaten OEM enterprises in developing countries at the low end of the value chain with large transaction orders to maintain the production position of low cost, high energy consumption and high pollution. The lock-in effect has seriously inhibited the enterprises' enthusiasm for green technology innovation in developing countries, making them locked in the low-end of manufacturing sector with high pollution and low technology for a long time (Yang and Lu, 1998; Zhong and Wang, 2000). The "crowding-out effect" is mainly because in the process of transforming from high pollution and low efficiency technology to low pollution and high efficiency green and clean technology, enterprises need to invest more money to transform existing equipment and technology, which will inevitably crowd out other development funds when they have limited funds. Therefore, the crowding-out effect will cause a decline of an enterprise's production profits in a short period of time, which is not conducive to the upgrading of the value chain (Yuan and Shen, 2000).

In the above studies, most scholars have only investigated the unidirectional promotion or inhibitory relationship between green technology innovation and the upgrading of the manufacturing value chain, and only a few scholars have explored the bidirectional nonlinear relationship. For example, Song et al. (2021) empirically analyzed the impact of green technology innovation on the upgrading of the manufacturing value chain, and believed that green technology innovation has a U-shaped impact on the upgrading of the manufacturing value chain.

2.2 Institutional environments and the upgrading of the manufacturing value chain

In the field of world economic research, in which the global value chain specialization is a hot topic, the importance of institutional factors has been repeatedly emphasized. Whether the institutional environments are good will affect a country's role in the global value chain, and the institutional environments have a positive effect on the upgrading of the global value chain (Nunn, 2007; Feenstra et al., 2013). Good institutional environments can reduce the uncertainty in enterprises' Research and Development (R&D), drive the development and application of high technology, and promote the continuous upgrading of value chain's status (Tebaldi and

Elmsile, 2013). Conversely, a country's participation in the international division of the global value chain will also promote the improvement of its institutional quality (Jin et al., 2008). The definition of institutions in these studies mainly involves legal rules and trade agreements in contract execution and property rights protection (Hu and Zhang, 2015), which do not include institutional reforms targeting the internals of a country and tend to adopt a marketization index to measure the institutional environment (Shen and Wang, 2019; Zhao et al., 2019). However, the differences in characteristics between the index of marketization and technological innovation may lead to incorrect conclusions (Xu, 2018).

In recent years, with the introduction of a series of national environmental regulation policies, although some scholars have explored the relationship between environmental regulation and the upgrading of the value chain (Han and Yan, 2020), they have ignored the role of informal institutional environment. The effective implementation of formal institutions such as environmental regulation cannot be separated from the external supervision and governance mechanisms (Becker and Murphy, 1993). Therefore, it is difficult to comprehensively and deeply reflect the current institutional environments and its relationship with the upgrading of manufacturing value chains in China only from the perspective of formal environmental regulation.

2.3 Institutional environments and green technology innovation

Regarding the impact of the institutional environments on green technology innovation, domestic and foreign scholars have mostly explored it from the perspective of formal environmental regulation, but they have not formed a unified understanding. There are mainly the following viewpoints: firstly, moderate environmental regulation is conducive to promoting green technology innovation (Potter and Van der Linde, 1995; Lee et al., 2010); secondly, environmental regulation is detrimental to firms' technological innovation (Gray and Shadbegian, 2003; Blind, 2012); thirdly, the relationship between environmental regulation and green technology innovation is nonlinear and environmental regulation has a U-shaped or inverted U-shaped impact on green technology innovation (Peng et al., 2017; Du et al., 2019). The reason why the above conclusions are inconsistent is that the research object and observation period are different, and the mechanism of different types of environmental regulation on green technology innovation is also different (Wang and Qi, 2016). At present, China's formal institutions are not perfect enough to effectively promote enterprises to carry out green technology innovation (Yang et al., 2021), and informal institutions can complement and support formal institutions, thus improving the performance of formal institutions and promoting the realization of environmental governance goals (Wheeler and Afsah, 2000; Féres and Reynaud, 2012). Therefore, it is necessary to explore this in more depth from the dual perspectives of formal and informal institutional environments.

3 Theoretical background and research hypothesis

3.1 Theoretical background

Institutional environments are composed of cognitive, normative, regulatory structures and activities (Scott, 1995). According to its nature, it can be divided into formal institutional environment and informal institutional environment. The formal institutional environment mainly includes political environment, legal environment, etc. While the informal institutional environment mainly includes culture, language, social ideology and public psychology (North, 1990). Formal environmental regulation is one of the institutional pressures imposed by the government on environmental behavior of enterprises, which can reflect the level of formal institutional environment in the region to a certain extent. Social trust and media attention are important elements of informal institutions, which have an important influence on enterprises' adoption of clean technology, attention to environmental management and reduction of pollution emissions (Becker and Murphy, 1993; da Motta and Moreira, 2006; Zhao and Zhang, 2020).

Institutional theory argues that institutional environments in which enterprises are located will have an important impact on the behaviors of enterprises (Oliver, 1991), which implies that we can promote enterprises to carry out green innovation activities by adjusting and improving the institutional environments and then promote the upgrading of the manufacturing value chain.

3.2 Research hypothesis

Due to the high input cost and a certain risk in the early stage of green technology innovation, only a few enterprises with huge capital and strong R&D capacity will choose to try, which cannot drive the transformation and upgrading of industries. With a further increase in the intensity of the formal institutional environment, the deterrent effect of administrative punishment may make enterprises perceive the increase of illegal risks and costs, so enterprises will increase their investment in green technology innovation, improve production efficiency, cut production costs. The resulting profits can compensate or even offset the costs brought by environmental regulation, thereby generating innovative compensation effect and promoting industrial transformation. Therefore, the effect of green technology innovation on the

upgrading of the manufacturing value chain changes with the formal institutional environment. And the level of formal institutional environment needs to reach a certain threshold before green technology innovation can promote the upgrading of the manufacturing value chain, that is, there is a non-linear relationship.

As media pay more attention to environmental issues, enterprises will increase investment in environmental protection to avoid damage to their public image, develop clean energy and green products, improve green innovation ability. In addition, a high level of social trust is more conducive to promoting enterprises to fulfil their social contract and obey environmental laws and regulations, which promotes the efficiency of the cooperation between enterprises and reduces the costs. Therefore, as the informal institutional environment improves, it will be good for green technology innovation to promote the upgrading of the manufacturing value chain. However, when the media pay too much attention to environmental issues, excessive public pressure may induce government's administrative punishment, which causes a strong burden of legitimacy to enterprises. Thus, the green technology innovation activities of enterprises, and even the survival and development of enterprises will be affected, which is not conducive to promoting the upgrading of the manufacturing value chain. It can be seen that the effect of green technology innovation on the upgrading of the manufacturing value chain will be different due to the different levels of informal institutional environment. Accordingly, this study proposes hypothesis:

Hypothesis. the effect of green technology innovation on the upgrading of the manufacturing value chain has nonlinear characteristics, and there is a threshold effect of formal and informal institutional environments.

4 Model settings and variable description

4.1 Model settings

It is necessary to study the direct relationship between green technology innovation and the upgrading of the manufacturing value chain. Therefore, we construct model (1). According to the previous analysis, the relationship between green technology innovation and the upgrading of the manufacturing value chain may be non-linear, we refer to the practice of Zhao and Xi (2022) by adding the quadratic term of green technology innovation and constructing the following two-way fixed effects panel model:

$$umvc_{it} = \beta_0 + \beta_1 gti_{it} + \beta_2 control_{it} + \mu_i + \eta_t + \varepsilon_{it} \tag{1}$$

$$umvc_{it} = \beta_0 + \beta_1 gti_{it} + \beta_2 gti_{it}^2 + \beta_3 control_{it} + \mu_i + \eta_t + \varepsilon_{it} \tag{2}$$

In order to avoid generating errors by artificial grouping and to effectively judge the significance of the threshold value, this study use Hansen's nonlinear panel threshold regression model to construct a piecewise function with the formal and informal institutional environments as threshold variables to verify whether green technology innovation has a nonlinear threshold effect on the upgrading of the manufacturing value chain. The multiple threshold panel model (taking a double threshold as an example) is as follows:

$$\begin{aligned} umvc_{it} = \beta_0 + \beta_1 gti_{it} \cdot I(ie_{it} \le \gamma_1) + \beta_2 gti_{it} \cdot I(\gamma_1 < ie_{it} \le \gamma_2) \\ + \beta_3 gti_{it} \cdot I(ie_{it} > \gamma_2) + \beta_4 control_{it} + \varepsilon_{it} + \mu_i \end{aligned} \tag{3}$$

In the above models, i denotes the province, t denotes the year, umvc (upgrading of the manufacturing value chain) is the explanatory variable, gti (green technology innovation) is the explanatory variable, gti^2 is the quadratic term of green technology innovation, ie (institutional environments) is the threshold variable (divided into formal and informal institutional environments), control denotes a set of control variables affecting the upgrading of the manufacturing value chain (human capital (hc), degree of openness (open) and financial development (fd)), I (·) is an indicative function, γ is threshold values, β_0 denotes intercept terms, $\beta_1, \beta_2, \beta_3, \beta_4$ are the coefficients of variables, μ_i is the individual effect, η_t is the time effect and ε_{it} is the random disturbance variables.

4.2 Variable description and data sources

4.2.1 Explained variable

Upgrading of the manufacturing value chain (umvc). At present, most of the quantitative indicators of the upgrading of the manufacturing value chain are measured by the manufacturing profit margin, manufacturing profits and taxes, the status index of the value chain, the export technological level and the participation index. However, according to the "smiling curve" theory, most developed countries are in high-end segments of the global value chain with high-tech and high-value-added while developing countries are mainly in low-end segments of the global value chain with low-tech and low-value-added, such as simple production, assembly, processing and manufacturing. Therefore, according to the logic that the trade structure reflects the production structure, under the global production network system, the technical complexity of a country or region's production and exports of products can reflect the position of a country or region in the global value chain. Based on the practice of Qiu et al. (2012), this study uses export complexity to measure the upgrading of the manufacturing value chain. The specific calculation formulas are as follows:

TABLE 1 Evaluation system of green total factor productivity in each province.

Type	Primary indicators	Secondary indicators
Input	Capital elements	Internal expenditures of R&D funds in each province
	Labor elements	Full-time equivalent of R&D personnel in each province
	Energy elements	Energy consumption in each province
Output	Desired output	GDP deflated to the constant price level based on 2009 in each province
	Undesired output	Industrial sulfur dioxide emissions in each province

$$PRODY_k = \sum_i \frac{x_{ik}/X_i}{\sum_i x_{ik}/X_i} Y_i \quad (4)$$

$$MVC_{in} = \sum_k \frac{x_{ink}}{x_{in}} PRODY_k \quad (5)$$

In model (4), PRODY denotes the industry export complexity; i denotes the province, k denotes the industry, X_{ik} denotes the export value of industry k in region i, X_i denotes the export value of all industries in region i, and Y_i denotes the per capita Gross Domestic Product (GDP) of region i. In model (5), MVC denotes the regional export complexity, X_{in} denotes the export value of year n in region i, X_{ink} denotes the export value of industry k in region i and year n.

4.2.2 Explanatory variable

Green technology innovation (gti). Green total factor productivity considers both socio-economic factors such as capital, labor and desired output in an integrated manner, as well as resource and environmental factors such as energy consumption and undesired output, which has been widely used (Qu et al., 2020). Given that the traditional Data Envelopment Analysis (DEA) model does not consider slack variables and cannot distinguish effective decision units whose efficiency is all 1, Tone (2002) proposed the super Slack Based Measure-Data Envelopment Analysis (SBM-DEA) model based on the traditional DEA model. Thus, this study refers to the practice of Lv et al. (2021) by using the Global Malmquist-Luenberger (GML) index of super SBM-DEA model to calculate green total factor productivity and using green total factor productivity to characterize the level of green technology innovation in each province. In addition, this study measures green total factor productivity from two aspects of input and output. The specific input and output indicators are shown in Table 1.

Since GML only reflects the rate of change of green technology innovation, this study refer to the practice of Song et al. (2018) by assuming that the level of green technology innovation in the base period of 2009 is 1, and the level of green technology innovation in 2010 is equal to the level of green technology innovation in 2009 multiplied by the GML index, and so on for other years to obtain the level of green technology innovation in each province from 2010 to 2019.

4.2.3 Threshold variables

Formal institutional environment (fie). At this stage, in order to restrict the environmental violations of enterprises, the Chinese government often uses environmental administrative penalties as the main means to impose sanctions on illegal enterprises in the process of implementing environmental regulations policies. In addition, sewage charge is the first negative market incentive tool adopted in China, which has a long implementation time, wide coverage and strong representativeness. The total number of environmental proposals of National People's Congress (NPC) and Chinese People's Political Consultative Conference (CPPCC) is an important form of public participation in environmental protection supervision, which represents the public's attention to environmental issues to a certain extent.

Therefore, this study draws on the practices of Wang et al. (2020), Yi et al. (2019) and Wu et al. (2020) by taking the number of environmental administrative penalties, sewage charges and total environmental proposals of NPC and CPPCC in each province to characterize the formal institutional environment. In addition, the entropy method is used to combine the number of environmental administrative penalties, sewage charges and total environmental proposals of NPC and CPPCC in each province to comprehensively measure the formal institutional environment.

Informal institutional environment (iie). Most of study use a single index to measure it, and this study uses the entropy method to combine social trust and media attention together, which is more reasonable. Referring to the relevant research of Wang and Li (2017), Liu and Li (2019), survey data from the China General Social Survey (CGSS) are used to measure the level of provincial social trust. The following question was included in all previous surveys: "In general, do you agree that the vast majority of people in this society can be trusted?" Respondents were asked to choose the most appropriate answer from a list of five options ranging from "completely disagree" to "completely agree". The five options are assigned values of 1, 2, 3, 4 and 5, respectively. The simple average of the respondents' answers in the area was

calculated as the level of regional social trust in the current year. The higher the score is, the higher the level of provincial social trust. Since survey data from 2014, 2016, 2018 and 2019 were unavailable during the sample period and social trust remains relatively stable for a certain period of time, the data from 2013 was used to measure the level of provincial social trust in 2014, the data from 2015 was used to measure the level of provincial social trust in 2016, and the data from 2017 were used to measure the level of provincial social trust in 2018–2019. Based on the practice of Xu et al. (2011), we use the number of environmental-related news reports in each province from 2009 to 2018 to reflect the degree of media attention in the area (considering the media lag, the 1-year lagged data are processed simultaneously with the data from 2010 to 2019). The data were collected from two authoritative official media outlets (News.com and People's Daily Online) and two market-oriented online media outlets (Sina.com and Sohu.com). We conduct searches using keywords such as "ecological environment, environmental pollution, closure of polluting enterprises, environmental accountability, green development, environmental governance, environmental taxation and environmental insurance", clean the data of related environmental reports, merge the reports with the same or similar contents, and finally obtain the number of environmental-related news reports in 28 provinces *via* manual sorting.

4.2.4 Control variables

Regarding the selection of control variables, relevant studies have confirmed that human capital (hc), degree of openness (open), financial development (fd) have a certain impact on the upgrading of industry. Therefore, this study introduces these three variables as control variables to limit errors. As for the selection of the measurement indicators of the variables, human capital (hc) is measured by the average years of education in each province and calculated by the formula: [(primary school population *6 years)+ (junior middle school population *9 years)+(senior high school population *12 years)+(junior college population and above* 16 years)]/(population aged 6 years and above), degree of openness (open) is measured by the ratio of total imports and exports volume to the GDP in each province, financial development (fd) is measured by the ratio of loan balance of financial institutions to the GDP in each province.

4.2.5 Data sources

Considering data continuity and availability, this study selects the panel data of 28 provinces from 2010 to 2019 for empirical evaluation. To obtain the data, China's statistical yearbook, China's science and technology statistical yearbook, China's energy statistical yearbook, China's environment yearbook, China's tax yearbook, the China General Social Survey, the international trade research and decision support system of China's research network, and the statistical yearbooks of various regions were consulted.

TABLE 2 Descriptive statistics of variables.

Variable	N	Mean	Sd	Min	P50	Max
umvc	280	10.790	0.210	10.289	10.819	11.104
gti	280	1.225	0.427	0.553	1.084	2.963
fie	280	0.251	0.196	0.010	0.200	0.935
iie	280	0.292	0.187	0.025	0.258	0.936
fd	280	1.340	0.449	0.655	1.255	2.585
hc	280	2.204	0.101	1.912	2.199	2.540
open	280	0.281	0.323	0.013	0.135	1.548

5 Results and discussion

5.1 Descriptive statistics

In order to eliminate the influence of heteroscedasticity, umvc and hc are processed with logarithm in this study. The descriptive statistical results of variables are shown in Table 2.

5.2 Model stationary test

5.2.1 Panel data unit root test

In order to avoid the existence of false regression, this study carries out unit root test on panel data before empirical analysis. The test results are shown in Table 3. It can be seen from Table 3 that *p*-value of LLC and PP-Fisher tests of the seven sequences are less than 0.05, so we can think all panel data are stable.

5.2.2 Multiple collinearity test

To avoid the interference of multiple multicollinearity, VIF (Variance Inflation Factor) method is used to diagnose the multicollinearity. The specific test results are shown in Table 4. It can be seen from Table 4 that VIFs of all variables are less than 5, indicating that there is no multicollinearity among the variables.

5.3 Regression results of basic model

First, the relationship between green technology innovation and the upgrading of the manufacturing value chain is estimated. The regression results are shown in Table 5. In model 1, the coefficient of green technology innovation is negative. In model 2, the coefficient of gti is significantly negative, and the coefficient of gti^2 is significantly positive. The possible reasons are as follows: the knowledge path and

TABLE 3 Unit root test results of panel data.

Variable	LLC test		PP-Fisher test		Conclusion
	Statistic	*p*-value	Statistic	*p*-value	
umvc	−17.1650***	0.0000	146.867***	0.0000	Smooth
gti	−2.1620**	0.0153	86.2109**	0.0059	Smooth
fie	−11.7363***	0.0000	107.491***	0.0000	Smooth
iie	−9.8713 **	0.0000	95.8858**	0.0007	Smooth
fd	−6.0622***	0.0000	126.7680***	0.0000	Smooth
hc	−16.5666***	0.0000	343.8660***	0.0000	Smooth
open	−8.2246***	0.0000	88.1287***	0.0040	Smooth

Notes: ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$. The same parameters are applied below.

TABLE 4 VIF multicollinearity test results.

Variable	VIF	1/VIF	Variable	VIF	1/VIF
gti	1.56	0.6406	fd	1.64	0.6099
fie	1.33	0.7516	hc	2.17	0.4608
iie	1.37	0.7294	open	2.00	0.4999
Mean VIF	1.68				

TABLE 5 Regression results of basic model.

Variables	Model 1	Model 2
gti	−0.0370**	−0.109*
	(−2.77)	(−2.44)
gti^2		0.0212*
		(2.20)
fd	0.0284***	0.0221***
	(4.27)	(4.58)
hc	0.243*	0.198*
	(2.14)	(2.17)
open	0.0849***	0.0908***
	(6.06)	(6.38)
constant	9.894***	10.05***
	(41.63)	(58.82)
N	280	280

Note: t statistics in parentheses; *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

market dependence lead to the embedded dependence of China's manufacturing industry in the global value chain, which means that manufacturing enterprises give priority to the use of low-cost technology in the value chain and refuse to implement high cost independent innovation (Hao and Zhang, 2016). Thus, enterprises may choose the scheme with the least economic loss to avoid the risk of green technology innovation, and cannot truly drive the industrial transformation and upgrading. With the gradual promotion of green technology innovation, the compensation effect produced by green technology innovation will reduce pollution costs while improving product quality and competitive advantage. When enterprises realize value-creating ability of green technology innovation, they will actively carry out green technology innovation, form a virtuous circle, and truly promote the upgrading and development of industry. Song et al. (2021) believed that there is a U-shaped relationship between green technology innovation and the upgrading of manufacturing value chain, that is, green technology innovation must exceed a certain threshold to promote the upgrading of the manufacturing value chain. Our results are consistent with Song et al. (2021).

5.4 Institutional environments threshold effect test

5.4.1 Endogeneity tests results

The threshold model developed by Hansen assumes that the threshold variable is not endogenous. We draw on the practices of Yang et al. (2019) and Zhang et al. (2022) by using the Durbin Wu Hausmann chi-square test to tset the endogeneity of threshold variables, and it shows formal institutional environment (fie) and informal institutional environment (iie) are not endogenous (chi-sq value is 0.12 and 0.42, respectively; *p*-values is 0.7337 and 0.5147, respectively).

5.4.2 Threshold effect significance test

Results of the threshold effect significance test corresponding threshold estimations and the 95% confidence intervals using formal and informal institutional environments as the threshold variables are shown in Table 6. It can be seen from Table 6 that both the single threshold and the double threshold pass the significance test.

TABLE 6 Significance test and confidence intervals of institutional environments thresholds.

Threshold variable	Model	Threshold estimates	F-value	*p*-value	95% confidence interval
fie	Single	0.152	15.907**	0.033	[0.139, 0.186]
	Double	0.370	41.444***	0.000	[0.336, 0.440]
iie	Single	0.218	49.063**	0.013	[0.218, 0.234]
	Double	0.516	19.510***	0.010	[0.457, 0.766]

Notes: (1) The *p* value is the result of 400 rounds of bootstrap repeated sampling.

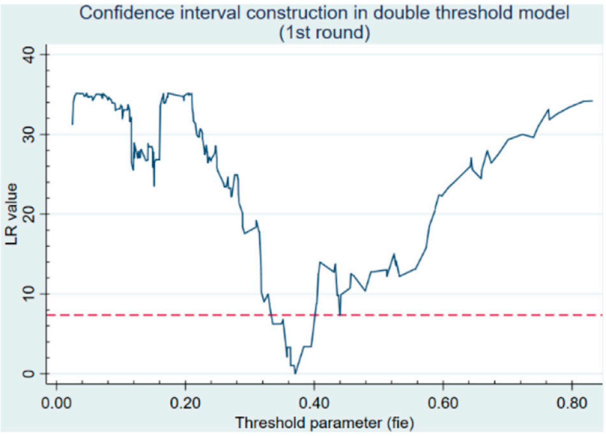

FIGURE 1
The LR map corresponding to the first threshold estimate of the threshold variable *fie*.

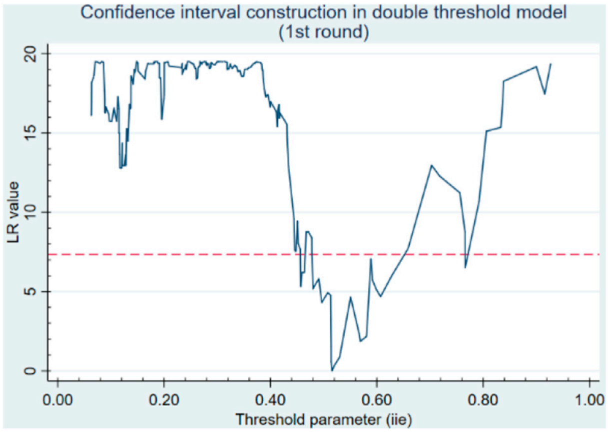

FIGURE 3
The LR map corresponding to the first threshold estimate of the threshold variable *iie*.

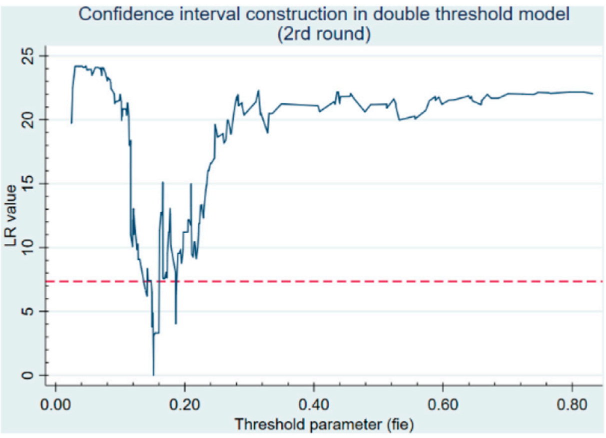

FIGURE 2
The LR map corresponding to the second threshold estimate of the threshold variable *fie*.

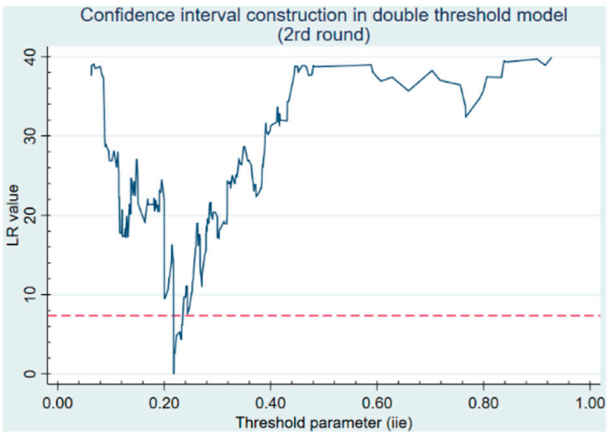

FIGURE 4
The LR map corresponding to the second threshold estimate of the threshold variable *iie*.

5.4.3 Threshold effect authenticity test

After completing the threshold effect significance test, we need to test the authenticity of the threshold estimation. When the upgrading of the manufacturing value chain is used as an dependent variable, the two thresholds estimated from the double threshold model of the formal institutional

TABLE 7 Threshold model estimation results.

Variable	(1)	Variable	(2)
fd	0.395***(12.89)	fd	0.281***(10.95)
hc	1.698***(12.75)	hc	1.772***(13.01)
open	−0.471***(−12.20)	open	−0.410***(−12.53)
gti (fie≤0.152)	−0.0150 (−0.58)	gti (iie≤0.218)	0.0880***(3.99)
gti (0.152 < fie≤0.370)	0.0565**(2.46)	gti (0.218 < iie≤0.516)	0.157***(7.19)
gti (fie>0.370)	0.145***(6.41)	gti (iie>0.516)	0.0766***(2.72)
Constant	6.586***(23.71)	Constant	6.470***(22.63)
F-value	328.69	F-value	371.06
R-squared	0.8693	R-squared	0.8825
Observations	280	Observations	280

environment are 0.152 and 0.370, respectively. The corresponding likelihood ratio function graph is shown in Figure 1 and Figure 2. The figures show that the two threshold estimates of the formal institutional environment fall within the acceptable domain of the original hypothesis, indicating that the two threshold estimates are equal to the true value and pass the threshold authenticity test. The two thresholds estimated from the double threshold model of the informal institutional environment are 0.218 and 0.516, respectively. The corresponding likelihood ratio function graph is shown in Figure 3 and Figure 4. Similarly, we can know that the two threshold estimates of the informal institutional environment are equal to the true value and pass the threshold authenticity test.

5.4.4 Threshold regression model estimation results

The threshold regression model estimation results for green technology innovation and the upgrading of the manufacturing value chain obtained by using formal and informal institutional environments as the threshold variables are shown in Table 7. Thus, hypothesis is proved.

The results show that the relationship between green technology innovation and the upgrading of the manufacturing value chain is U-shaped under formal institutional environment. When the level of formal institutional environment is lower than 0.152, green technology innovation has a negative effect on the upgrading of the manufacturing value chain, but the effect is not significant. When the level of formal institutional environment ranges from 0.152 to 0.370, the effect of green technology innovation on the upgrading of the manufacturing value chain shift from negative to positive. This result shows that with the increase of the level of formal institutional environment, green technology innovation begins to promote the upgrading of the manufacturing value chain. When the level of formal institutional environment is greater than 0.370, the positive effect is enhanced. The possible reasons are as follows:

As green technology innovation is still in the preliminary stage of development, with strong economic externalities, as well as the characteristics of high investment and high risk, enterprises lack sufficient motivation to carry out it. As the level of formal institutional environment increases, in order to avoid the adverse impact of administrative penalties on production and operation, enterprises will improve the production process, develop new green products and increase the added value of products through green technology innovation, thus improving the competitiveness of enterprises and promoting the upgrading of the manufacturing value chain.

According to the threshold model estimation results in Table 7, there is a complex nonlinear relationship between green technology innovation and the upgrading of the manufacturing value chain under informal institutional environment. When the level of informal institutional environment is less than 0.218, green technology innovation has a positive effect on the upgrading of the manufacturing value chain, with a coefficient of 0.0880 significant at the 1% level. When the level of informal institutional environment ranges from 0.218 to 0.516, green technology innovation still significantly and positively promotes the upgrading of the manufacturing value chain. However, when the level of informal institutional environment is greater than 0.516, the positive effect diminishes to some extent. The possible reasons are as follows: after the events of environmental pollution are reported by the media, it will generate public opinion pressure on enterprises and force them to take corresponding improvement measures, so as to promote enterprises to implement green technology innovation. This is not only conducive to solving the public's demands for environmental protection, but also helps enterprises achieve certain economic benefits through energy conservation and emission reduction. In addition, a high level of social trust is more conducive to promoting enterprises to fulfill their social contract and obey environmental laws and regulations, which promotes the efficiency of the cooperation between enterprises and reduces

the transaction cost. However, when media pay too much attention to environmental issues, it will have a negative effect on the enterprise's green technology innovation. This is mainly because the public will have a higher degree of acceptance of the negative information with the massive exposure of the negative news, which will seriously damage the social reputation and image of enterprises, and is not conductive to promoting green technology innovation and strategy of development.

In terms of control variables, the regression coefficient of financial development (fd) is significantly positive, indicating that financial development is conducive to promoting the upgrading of the manufacturing value chain, probably because a developed financial system can provide financial support for green innovation and relieve financial pressure. The regression coefficient of human capital (hc) is positive at 1% significance level, indicating that the cultivation of human capital has a positive effect on the upgrading of the manufacturing value chain, probably because high-quality human capital can provide solid intellectual support for the upgrading of the manufacturing value chain. The regression coefficient of degree of openness (open) is significantly negative, indicating that degree of openness has a negative effect on the upgrading of China's manufacturing value chain at this stage, which may be related to the low technology content of China's foreign trade products for a long time.

5.5 Model robustness test

In order to further enhance the reliability of the research results, we used alternative measures of institutional environments to test the robustness. Considering the number of environmental petitions and the total number of environmental proposals of the NPC and CPPCC are both an important form of public participation in environmental protection supervision, which represent the public's attention to environmental issues to a certain extent, we use the number of environmental petitions replace the total number of environmental proposals of the NPC and CPPCC to calculate the level of formal institutional environment. As for informal institutional environment, we have changed the calculation method of social trust. The original calculation method was to assign values of 1, 2, 3, 4 and 5 to the five options from "completely disagree" to "completely agree", and the simple average of the respondents' answers in the area was calculated as the level of regional social trust in the current year. Now, we draws on the practices of Liu and Li (2019) by using the proportion of "completely agree" and "relatively agree" in the total number of respondents in the area as the level of regional social trust. Robustness test results are shown in Table 8. The double threshold effect still exists and the coefficient symbol of each variable does not change significantly. Therefore, our empirical analysis is reliable and stable.

5.6 Regional institutional environments threshold effect test

5.6.1 Regional threshold effect significance test

In order to further reveal the regional heterogeneity of the relationship between green technology innovation and the upgrading of the manufacturing value chain, and get more targeted research conclusions, this study divides the samples into three groups (including Eastern region, Central region, Western region). Based on the regional significance test and confidence intervals of institutional environments thresholds in Table 9, it is found that the single threshold of Eastern region and Western region, double threshold of Central region pass the significance test when taking formal institutional environment as the threshold variable. Similarly, the double threshold of Eastern region and Central region, the single threshold of Western region pass the significance test when taking informal institutional environment as the threshold variable.

5.6.2 Regional threshold regression estimation results

The regional threshold regression results for green technology innovation and the upgrading of the manufacturing value chain obtained by using the formal institutional environment as the threshold variable are shown in Table 10. The results show that there is significant regional heterogeneity in the relationship between green technology innovation and the upgrading of the manufacturing value chain in Eastern region, Central regional and Western region. The details are presented as follows:

1) In Eastern region, green technology innovation has a positive effect on promoting the upgrading of the manufacturing value chain. When the level of formal institutional environment is greater than the first threshold value of 0.384, the promotion effect is further enhanced. 2) In Central region, green technology innovation has a U-shaped effcet on the upgrading of the manufacturing value chain. When the level of formal institutional environment is less than 0.103, green technology innovation will inhibit the upgrading of the manufacturing value chain. When the level of formal institutional environment is greater than 0.103, the effect of green technology innovation on the upgrading of the manufacturing value chain will shift from negative to positive. When the level of formal institutional environment is greater than the second threshold value of 0.226, the promotion effect is further enhanced. 3) In Western region, green technology innovation also has a U-shaped effect on the upgrading of the manufacturing value chain. When the level of formal institutional environment is less than 0.114, green technology innovation will inhibit the upgrading of the manufacturing value chain. When the level of formal institutional environment exceeds 0.114, the effect of green technology innovation on the upgrading of manufacturing value chain shift from negative to positive. The possible reasons are as follows: Eastern region has a more perfect environmental protection institutions and stronger enforcement of

TABLE 8 Robustness test results.

Variable	(1)	Variable	(2)
fd	0.402***(13.22)	fd	0.290***(11.17)
hc	1.658***(12.67)	hc	1.801***(12.92)
open	−0.449***(−11.78)	open	−0.431***(−12.94)
gti (fie≤0.167)	−0.0137 (−0.55)	gti (iie≤0.246)	0.101***(4.50)
gti (0.167 < fie≤0.370)	0.0609**(2.58)	gti (0.246 < iie≤0.591)	0.154***(6.82)
gti (fie>0.370)	0.145***(6.63)	gti (iie>0.591)	0.0531*(1.67)
Constant	6.657***(24.39)	Constant	6.404***(21.90)
F-value	340.11	F-value	352.70
R-squared	0.8732	R-squared	0.8771
Observations	280	Observations	280

TABLE 9 Regional significance test and confidence intervals of institutional environments thresholds.

Threshold variable	Region	Model	Threshold estimates	F-value	*p*-value	95% confidence interval
fie	Eastern region	Single	0.384	14.775**	0.028	[0.363, 0.660]
	Central region	Double	0.103	28.007*	0.056	[0.072, 0.328]
			0.226	21.656***	0.000	[0.128, 0.322]
	Western region	Single	0.114	11.303**	0.052	[0.102, 0.152]
iie	Eastern region	Double	0.224	16.396**	0.024	[0.181, 0.358]
			0.494	19.975*	0.056	[0.462, 0.651]
	Central region	Double	0.260	21.115*	0.080	[0.233, 0.407]
			0.407	25.860***	0.000	[0.077, 0.515]
	Western region	Single	0.153	35.648*	0.092	[0.151, 0.199]

Notes: (1) The *p* value is the result of 250 rounds of bootstrap repeated sampling.

environmental regulation policies, so the formal institutional environment show a better effect. However, economic development in Central and Western region is relatively dropped behind. Considering the maintenance of enterprises' competitive advantage, the protection of employment and the development of economy in this area, local governments may have a "weak enforcement" of environmental regulations. Therefore, the level of formal institutional environment in Central and Western region must exceed a certain threshold to promote green technology innovation and then realize the upgrading of the manufacturing value chain.

The regional threshold regression results for green technology innovation and the upgrading of the manufacturing value chain obtained by using the informal institutional environment as the threshold variable are presented as follows:

1) In Eastern region, the relationship between green technology innovation and the upgrading of the manufacturing value chain is nonlinear. When the level of informal institutional environment is less than 0.224, green technology innovation will promote the upgrading of the manufacturing value chain. When the level of informal institutional environment is between 0.224 and 0.494, the promotion effect will be enhanced. However, when the level of informal institutional environment is greater than 0.494, the promotion effect will be diminished. 2) In Central region, the relationship between green technology innovation and the upgrading of the manufacturing value chain is also nonlinear. When the level of informal institutional environment is less than 0.260, green technology innovation will promote the upgrading of the manufacturing value chain. When the level of informal institutional environment ranges from 0.260 to 0.407, the promotion effect will be enhanced. When the level of informal institutional environment is greater than 0.407, the promotion effect will be further enhanced. 3) In Western region, green technology innovation has a U-shaped effect on the upgrading of the manufacturing value chain. When the level of informal institutional environment is less than 0.153, green technology innovation will inhibit the upgrading of the manufacturing value chain. When the level of informal institutional environment exceeds 0.153, the effect of green technology innovation on the upgrading of the manufacturing value chain will shift from negative to positive. The possible reasons are as follows: Eastern region has a higher level

TABLE 10 Regional threshold model estimation results.

Variable	Formal institutional environment			Informal institutional environment		
	Eastern region	Central region	Western region	Eastern region	Central region	Western region
fd	0.138**	0.593***	0.458***	0.122***	0.390***	0.336***
	(2.58)	(9.07)	(12.62)	(3.50)	(6.20)	(10.72)
hc	1.554***	2.388***	1.735***	1.253***	1.950***	2.426***
	(6.02)	(11.88)	(9.03)	(7.08)	(8.09)	(12.81)
open	−0.285***	−0.985***	−0.786***	−0.456***	−0.661*	−0.821***
	(−6.19)	(−2.89)	(−3.87)	(−9.71)	(−1.69)	(−3.64)
gti1	0.129***	−0.0374	−0.106**	0.136***	0.0913**	−0.0268
	(3.97)	(−0.95)	(−2.05)	(5.14)	(2.24)	(−0.51)
gti2	0.222***	0.0315	0.0742*	0.208***	0.169***	0.0968**
	(7.60)	(0.73)	(1.72)	(7.96)	(3.70)	(2.49)
gti3		0.0833**		0.136***	0.253***	
		(2.09)		(4.77)	(4.72)	
Constant	7.002***	4.966***	6.495***	7.817***	5.992***	3.843***
	(12.79)	(11.91)	(16.74)	(21.54)	(11.65)	(6.38)
F-value	122.71	190.02	113.06	124.68	177.03	141.51
R-squared	0.8783	0.9341	0.8693	0.8800	0.9296	0.8927
Observations	100	80	100	100	80	100

of development, more access to resources, higher information transparency, and people are more sensitive to environmental issues. However, the ability to obtain resources is relatively weak in Central and Western regions, and the degree of information asymmetry is higher. In Eastern region, moderate media attention is conducive to promoting the implementation of policies and supervising the innovation behavior of enterprises, while excessive media attention may bring negative effect; in Central and Western regions, media attention can greatly alleviate information asymmetry, improve information transparency, alleviate "weak enforcement", further promote enterprises' innovation and then realize the upgrading of the manufacturing value chain.

6 Conclusions and policy recommendations

With the development of globalization, China has increasingly participated in the international division of labor, and the scale of foreign trade is also expanding. However, China's manufacturing industry has fell into the dilemma of "low-end locking" when the industry was integrated into the system of the division of labor in the global value chain. It has been indicated by some research that green technology innovation is an important driving force to promote the upgrading of manufacturing value chain. Due to the externalities of green technology innovation, it is difficult to promote enterprises to carry out green technology innovation activities only by the market mechanism. According to the institutional theory, the institutional environments in which an enterprise is located will have an important impact on its behavior. Therefore, what impact do institutional environments have on the relationship between green technology innovation and the upgrading of the manufacturing value chain? To this aim, the panel data of 28 provinces in China from 2010 to 2019 and panel threshold regression model are applied. The empirical results show that green technology innovation can promote the upgrading of the manufacturing value chain in the long run. There is a nonlinear relationship between green technology innovation and the upgrading of the manufacturing value chain under institutional environments, and the role of formal and informal institutional environments are different. In addition, when we divide the sample into three regions (Eastern, Central, Western), the effect of green technology innovation on the upgrading of the manufacturing value chain under institutional environments shows regional heterogeneity. These findings can help us to clarify the internal logic between the three variables and provide reference for the government to implement policies accurately. According to the above results, some policies can be implemented to promote enterprises to carry out green technology innovation and realize the upgrading of manufacturing value chain:

1) Restrict harmful non-green innovation activities. It can be seen from the above empirical results that green technology innovation can promote the upgrading of the manufacturing value chain in the long run. Therefore, while guiding

enterprises to carry out green technology innovation, the government should make good use of the dual effect of institutional environments to supervise and restrict the non-green innovation activities that may cause negative externalities to the ecological environment.

2) Measure the performance of green technology innovation from a comprehensive perspective. Enterprises should not use simple income and expenditure to measure the benefits of green technology innovation. They should realize that the mode of high energy consumption and high pollution will not only have a negative impact on the environment, but also go against the sustainable development of itself. Therefore, they should actively carry out green innovation activities, which are not only beneficial to enterprises to gain market competitive advantage, but also can promote the transformation and upgrading of manufacturing industry.
3) Take effective actions to reduce the risk of uncertainty. Rising uncertainty is one of the prominent phenomenon of today's modern economic systems, it not only affects some macroeconomic parameters (Işık et al., 2020), but also affects green innovation decision-making behavior of enterprises. Therefore, we should actively take the following measures: 1) the government should aim at the forefront of green technology innovation, focus on key areas, and publish a green technology demand directory to point out the direction for enterprises; 2) we should create an environment with high social trust, alleviate information asymmetry, reduce transaction costs, and strengthen the supervision of green technology innovation of enterprises; 3) the government should try to maintain consistency and continuity in formulating and implementing policies. At the same time, we must suit our measures to different conditions in terms of locality and time rather than "one size fits all" when adjust the regional institutional environment.

7 Limitations and future research

Due to various factors, this study still has the following limitations and the follow-up research can be improved from the following aspects: 1) Research object: This study mainly takes China as the research object without considering other countries. Future research can take other countries as the object to verify whether our conclusions are universal. 2) Sample size: This study mainly uses the data of 28 provinces in China from 2010 to 2019. Although it is enough to carry out the research in this study, future research can expand the time scope to make the research results more comprehensive. 3) Research perspective: Most of the previous studies are based on the perspective of formal environmental regulation to explore the relationship between the institutional environments, green technology innovation and the upgrading of the manufacturing value chain while ignore the possible impact of the informal institutional environment, thus making the research results not comprehensive. Although this study considers the perspective of informal institutional environment, it does not consider the synergy of the formal institutional environment and informal institutional environment. Future research can consider the synergy of the two to further enrich the Porter hypothesis and global value chain theory.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Author contributions

XW: Conceptualization, methodology, validation, supervision, project administration, writing—review and editing. JZ: Software formal analysis, data curation, writing—original draft preparation. QM: review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.994323/full#supplementary-material

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The Women University, Pakistan
Rabia Saleem,
University of Derby, United Kingdom

*CORRESPONDENCE
W. Ahmad Watto,
waqasbzu67@gmail.com

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Role of artificial intelligence in moderating the innovative financial process of the banking sector: a research based on structural equation modeling

M. R. Rabbani [1], A. Lutfi [2,3], M. A. Ashraf [4], N. Nawaz [5] and W. Ahmad Watto [6]*

[1]Department of Economics and Finance, College of Business Administration University of Bahrain, Sakhir, Bahrain, [2]Department of Accounting, College of Business, King Faisal University, Al-Ahsa, Saudi Arabia, [3]Applied Science Research Center, Applied Science Private University, Amman, Jordan, [4]Visiting Faculty Member at Department of Accountancy Superior, University of Lahore, Lahore, Pakistan, [5]Associate Professor Department of Business Management College of Business Administration, Kingdom University, Riffa, Bahrain, [6]Department of Commerce, Bahauddin Zakariya University Multan, Multan, Pakistan

This study seeks to find the moderating role of AI in the association between a bank's innovative financial process and the bank's market share. The data were analyzed using SPSS and SmartPLS software. The estimations were performed using structural equation modeling estimation techniques such as the measurement model, outer loading, convergent validity, discriminant validity, and SEM estimations. The initial estimations indicated factor as well as construct reliability and validity. The study concluded that an innovative financial process plays a vital role in enhancing the bank's market share. However, artificial intelligence could not significantly moderate the relationship. The policymakers in the banking industry of Pakistan need to consider the up-gradation in the system of their financial process by innovation and artificial intelligence usage awareness in their existing staff as well their banking customers. Future research may include a similar model for Islamic as well as commercial banks in a comparative model. Additionally, future research may also include more banks as innovative financial institutions to get a greater sample size for a possible influence of artificial intelligence.

KEYWORDS

innovative financial process, bank's market share, artificial intelligence, Silkbank, silk

1 Introduction

The technological advancement of the banking sector in the modern era is based on the type of services provided as per the requirements and facilitation of customers backed by an innovative process of financial services along with the right use of artificial intelligence (Omoge et al., 2022). The usage of AI in the bank's financial system has accelerated the financial data in the banking industry providing a broader customer base

in the form of digital apps, digital payments, and chat-bot systems (Karim et al., 2021; Rabbani 2022). Pakistan is one of those countries where the system of AI for the banking industry is still under process as compared to developed nations (Hassan et al., 2020; Khan et al., 2021; Rabbani et al., 2022a, b). A company's market share is indeed the percentage of total income it earns in a given industry (Hussain M. K et al., 2022). Artificial intelligence is regarded as the future of banking as it brings innovative financial solutions to prevent fraudulent financial transactions, brings efficiency, and also improves compliance (Doumpos et al., 2022). It is important to study the role of artificial intelligence in moderating the innovative financial services in the banking sector.

Market share is typically measured by dividing a firm's revenue for a certain time by some sector's total sales for the same time (Caminal and Vives, 1996). The market share of such a corporation is a vital indicator of its performance (Tash et al., 2014). A firm's profitability can be improved by increasing its market share (Akhisar et al., 2015). Offering breakthrough technologies to clients, building customer loyalty, attracting brilliant workers, and gaining a competitive advantage are all ways for an organization to generate its market share (Goyal et al., 2016). Innovation is one strategy for a company to obtain market share (Musiega, 2016). When a company provides new products/services that its competitors do not currently offer, buyers who need them will buy them from another company, even if they previously dealt with a competitor (Nisar, 2017, August 28). The field of financial innovation has emerged as an important domain to consider for increasing the market share of any organization (Gruin and Knaack, 2020; Kaur, 2020). The majority of those individuals become repeat customers, boosting the corporation's market share and simultaneously diminishing the market share of the company from which they switched (Nazaritehrani and Mashali, 2020).

Shannak (2013) discussed some benefits and drawbacks of using an internet banking facility which includes the fast service for the transfer of funds but includes the risk of sharing information on multiple devices. Today's world is transforming toward a cashless economy through internet banking facilities as the mode of innovative financial service (Fung et al., 2015). There are many factors responsible for the variation in the market share of a bank such as internet, mobile, telephone, and ATM banking (Saravani et al., 2015). The banking sector around the globe is rapidly changing the types of services offered to its customers by introducing more convenient and cost-effective channels through innovation (Nisar, 2017, August 28). With the addition of innovative financial services, a bank can enhance its share in the market (Ahamed and Mallick, 2019). Those banks which could not compete with the modern era requirements lose their market share as compared to other banks (Nazaritehrani and Mashali, 2020). Pakistan is amongst the developing nations that are facing continuous challenges to adopt modern tools and techniques to upgrade their banking systems as per the changing needs of their customer and to compete for the global banking system around the world (SAMA, 2020, September 11). The innovative finance process not only provides the acceleration for the bank's market share but also cost efficiency (Khalifaturofi'ah, 2021; Yang, 2021; Zouari-Hadiji, 2021).

To be competitive in the modern world, the banks need to be innovative in terms of their financial process which requires the adoption of innovative financial services with the application of artificial intelligence in the financial industry (Işık et al., 2021; Karim et al., 2021; Rabbani et al., 2022a; Rabbani et al., 2022b). The study adds to the existing strand of literature by being the first study to highlight the role of artificial intelligence in moderating the innovation process in the banking sector. The outcomes of this study are comparable within the banking sector.

The primary goal of this investigation was to determine the direct role of digital financial processes mostly on the market share of the most innovative bank in Pakistan. The secondary area of research interest is to examine the influence of artificial intelligence on Pakistan's most innovative bank in terms of creative financial procedures for market share. The specific aims of the study are—first, examining the impact of the innovative financial process such as internet, mobile, telephone, ATMs, and POS banking on the market share of the most innovative bank in Pakistan. The second is to analyze the impact of artificial intelligence for accelerating the market share of the most innovative bank in Pakistan. The third is to explore the moderation effect of artificial intelligence concerning the innovative financial processes and the market share of the most innovative bank in Pakistan.

The primary and secondary focus of the present research study is analyzed by considering the following research questions.

RQ1. How does the usage of innovative financial processes such as the internet, mobile phones, ATMs, and POS terminals affect the market share of Pakistan's most innovative bank?

RQ2. Does artificial intelligence affect the market share of the most innovative bank in Pakistan?

RQ3. How does artificial intelligence play its role in moderating the relationship between innovative financial processes and the market share of the most innovative bank in Pakistan?

Since this helps banks enhance their operations and cost-effectiveness by requiring fewer workers and conventional branches, innovation has been used by the commercial banks to build business intelligence as well as a strategic advantage. Customers may easily execute online transactions mostly as a result of the impact of information systems on financial products, which improves confidence in banking and enables the growth of technology that can first provide a more rapid and efficient operation.

The remaining study is organized as follows. In Section 2, we provide an extensive review of the literature along with the

theoretical background. Section 3 describes the methodology used in the study. Section 4 analyzes data and provides the measurement model used in the study, and finally, in Section 5 and Section 6, we conclude and provide the further scope of the study.

2 Literature review

Financial risk is more concerning to the banking industry (Işık et al., 2020; Lutfi et al., 2022). Operational risk and liquidity risk are more concerning for the policymakers and shareholders because this may cause loss of capital (Hussain S et al., 2022). But the use of new technological innovation in the financial industry may cause a decrease in the cost of business (Xiang et al., 2022). Financial services are provided through the telephone; internet cards have impact on the financial preface of the banking industry (Isik et al., 2021). This is the era of the digital economy which affects the overall country's growth and financial development (Işık et al., 2022). The purpose of this study was to look first at the direct impact of innovative financial processes on increasing the market share of banks in Pakistan. In addition, the study also tries to find the moderation impact of artificial intelligence adaptation for the same sector in Pakistan. For achieving these objectives, the study critically analyzes the historical findings to explore the aforementioned relationships in their default form.

2.1 Internet banking impact on market share

An electronic payment system allows the customer to perform various monetary transactions on the website of the bank (Rajasulochana and Khizerulla, 2022). Internet banking allows the customer to engage with their transaction on the website 24 h and 7 days a week (Chauhan et al., 2022). At home, customers enjoy the same facilities as those at traditional branch banking. Online banking or internet banking reduces the dependency on branch banking which ultimately cuts the cost of banking operation (Akhter et al., 2022). It is a secure, convenient, and easy approach to customer bank accounts on which payments are made through the internet (Cui and Xu, 2022). Internet banking has a positive impact on market share in emerging economy of Syariah Indonesia (Siska, 2022). Pakistan has been using internet banking for over a decade, although evidence indicates that it is increasing the bank's market share (Raza et al., 2017). Internet banking does have a greater impact on the financial sector's market share in Nigeria unlike manual banking (Sathiyavany and Shivany, 2018). Similarly, due to the extreme heterogeneity in internet banking with market share, the outcomes of a comprehensive investigation revealed that several variables had the anticipated negative association (Akhisar et al., 2015). Keeping in view the majority of studies indicating the positive link of online banking with the market share of banks, the present research study establishes the following hypotheses to be tested.

H_1: Internet banking should have a strong optimistic behavior for a bank's market share in Pakistan.

2.2 Telephone banking impact on market share

Telephone banking service is provided by the banks which is a financial transaction performed by its customer without visiting a bank branch and without any cash or financial instrument (Payne e al., 2021a). Telephone banking and market share have a positive relationship (Jagathi, 2021). Modern world customers want easy services and on the spot payment without delay and transportation cost (Mahardini et al, 2022). Al Shawi et al. (2022) suggested that the private banking market share is relevant to the mobile banking, telephone banking, and ATM transaction. The main reason is on the spot transaction without delay and waiting for the check clearance. The importance of telephone banking after the COVID-19 situation increased (Hussain I et al., 2022; Irwan et al., 2022). In Kenya, a comparable study discovered that new financial processes such as phone banking used to have a favorable impact on the banking industry's share of the market (Mwangi, 2014a). Finally, consumers with smartphones can use the phone banking facility to monitor their balances, pay bills, as well as send money *via* texting, and this type of banking has a solid association with boosting the market share of banks (Raghavan, 2006). As no adverse relationship could be determined in the past literature for telephone banking and its market share, the following hypotheses are being established to test its application in the banking sector of Pakistan.

H_2: Market share of Pakistani banks is expected to be enhanced with efficient effect utilization of telephone banking.

2.3 Mobile banking impact on market share

Mobile banking means to use any mobile device to carry on the financial transaction (Uddin, 2022). Financial institutions allow their customers to carry forward remote transactions with the help of devices such as mobiles or tablets (Isik et al., 2021; Uddin, 2022). Market share means the percentage of company sales within a given industry (Nguyen et al., 2022). Mobile banking enhances the market share due to easy transaction and on the spot sale (Ma and Zhu, 2022). Mobile banking has positive and significant impact on Islamic banks' market share (Payne et al., 2021a). Furthermore, a vast majority of banks now provide mobile banking, which boosts bank profits, market share, as well as provide economic advantages (Mullan et al., 2017). In the same way, a study by Muthinja and Chipeta (2018) concluded that technological development in the banking sector in the form

of mobile banking can strongly influence the bank's market share. In contrast, according to Turkish study research, the banks use mobile banking mostly when overall deposits, as well as loans, improve and then their revenue, including interest revenue, and market share fall (Onay and Öztaş, 2018). As per a survey of European nations' banking sectors, digital technologies and modern mobile banking prospects have a significant impact on the market share of banking institutions (Druhov et al., 2019a). Consequently, the decisive outcomes of an investigation revealed that financial innovations such as financial inclusion, mobile, internet, including ATM banking had a beneficial effect on commercial banking performance, hence, increasing its market share (Ahmed and Wamugo, 2019). The historical literature provides the majority of evidence in support of the optimistic behavior of mobile banking for enhancing the market share, so the present research investigation expects the positive behavior of the same for the market share of the banking sector in Pakistan in the following way.

H_3: An optimistic behavior of mobile banking is expected in response to increasing the market share of Pakistani banks.

2.4 Impact of ATM on market share

An ATM is an electronic outlet which allows the customer to perform financial transactions without going to bank branches (Oluwafemi et al., 2022). Simple ATMs are used for cash withdrawals, balance enquiry, and fund transfers, while advanced ATMs are used for cheque deposits and cheque transfers at any time without interference from bank staff (Gautam et al., 2022). The use of ATMs has an effect on market share of the banking industry (Siska, 2022). Mobile banking and ATMs enhance the market share in the Afghan banking sector (Faryal and Tikhomirov, 2022). Furthermore, according to the conclusions of the research, the use of ATMs would have a positive behavioral impact on the banking industry's market share (Abd El Aziz et al., 2014b). Another survey found that Thailand seems to have a big potential for ATM but also mobile banking services, as well as a significant retail system, indicating the banking industry's market share increase (Wonglimpiyarat, 2014). Similarly, a Kenyan study looked at financial intermediation as a crucial component of such a banking system and found that ATMs have a major effect on a bank's market share (Kithinji, 2017). Similarly, the research investigated by Muthinja and Chipeta (2018) showed that ATM and bank market share had an optimistic strong link. Furthermore, a study conducted on Kenyan banks found that banks throughout the vicinity should boost their volume of ATM locations while also expanding their branch offices to significantly improve existing market share (Ahmed and Wamugo, 2019). In the same way, a research investigation by Le and Ngo (2020) discovered that when the volume of ATMs grows, the bank's share in the market grows as well, coupled with the presence of ATMs at all hours of the day and night in any nearby area. On the contrary, a study found that ATMs are inversely associated with the market share of banks due to a lack of understanding of cashless transactions (Kamboh and Leghari, 2016). Furthermore, another study found that ATMs need not significantly increase a corporate bank's share in the market (Victor et al., 2017). Keeping in view the direction of a large number of studies as being optimistic in relation to ATM usage and bank's market share, the present research establishes the following hypotheses for the banking sector of Pakistan.

H_4: A rise in the volume of ATMs that is both productive and useful can help Pakistani banks to grow their market share.

2.5 POS terminals' impact on the market share

POS terminal is a device which is used to make payments in a retail environment (Shafei and Sijanivandi, 2022). A portable device is used by the local card holder for the payment of goods and services in the local retail market (Kajdi and Kiss, 2022). POS has a positive effect on market share in Kenya banking context (Mukira et al., 2022). Earlier studies have shown that point of sale is favorably related to financial industry market share as per the conclusive findings of Kamboh and Leghari (2016). Similarly, as per the research investigation of Le and Ngo (2020), growth in the volume of POS terminals boost the bank's profit including its market share, and yet this element must be regarded vital if the bank's share in the market in the region is to be increased. As small pieces of evidence supported the usage of POS concerning bank's market share worldwide and indicated the optimistic relationship between both, the following hypotheses in this regard could be established to facilitate the same domain in the case of the banking sector of Pakistan.

H_5: There should be an optimistic relationship between point-of-sale terminals and the bank's market share in Pakistan.

2.6 Artificial intelligence and innovative financial services

The concept of artificial intelligence was introduced in recent years. Especially, in the case of the financial industry, its usage was confirmed in the form of chat-box and virtual assistants in social media, websites, and mobile apps of the banks as evidenced by Kruse et al. (2019). More specifically, the AI application in innovating financial processes such as mobile banking, internet banking, ATMs, and POS has accelerated the banking services with time and cost-saving and has increased the market share of banks (Ayllon, 2020). AI provides an opportunity for banking customers to naturally interact with banks in terms of gesturing, writing, and talking, especially in the case of mobile banking with the inclusion of artificial intelligence technology (Payne et al.,

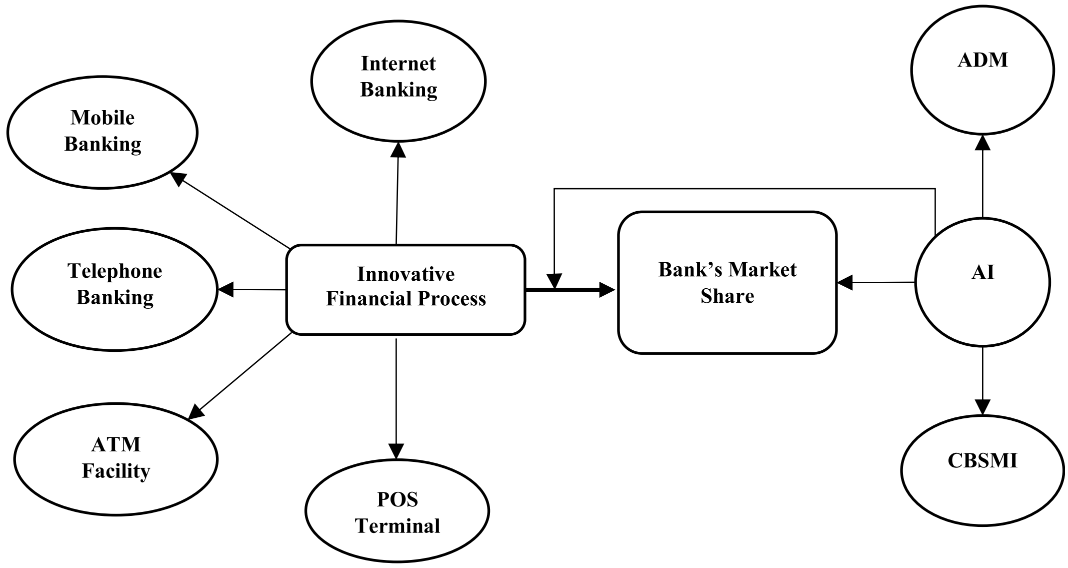

FIGURE 1
Conceptual model source: author's own architecture.

2021b). Similarly, another research investigation in the same domain asserted that artificial intelligence in the form of mobile and digital banking, social media interactions, messenger chat-bots, automated decision-making, and friendly customer journey can transform the traditional financial process into an innovative finance process to accelerate the banking's market share (Ashta and Herrmann, 2021). As the limited number of studies provides the optimistic moderating relationship of AI usage for accelerating the innovative finance process for gaining the higher market share, the following hypotheses can be established in the case of the banking sector of Pakistan.

H_6: The application of artificial intelligence in the financial process can strongly moderate the innovation to get a higher market share in the banking industry of Pakistan.

The historical literature indicated that the majority of the studies are either considered for other regions around the world or a very limited number of studies only considered internet banking in Pakistan (Raza et al., 2017). Similarly, the innovative finance process concerning banking share with a special reference to the Sehar bank in Iran was examined by Nazaritehrani and Mashali (2020). However, a complete set of innovative financial processes concerning a bank's market share was never studied for the banking sector of Pakistan. In addition, the application of artificial intelligence in the banking sector of Pakistan was never analyzed as per the historical literature. So, the present research tries to examine this domain with the special reference of the Silkbank being considered as the most innovative retail banking in Pakistan as per SAMA (2020, September 11). Based on the historical and critical literature review and by following the aims and objective of this exploratory research examination, the following conceptual research model indicating the direct as well as moderating impact between the innovative financial process, acritical intelligence application, and bank's market share is depicted in Figure 1.

3 Methodology

The present research study is primarily meant to explore the direct impact of the innovative finance process on the market share of the most innovative bank in Pakistan. In addition, artificial intelligence as moderation is also considered between innovative financial processes and market share of the most innovative bank in Pakistan.

3.1 Population and sampling

As per the recent report of SAMA (2020, September 11), the Silkbank was awarded as the most innovative retail bank in Pakistan. The population of the study consists of 123 branches of the Silkbank located in 39 cities in Pakistan. The unit of analysis comprises each bank branch, while the respondent includes the branch as well as the operation manager. The study uses cluster-based sampling to locate the branches on geographical grounds at first. Then, the final sample is drawn based on a cluster simple random sampling approach as per the suggestions of Acharya et al. (2013).

3.2 Data collection

To collect data, the study uses a self-administrative type of survey questionnaire. The questionnaire consisted of four sections. Section 1 consisted of socio-economic and demographic factors such as gender, age, qualification, experience, the term of employment, and average monthly salary. Section 2 consisted of question statements related to innovative financial processes such as internet banking, mobile banking, telephone banking, ATMs, and point-of-sale terminals. Section 3 consisted of question statements related to the bank's market share. Finally, Section 4 consisted of question statements related to artificial intelligence applications in the banking sector of the Silkbank. The online questionnaire was divided into two separate booklets. Both separate booklets were targeted from the same respondents at a different point in time for avoiding the issue of common method biases (CMBs). The first booklet contained Section 1 and Section 2 of the questionnaire. The second booklet contained the question statements related to Sections 3 and Section 4. The first booklet was emailed to the targeted respondents in the Silkbank at one point in time. The respondent was allowed to provide his/her valuable responses within a week of receiving the first booklet. After collecting the booklet, the second booklet was sent to the same respondent after a gap of 3–7 days to control the common method biases. The questionnaire in the form of two separate booklets was sent to more than 200 respondents (branch managers and operation managers). Out of these 200 booklets, the researcher received 154 booklets with only 1 + 2 completed in all respects with unbiased responses.

3.3 Operationalization of variables

The present study aimed at investigating the impact of the innovative financial process on the market share of the most innovative banks in Pakistan. Additionally, artificial intelligence was used to analyze the moderation impact concerning the innovative financial processes and the bank's market share in Pakistan. The *dependent variable* of the study was market share which was measured by considering 10-item statements as adopted by the study of Nazaritehrani and Mashali (2020). We used five-point type of Likert categories comprising, "1 = Strongly disagree—5 = Strongly agree." The innovative financial process was used as the *independent variable* in the form of internet banking (4 items), mobile banking (4 items), telephone banking (3 items), ATM facility (4 items), and point-of-sale terminals (4items), adopted from the study of Raza et al. (2017); Nazaritehrani and Mashali (2020). It was also scaled on five-point type of Likert categories comprising, "1 = Strongly disagree—5 = Strongly agree." Finally, artificial intelligence was used as the *moderating variable* with the help of two dimensions such as automated decision making (4 items) and chat-bot and social media interactions (4 items), adopted from the study of Kruse et al. (2019); Ayllon (2020). It was scaled too on five-point type of Likert categories comprising, "1 = Strongly disagree—5 = Strongly agree."

3.4 Methods of estimation

We applied structural equation modeling techniques to analyze and interpret the primary data collected for the study. For this purpose, SPSS was used for the estimation of descriptive statistics for the socio-economic and demographic factors, while the remaining estimations were executed with the help of SmartPLS in the form of factor analysis, reliability and validity of construct estimation, structural equation modeling, and their estimations, *etc.*

4 Data analysis and result discussion

The examination of the present research requires investigating the effect of the innovative financial processes on the market share of the most innovative bank in Pakistan. Additionally, artificial intelligence was used to assess the moderation impact between innovative financial processes and the market share of the innovative banks in Pakistan. For achieving these aims and objectives, the study used a questionnaire based on survey research for primary data using the method adopted by Nazaritehrani and Mashali (2020) for measuring the market share of banks, similarly, an innovative financial process was adopted from the study of Raza et al. (2017; Nazaritehrani and Mashali (2020). Finally, the moderating variable; artificial intelligence was adopted from the study of Kruse et al. (2019); Ayllon (2020). All the measures were scaled at a five-point Likert type of scale measure. The data were collected using a cluster-based sampling technique due to the fact of the geographical distribution of banks in different cities. A total number of more than 200 questionnaires were shared while 154 respondents actively filled out the responses. Therefore, the response rate was 77%. For analyzing the research, structural equation modeling using SmartPLS was adopted for evaluating the hypothesis of the study. These estimations include demographic and socio-economic summary using SPSS, measurement model, outer loadings, convergent and discriminant validity as well as the SEM estimates using SmartPLS. The estimations were interpreted under their specific headings as follows.

4.1 Socio-economic and demographic summary

Table 1 reports the socio-economic and demographic details of the respondents in the form of gender, age, qualification, working experience, term of employment, and monthly average

TABLE 1 Socio-economic and demographic summary.

Demographic and socio-economic factors	Min	Max	Mean	N	%
Gender	0	1	.71	**154**	**100**
Female				45	29.2
Male				109	70.8
Age	1	5	3.51	**154**	**100**
30–35 years				11	7.1
36–40 years				28	18.6
41–45 years				33	21.2
46–50 years				34	22.1
51 or above years				48	31.0
Qualification	1	3	2.06	**154**	**100**
Graduate				46	30.1
Post-graduate				52	33.6
Others (specialized banking diplomas/degrees)				56	36.3
Work experience	1	3	2.29	**154**	**100**
3–5 years				37	23.9
5–10 years				35	23.0
Above 10 years				82	53.1
Term of employment	1	3	2.52	**154**	100
Temporary				5	3.5
Fixed contract				63	40.7
Permanent				86	55.8
Monthly average salary	1	4	2.59	**154**	100
Rs. 50,000–Rs.100,000				3	2.1
Rs. 101,000–Rs.150,000				43	27.8
Rs. 151,000–Rs.200,000				50	31.8
Rs. 201,000 or above				58	38.3

N 154 means total number of questioner received from the respondents which is 100 percent .Now 45 female respondents which is 29.2 percent, while male respondents 109 which is 70.8 percent. Total 100 percent.

salary. The first demographic feature such as gender represents a total number of 154 respondents that comprised 45 females (representing 29.2%) and 109 males (representing 70.8%). As the study was targeted toward the operational and branch managers of the banking sector in Pakistan, especially in Silkbank, therefore, we conclude that this bank is male-dominated. The second demographic feature such as age represents that the majority of the respondents were from the age category of 41 or greater. As the respondent is from the operational and branch managerial levels, so most of the respondents have more experience than others. Similarly, the qualification of the respondents indicates that the majority of the respondents are post-graduate or have other specialized certifications such as IBP qualification/ACCA/CA. Additionally, the working experience of the majority of the respondents is >5 years. However, the term of employment indicates that five of the respondents are holding temporary positions, 63 for fixed contracts, and 86 are holding their position permanently in Silkbank. It infers that the majority of the senior staff is holding either fixed contract or permanent positions at operational or branch banking. Finally, the collected data indicated that the majority of the respondents are earning >151,000 PKR as the average monthly salary in the Silkbank.

It is inferred from the previous table that the majority of the respondents from the Silkbank are male, having the age category of 41 or >, holding a qualification of post-graduate or higher, with an experience of >5 years for working in the banking sector, and they have fixed or permanent employment with a salary package of 151,000 or greater.

4.2 Measurement model

Figure 2 indicates the measurement model which consists of the indicators measuring their latent variables as well as the path coefficients between constructs along with the R-square values. According to Hair Jr, Hult, Ringle, and Sarstedt (2016), the measurement model indicates how the latent variable is measured using related indicators. As per the reliability of the

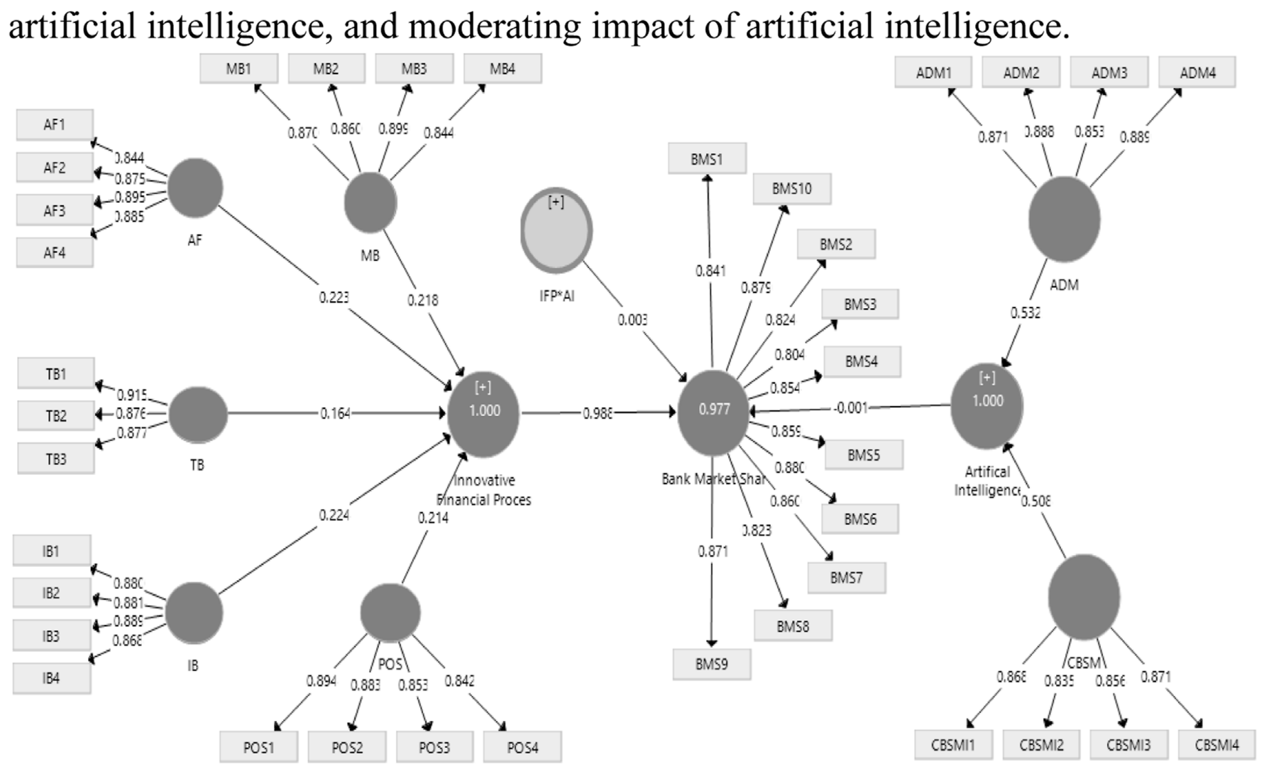

FIGURE 2
Measurement model.

measurement model is concerned, Hair, Anderson, Babin, and Black (2019) stated the rule of thumb reliability indicator in the measurement model with a loading value of 0.708 or greater. By considering this rule of thumb, it is inferred that all the latent variables of this study are valid and dependable. Additionally, Figure 2 indicates that a positive relationship is observed between innovative financial processes and a bank's market share with a path coefficient value of 0.988. Similarly, there is a negative relationship between artificial intelligence and a bank's market share which is indicated by a path coefficient value of −0.001. Likewise, a positive relationship was estimated between the moderating impact of artificial intelligence between innovative financial processes and the bank's market share with a path coefficient of 0.003. Finally, the bank's market share as the dependent variable of the study indicates an R-square of 0.977 which indicates that approximately 98% of the variance in the bank's market share is explained by the variance in the innovative financial process, artificial intelligence, and moderating impact of artificial intelligence.

4.3 Outer loadings and convergent validity

Table 2 indicates the values of the outer loading of factors used for measuring the constructs of the study. It also includes the convergent validity measures such as Cronbach alpha, composite reliability, and average variance extracted from the study. Cronbach alpha and composite reliability indicate the internal validity of the constructs while the average variance extracted indicates the external validity of constructs. As per the reliability of individual factors/indicators is concerned, Hair et al. (2019) stated the rule of thumb for indicator/factor reliability for outer loading values with a value of 0.708 or greater. It is inferred that all the factors measuring their relevant constructs are reliable and valid. Similarly, the rule of thumb for convergent reliability and validity as per the suggestions of Hair et al. (2019) is 0.708 for Cronbach alpha, 0.70 for composite reliability, and 0.50 for average variance extracted. Therefore, it is inferred that the constructs of the study are valid and reliable as per the rule of thumb established by Hair Jr et al. (2016); Hair et al. (2019).

4.4 Discriminant validity

According to the arguments and suggestions of Hair Jr et al. (2016), the discriminant validity of constructs ensures the uniqueness of one construct from all other constructs. Similarly, Hair et al. (2019) stated that discriminant validity is

TABLE 2 Outer loadings and convergent validity.

Constructs and their items	Factor loading	Cronbach alpha	CR	AVE
Innovative financial process (IFP)		0.977	0.978	0.704
Internet banking (IB)		0.902	0.932	0.774
IB1	0.880			
IB2	0.881			
IB3	0.889			
IB4	0.868			
ATM facility (AF)		0.898	0.929	0.766
AF1	0.844			
AF2	0.875			
AF3	0.895			
AF4	0.885			
Mobile banking (MB)		0.891	0.925	0.754
MB1	0.870			
MB2	0.860			
MB3	0.899			
MB4	0.844			
Point-of-sale terminal (POS)		0.891	0.925	0.754
POS1	0.894			
POS2	0.883			
POS3	0.853			
POS4	0.842			
Telephone banking (TB)		0.868	0.919	0.791
TB1	0.915			
TB2	0.876			
TB3	0.877			
Bank's market share (BMS)		0.957	0.963	0.722
BMS1	0.841			
BMS2	0.824			
BMS3	0.804			
BMS4	0.854			
BMS5	0.859			
BMS6	0.880			
BMS7	0.860			
BMS8	0.823			
BMS9	0.871			
BMS10	0.879			
Artificial intelligence (AI)		0.937	0.948	0.693
Moderating (AI*IFP)		0.994	0.993	0.588
Chat-bot and social media interactions (CBSMI)		0.880	0.918	0.736
CBSMI1	0.868			
CBSMI2	0.835			
CBSMI3	0.856			
CBSMI4	0.871			
Automated decision making (ADM)		0.898	0.929	0.766
ADM1	0.871			
ADM2	0.888			
ADM3	0.853			
ADM4	0.889			

TABLE 3 Discriminant validity of constructs (Fornell–Larcker criterion).

	ADM	AI	BMS	CBSM	IB	IFP*AI	IFP	MB	POS	TB
ADM	**0.875**									
AF	−0.062									
AI	0.863	**0.833**								
BMS	−0.066	−0.057	**0.850**							
CBSM	0.847	0.759	−0.042	**0.858**						
IB	−0.055	−0.045	0.764	−0.031	**0.880**					
IFP*AI	−0.029	−0.044	0.156	−0.056	0.161	**0.698**				
IFP	−0.069	−0.056	0.789	−0.038	0.762	0.155	**0.839**			
MB	−0.051	−0.032	0.758	−0.009	0.813	0.120	0.764	**0.868**		
POS	−0.084	−0.063	0.730	−0.036	0.788	0.158	0.758	0.711	**0.868**	
TB	−0.084	−0.079	0.708	−0.068	0.782	0.141	0.738	0.773	0.779	**0.889**

Note: The values in bold represent the square root of the AVE.

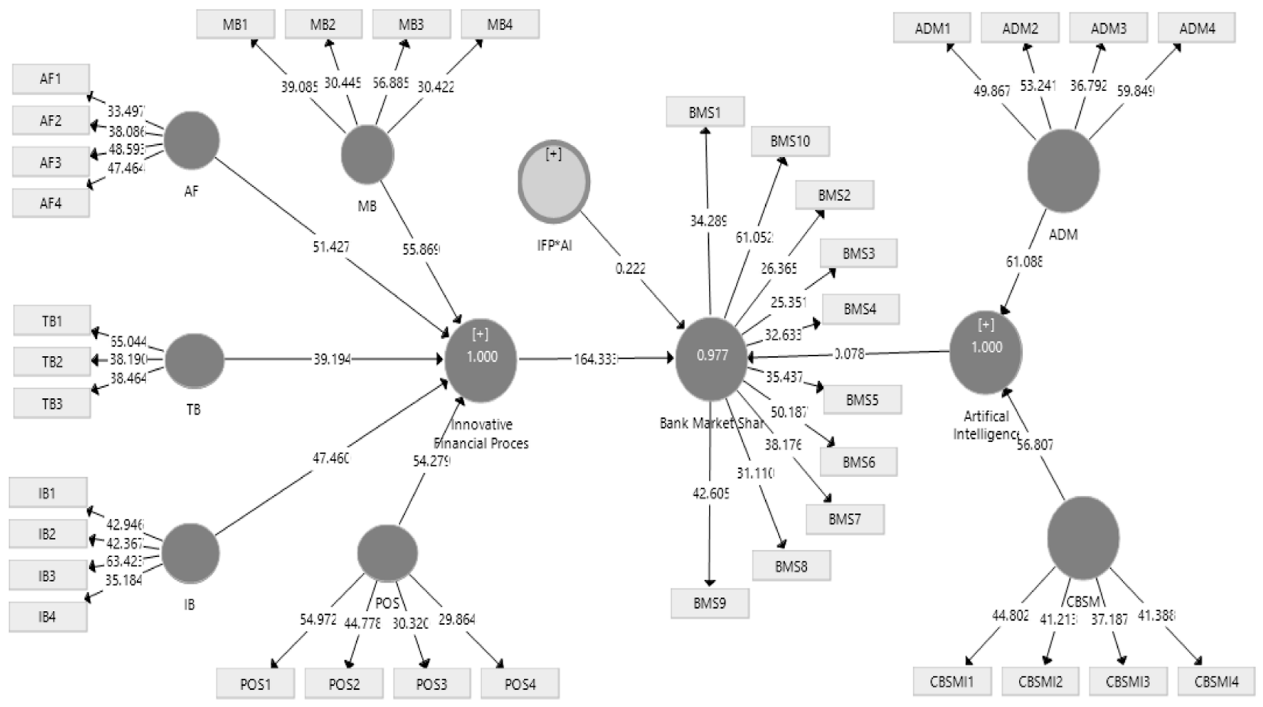

FIGURE 3
Structural model source: SmartPLS output.

established when the shared variance of one construct is greater than that of all other constructs. The rule of thumb for this criterion is that the square root of AVE for each construct should be > the highest correlation values of other constructs (Hair Jr et al., 2016; Hair et al., 2019). Therefore, using Table 3 values of Fornell and Larcker (1981) for each construct, the discriminant validity is established in this study.

4.5 Structural model

According to Hair Jr et al. (2016), a structural model can be described as a model that indicates the relationship between constructs/latent variables of the study. The rule of thumb for the significance of these relationships is that the t-values must be 1.96 or greater (Hair et al., 2019). Figure 3 indicates that there is a statistically significant

TABLE 4 SEM model estimations.

Structure	O	M	STD	T-value	*p*-value
ADM -> BMS	−0.001	−0.001	0.007	0.078	0.938
AF -> BMS	0.220	0.220	0.004	51.791	0.000
AI -> BMS	−0.001	−0.001	0.013	0.078	0.938
CBSM -> BMS	−0.001	−0.001	0.007	0.078	0.938
IB -> BMS	0.221	0.221	0.005	48.514	0.000
*IFP*AI -> BMS*	0.003	0.005	0.014	0.222	0.824
IFP -> BMS	0.988	0.987	0.006	164.333	0.000
MB -> BMS	0.216	0.216	0.004	57.406	0.000
POS -> BMS	0.211	0.211	0.004	49.790	0.000
TB -> BMS	0.162	0.162	0.004	37.623	0.000

link between innovative financial processes and a bank's market share with a t-value of 164.33 which is higher than the minimum threshold level. However, the link between artificial intelligence and bank's market share and the link between moderating variable and bank's market share are insignificant due to t-values of 0.078 and 0.222, respectively.

4.6 Estimation of the SEM model

Table 4 indicates the structural equation modeling estimation using the robust technique used in SmartPLS in the same way as the OLS technique in regression. The objective of the study was to determine the direct impact of the innovative financial process as well as the moderation impact of artificial intelligence for the bank's market share on the most innovative bank in Pakistan, Silkbank. The table reports that innovative financial processes have a positive as well as highly significant impact on the bank's market share in Pakistan. The path coefficient for this structural link between IFP and BMS is 0.988 with a *p*-value of 0.000 ($p < 0.01$) which confirms the positive and highly significant link between the variables. The positive and highly significant (strong) link between IFP and BMS accepted the first hypothesis ($\boldsymbol{H_a}$). This positive and highly significant link between IFP and BMS is also consistent with the findings of similar research studies conducted by Nazaritehrani and Mashali (2020); Zouari-Hadiji (2021). The possible interpretation of this strong and positive link between the variables is that usage of modern technology for facilitating the bank's customer enhances the competitive edge of that bank which ultimately enhances its market share as per Nazaritehrani and Mashali (2020). Similarly, the dimensions of the innovative financial process such as mobile banking (MB), telephone banking (TB), internet banking (IB), ATM (AF), and (POS) terminals also indicate a positive and a highly considerable influence for determining the bank's market share. The path coefficients for these dimensions are 0.216, 0.162, 0.221, 0.220, and 0.221, respectively, with their respective *p*-values as 0.000 ($p < 0.01$) with highly significant and positive impact. This strong optimistic relationship between MB, TB, IB, ATM, POS, and BMS accepts the relevant hypothesis (H_{1a} -H_{5a}). These optimistic and strong relations were also confirmed from the similar findings of Abd El Aziz et al. (2014a); Akhisar et al. (2015); Ayllon (2020); Druhov et al. (2019b); Kamboh and Leghari (2016); Kaur (2020); Khandelwal (2012); Mwangi (2014b); Nazaritehrani and Mashali (2020); Nisar (2017, August 28); Onay and Öztaş (2018); Sathiyavany and Shivany (2018); Siyanbola (2013); Tinashe and Kelvin (2016); and Zouari-Hadiji (2021).

However, the study could not find a strong link between artificial intelligence and a bank's market share. In fact, a negative and insignificant link was estimated between the variables with the path coefficient value as −0.001 and *p*-value as 0.938 ($p > 0.10$). This finding rejects the hypothesis (H_B) and concludes that there is no relationship between artificial intelligence and bank's market share in Pakistan. Similarly, a negative and insignificant link between BMS and the dimensions of AI; (ADM), and chat-bot and social media interaction shows similar path coefficients and *p-values* > 0.10. The possible reason for this negative and insignificant link between AI (including its dimensions) and BMS could be that the banking sector of Pakistan has not introduced the usage of artificial intelligence due to less trust in this domain. This may be due to unfamiliarity with artificial intelligence tools and techniques such as automated decision and chat-bot and social media interaction by the banking employees or it may either be due to unawareness of banking customers regarding the benefit of artificial intelligence and efficient usage of its sub-domains in Pakistan. Finally, the moderation impact of artificial intelligence on the relationship of IFP and BMS indicates a positive but insignificant link. The path coefficient value for this link is 0.003 with a *p*-value of 0.824 ($p > 0.10$). It partially accepts the relevant hypothesis (H_C) due to its positive impact but it partially rejects the same due to its insignificant impact. It is inferred that the familiar and efficient usage of artificial intelligence may moderate (insignificantly) the innovative financial process in enhancing the bank's market share.

The findings of this study inferred that innovative financial processes have a strong and optimistic potential in determining the bank's market share for innovative banks in Pakistan. However, the banking sector of Pakistan needs to upgrade its innovative banking channels such as mobile banking, telephone banking, internet banking, point-of-sale terminals, and ATMs to align with the modern technology of artificial intelligence and give awareness to their customers regarding its efficient and effective usage to further accelerate their market share.

5 Conclusion

This research study aimed to examine the role of the innovative financial process along with its dimensions; IB, MB, ATM, AF, POS, and TB in explaining the bank's market share of the most innovative

bank, Silkbank. Additionally, artificial intelligence with its dimension; ADM, chat-bot and social media interactions were used as moderating variables of the study. The present study was primarily with quantity data collection procedure using a survey questionnaire. The target population was Silkbank being nominated as the most innovative bank in Pakistan (SAMA, 2020, September 11). A total number of 200 questionnaires were shared with different branches of Silkbank across the country for which 154 respondents completely responded to the questionnaire with two booklets comprising Section 1 and Section 2 were shared at a different point in time with the gap of 3–7 days for each. The study uses cluster-based sampling due to the fact that Silkbank's branches are located in different cities and towns across Pakistan. The research instrument used in the present study was a survey questionnaire comprising four segments; first for socio-economic and demographic features, second for statements of the innovative finance process, third for the statements related to bank's market share, and finally, the fourth part related to the statements of artificial intelligence and its dimensions.

For analyzing the present research study, the structural equation modeling technique was used with the help of SmartPLS software due to the fact of the limited sample size of 154. The estimations include the demographic and socio-economic summary using SPSS, measurement model, convergent validity, outer loadings, discriminant validity, and structural equation modeling with the help of SmartPLS software. All the factors in the relevant table estimates indicate that the constructs of the study such as innovative financial process, bank's market share, and artificial intelligence along with their dimensions are strongly measured by their relevant factors as indicated in Table 2; Figure 2. The threshold level of the factor to be considered for measuring a construct is 0.70, therefore, the factor less than this level is removed from the analysis procedure. Only final values indicating the factor loading for each construct were included and reported in the final estimations. It is inferred that the constructs of the study are valid and reliable as per the rule of thumb for convergent validity as 0.70 for Cronbach alpha, 0.70 for composite reliability, and 0.50 for average variance extract. Therefore, all the constructs are valid and dependable according to this criterion. The rule of thumb for this criterion is that the square root of AVE for each construct should be more than the highest correlation values of other constructs. By meeting this criterion, all the constructs are valid using the Fornell–Larker rule of thumb.

6 Recommendations

The findings of this study inferred that innovative financial processes have a strong and optimistic potential in determining the bank's market share for innovative banks in Pakistan. However, the banking sector of Pakistan needs to upgrade its innovative banking channels such as mobile banking, telephone banking, internet banking, point-of-sale terminals, ATMs, and digital banking to align with the modern technology of artificial intelligence and give awareness to their customers regarding its efficient and effective usage to further accelerate their market share. The study concluded that an innovative financial process plays a key role in enhancing the bank's market share. However, there is a lack of awareness regarding the usage of artificial intelligence in the banking sector of Pakistan, which needs to be efficiently upgraded in the running system of innovative financial processes to further accelerate the banking sector in Pakistan. The study implies that the policymakers and decision-makers in the banking industry should focus to consider innovative financial processing channels such as mobile banking, internet banking, point-of-sale, telephone banking, and ATMs to enhance the market share of their respective banks. Additionally, they need to enhance public awareness as well as the training of existing staff to properly utilize the benefits of artificial intelligence integration in their existing financial process. This study adds to the existing literature with the usage of artificial intelligence in the banking sectors and their process of financial transactions, especially in the banking industry of Pakistan. The present study is analyzed on the banking industry with a specific focus on the most innovative financial bank in Pakistan, Silkbank. The findings of the present research are only generalizable in the banking sector only and cannot apply to other industries due to the specific nature of their business. Future research may include the Islamic and traditional bank comparison based on this study. Additionally, more than one bank can be selected to enhance the sample size, which may change the impact of artificial intelligence in future studies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Ethics statement

Ethics review and approval/written informed consent were not required as per local legislation and institutional requirements.

Author contributions

Conceptualization; MA, WAW, and AL; Methodology; MA, WAW, and AL; Formal analysis; MA, WAW, and AL; Investigation; MA, WAW, and AL; Writing—original draft preparation MA, WAW, and AL; Writing—review and editing; MRR and NN; Funding; MRR and NN; Project

administration; MRR and NN; All authors have read and agreed to the published version of the manuscript.

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Methodology: MS, ITW; formal analysis: AB; investigation AB, ITW: writing—original draft preparation: ES; and writing—review and editing: DNSW.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Glossary

ACCA association of chartered certified accountants

ADM automated decision making

ATM automated teller machine

BMS bank market share

CA chartered accountant

CMB common method biases

IB internet banking

IBP integrated business planning

IFP innovative financial process

MB mobile banking

OLS ordinary least square

PR Pakistani rupees

PLS partial least squares

POS point of sale

RQ research question

SAMA Saudi Arabia monetary agency

SEM structural equation modeling

SPSS software package for social sciences

TB telephone banking

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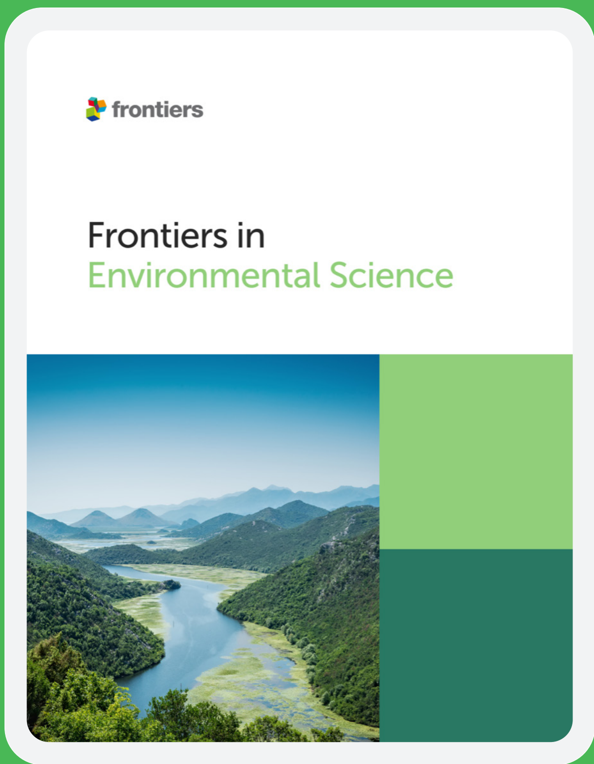

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