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RESEARCH ARTICLE

Impact of environmental regulation on green total factor productivity: a new perspective of green technological innovation

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Abstract
Green total factor productivity (GTFP) is an essential indicator to measure economic and environmental efficiency. Moreover, formulating a reasonable environmental regulation system and promoting green technological innovation is a systematic way to improve GTFP. However, previous related studies lack to investigate the impact of environmental regulation on GTFP from the perspective of green technological innovation. For this purpose, this paper aims to examine the specific impact of environmental regulation on GTFP based on the perspective of green technology innovation, so as to provide some policy insights for the formulation of more effective implementation of environmental regulation, improve green technology innovation level, and achieve a win–win situation for both economic growth and environmental protection. Furthermore, epsilon-based measure (EBM), which includes both radial and non-radial distance functions, is used to measure the GTFP. The spatial autoregressive method is also employed to quantify the impact of environmental regulation on GTFP from the perspective of green technological innovation using panel data of 269 prefecture-level cities in China from 2004 to 2018. The main findings indicate that there is a significant spatial autocorrelation between environmental regulation and GTFP. Environmental regulation has a significant positive effect on GTFP. Environmental regulation in the local regions also significantly contributes to GTFP in neighboring regions. Besides, environmental regulation indirectly promotes GTFP by enhancing green technological innovation level. Regional heterogeneity results show that environmental regulation can not only directly promote GTFP but also indirectly significantly promote GTFP through green technological innovation in the eastern and central regions, but insignificant in the western region. Based on the above findings, we conclude that policymakers should not only develop differentiated environmental regulation standards and steadily improving the intensity and rationality of environmental regulation but also add green innovation funds supply, enhance green innovation factor allocation efficiency, and strengthen R&D talents, funds, and policies to green technology innovation, so as to drive GTFP improvement.

Keywords Spatial spillover effect · Environmental regulation · Green total factor productivity · Green technological innovation · Heterogeneity effect

Introduction

Although China has experienced rapid economic growth since 1978, owing to the traditional resource-consuming economic growth model has left the country with very rapid resource consumption and increasingly serious environmental pollution problems (Meng et al. 2021; Cao et al. 2021; Ren et al. 2021). According to survey data, only about 35.8% of the 338 prefectures in China met ambient air quality standards in 2018 (Yang et al. 2021a). The World Health Organization reports that approximately 656,000 people die each year in China because of diseases caused by air pollution. It is evident that environmental pollution has brought certain harm to the health condition of residents (Wu et al.

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2021a; Hossain et al. 2021; Yamashita et al. 2021; Abid et al. 2020). Given the growing environmental problems, it is unlikely that Chinese government will follow the path of pollution before treatment (Zhu et al. 2019; Hao et al. 2021a). In this context, the Chinese government has introduced several environmental protection laws and regulations to address and improve environmental pollution problems. For instance, the Environmental Protection Law Amendment was produced in 2014, which was called the toughest new law in history. These environmental policies serve as a means of environmental regulation for the government and have a major role to play in protecting the environment (Han and Li 2020). Therefore, the 19th Party Congress report suggests that "the market-oriented green technology innovation system should be constructed, the strictest ecological system should be implemented, and good development and life style should be formed" (Xu et al. 2021; Yan et al. 2021; Ai et al. 2021). Meanwhile, the Chinese government has also put forward the idea of promoting total factor productivity and effectively solving the problem of "resource and environmental constraints forcing growth transformation" (Wang et al. 2021a; Li et al. 2021a; Liu et al. 2020; Wang et al. 2021d).

Environmental regulation, as a vital tool for the government to solve the market failure of environmental problems, affects the transformation of production methods and the improvement of production efficiency while adjusting the factor input structure (Hailing and Zhenni 2020; Jin et al. 2019; Shen et al. 2019). In this context, the evaluation quality of green total factor productivity (GTFP) is more in line with the assessment requirements of the green economy than total factor productivity (Zhong et al. 2022). However, scholars have long been debating whether environmental regulation can promote GTFP, ultimately developing two distinct viewpoints: the disincentive theory and the facilitation theory. Scholars who support the "disincentive theory" argue that environmental regulations negatively affect GTFP through adding additional costs to enterprises' normal production and operations. For example, Popp and Newell (2012) suggest that the negative effect of environmental regulation is mainly due to the insignificant effect of green technological progress on productivity caused by environmental regulation intensity. Chaofan (2016) finds that the effect of environmental regulations on GTFP in China has not yet crossed the "Porter's inflection point" and has a negative effect overall based on a panel data of Chinese industrial sectors. However, the "facilitation theory," represented by the Porter hypothesis, argues that although environmental regulation increase enterprise costs, it can force enterprises to strengthen technological research and development, achieve technological progress, and ultimately positively contribute to GTFP (Peng 2020; Peng et al. 2021). Ronghui (2017), for example, uses a two-stage model to find that environmental regulation indirectly promotes GTFP through the channel of environmental technology innovation, achieving a "win–win" for long-term environmental protection and economic development. Albrizio et al. (2017) confirm that environmental regulation not only drives total factor productivity in advanced technology industries but also plays a positive role in promoting some firms with higher productivity levels. Therefore, currently the impact of environmental regulations on green total factor productivity is ambiguous.

Considering the time dimension, the final relationship between the above two depends on whether the positive or negative effect is higher, with the negative effect of cost following being mainly in the short-term static perspective and the positive effect of innovation compensation focusing on the long-term dynamic perspective. It is obvious, however, that proponents of both views believe that environmental regulation increases the cost of production and operation, and that the reason for this disagreement is whether environmental regulation provides incentives for firms to achieve green technological progress (Deng et al. 2019; Wang et al. 2021c; Abid et al. 2021a, b). Since green technology innovation plays a pivotal role in sustainable economic development, green technology innovation can alleviate the contradiction between environmental protection and economic growth from the source (Wang et al. 2021d; Du et al. 2021; Zhang and Li 2020). Therefore, green technology innovation will become an effective way to strengthen environmental protection and promote economic development. Moreover, the government's environmental regulation level directly affects the improvement of enterprises' green technology innovation ability and the solution of environmental pollution problems. Therefore, environmental regulation sponsored by the government as well as those green technology innovations motivated by enterprises, society, and research institutes together constitute the two major drivers for solving China's environmental pollution problems and enhancing GTFP (Liu et al. 2020). Then, the practical question that needs to be considered are whether the implementation of environmental regulation can promote continuous improvement of GTFP? Does the impact of environmental regulation on GTFP differ if influenced by the mediation variable of green technology innovation? If environmental regulation has an impact on GTFP through green technology innovation, will there be regional heterogeneity? At present, scholars have not obtained a consensus on the above issues. Therefore, this study first selects GTFP as the dependent variable, which examines both economic development and green development, and then employs the spatial autoregressive model to analyze the impact of environmental regulation on GTFP and the mediation role of green technology innovation in the impact of environmental regulation on GTFP, aiming to provide theoretical support and policy guidance for formulating reasonable environmental regulation policies, promoting green technology innovation level, and realizing green economy in the future. Finally, it also provides some empirical evidence for other developing countries with economic development similar to China's, as well as useful insights for China's economy to achieve a transition from high growth to quality development.

To sum up, previous studies have each focused on how environmental regulation relates to GTFP, technological innovation, and GTFP, while generally neglecting to include all three in the same research framework for systematic analysis. In particular, the role of green technological innovation in bridging the gap between environmental regulation and GTFP has not been emphasized. Therefore, our findings differ from previous studies mainly in the following aspects. First, this study incorporates environmental regulation, green technological innovation, and GTFP into a unified research framework to quantify the intrinsic association between environmental regulation, green technological innovation, and GTFP. Second, a spatial panel model is constructed to empirically examine the spatial effects of environmental regulation on GTFP and identify the mediation effect among environmental regulation, green technological innovation, and GTFP. More carefully, this study also explores the effects of environmental regulation on GTFP based on the perspective of green technology innovation at the region heterogeneity. Finally, the relationship between the three of environmental regulation, green technological innovation, and GTFP is explored in more detail at the prefectural-level cities, aiming to provide some reference for policy formulation and action implementation at the prefecture-level cities to enhance GTFP.

Literature review

Environmental regulation and GTFP

Environmental regulation is a series of government policies or measures to regulate the production activities of enterprises so that they can take external costs such as environmental pollution into account when making production decisions, thus, solving the environmental pollution problems caused by the production process (Hao et al. 2021b; Wu et al. 2020). Since environmental regulation directly affects the production activities of enterprises, scholars began to reveal the nexus environmental regulation and corporate profits, total factor productivity, and other variables at an early stage, among which total factor productivity, as a measure of enterprise competitiveness, has attracted extensive attention from scholars. However, research on environmental regulation and GTFP is still emerging. In fact, GTFP introduces environmental factors into the evaluation of GTFP under the indicators that evaluate the area economic development level. There are available works on various facets of the interface that exist about environmental regulation and GTFP. First, some scholars argue that reasonable environmental regulation can generate innovation compensation effects to compensate for the reduction in firm profits because of cost increases in the short run, supporting the view of the strong Porter hypothesis. Song and Wang (2016) suggest that if environmental factors are incorporated into the consideration, enterprises can promote environmental quality through activities such as increasing in environmental management costs and technological innovation. Lanoie et al. (2008), using empirical analysis of data from the manufacturing industry in Quebec, indicate that there is a time lag in environmental regulation to improve GTFP. Li and Lin (2016) measure China's manufacturing data from 2006 to 2010 and identify that reasonably moderate environmental regulation contributes to industrial GTFP. Peng et al. (2021) reveal that environmental regulation improves industrial firms, which converges to diminish slowly as time progresses. Secondly, some scholars believe that environmental regulations can attach additional environmental management expenses to firms or incur fines for failing to meet environmental standards, which invariably increase costs and crowd out productive investment space, thus raising the entry barrier to the industry and ultimately discouraging the increase in GTFP. Walley and Whitehead (1994), Conrad and Wastl (1995), and Greenstone et al. (2012) confirm that environmental regulation imposes high levels of compliance costs, negatively affects firms' green innovation, constrains firms' productive investment, and technological innovation and negatively affects the change in GTFP. Gray and Shadbegian (1995), however, reached a similar conclusion that environmental regulation does not contribute significantly to technical progress and efficiency improvements in GTFP. Third, some scholars support that the influence of environmental regulations on GTFP is indeterminate or nonlinear (Peuckert 2014; Wang and Shen 2016). Becker (2011), for example, analyzes that command-and-control environmental regulation fails to influence GTFP, i.e., although the coefficient of effect is positive, it fails the significance test. Sanchez-Vargas et al. (2013) analyze using industry data from Mexico and indicate that the effect of environmental regulation on TFP is nonlinear. Qiu et al. (2021) confirm that the relationship between environmental regulation and GTFP is not linear but "U" shaped, with China still in the left half of the "U" curve. Li and Li (2021) use industry data to confirm that environmental regulation has a "U"-shaped relationship with GTFP across industries with an insignificant inflection point, while in light polluting industries, in which there is no nonlinear effect.

Environmental regulation and green technology innovation

Most scholars support that environmental regulation can significantly enhance green technology innovation. For example, Porter and Van Linde (1995) validate the "Porter hypothesis," which shows that moderate environmental replication has a positive incentive effect on firms' innovation behavior. Jaffe and Palmer (1997) opin that strict increased pollution control costs are associated with increased R&D expenditures. A more surprising finding is made by Cai et al. (2020), who find that for heavily polluting industries, environmental regulations create strong and significant incentive green technology innovation and that environmental regulations are more important for green technology innovation in state-owned listed companies in such industries. Frondel et al. (2007) argue that the tougher the environmental regulatory policy is, the greater the incentive for firms to innovate green technology. Some scholars oppose the above opinion and argue that environmental regulations do not promote but rather inhibit firms' green technology innovation activities. The neoclassical economics-related theory concludes that that environmental regulation augments the cost of environmental compliance (environmental governance and environmental compliance) for firms. Gollop and Roberts (1983) argue that environmental regulations cause an overall decrease in firm productivity. Barbera and McConnell (1990) identify the primary reason for the general decline in the performance of US industries such as steel, nonferrous metals, paper, chemicals, and nonmetallic mineral products as the increase in pollution control inputs due to environmental regulations. Guo et al. (2019) examine the relationship between environmental regulations on green technology innovation from a spatial spillover perspective and find that environmental regulation inhibits green technology innovation, but does not significantly impact the neighboring areas. Wagner (2007) reaches a similar conclusion, revealing that environmental regulation increases firms' operating costs and thus hinders green technology innovation. In addition, some scholars have argued that the impact of environmental regulation on green technology innovation is uncertain (Lanjouw and Mody 1996; Baker et al. 2008). Guo et al. (2018), for example, find that there is an "inflection point" where environmental regulation contributes to green technology innovation. Ai et al. (2021) show a U-shaped effect of environmental regulation intensity on green technology innovation.

Environmental regulation, green technology innovation, and GTFP

The investigation of environmental regulation and green technological progress on GTFP is mainly supported by the Porter hypothesis and the pollution havens hypothesis. Some scholars argue that local environmental regulations will raise the costs of end-of-pipe pollution control and inefficient environmental allocation for firms. The cost of environmental protection is significantly greater than the cost of relocation, and enterprises will choose to relocate or divest. The above corporate behavior will largely negatively affect the strategy and behavior, and the rate of improving GTFP will be reduced (Zhang et al. 2021a; Wang et al. 2021a, b, c, d, e; Shen et al. 2019). On the contrary, if rational environmental regulation acts as the internal capital of firms on the value of ecological services, stimulates firms to engage in technological progress activities, and uses resource allocation schemes to maximize the net benefits of resource use, GTFP will also be enhanced (Jin et al. 2019; Zhao et al. 2018). Wang et al. (2021a, b, c, d, e), for example, found a significant positive effect of green technology innovation on the change of their GTFP over the study period after applying a spatial economic model analysis. Liu et al. (2020), through analyzing data from the Yangtze river basin economic zone from 2008 to 2016, point out that it has a significant heterogeneity in the influences of environmental regulations and green technological innovation to positively influence GTFP over time. Green-biased technological advances can significantly contribute to GTFP in the surrounding areas through existing environmental regulations. Liu et al. (2020) investigate the influence of environmental regulation on GTFP in terms of independent innovation, foreign technology importation, and domestic technology and reveal that environmental regulation not only contributes to GTFP growth directly but also indirectly through independent innovation and foreign technology importation. Peng (2020) reveal that local environmental regulation facilitates GTFP, while environmental regulation in the surrounding area inhibits GTFP, but local and surrounding area environmental regulation can influence green total factor productivity through the channels of green innovation and pollution transfer. Hailing and Zhenni (2020) point out that the interaction of local environmental regulatory policies strengthens the spatial spillover effect of GTFP between regions, while technological progress is the key to GTFP improvement, i.e., the revenue generated by innovation can offset or exceed pollution control cost by enterprises to achieve innovation compensation.

As mentioned above, scholars have investigated the nexus between environmental regulation, green technological innovation, and GTFP from different perspectives and using various methods and have obtained favorable research findings. However, there are still some gaps. Firstly, most scholars investigate the relationship between environmental regulation and GTFP with technological factors as a dedicated object of study, but rarely separate green technological innovation from technological innovation for research. Second, previous studies consider only geographical distance when analyzing the spatial weights of the spatial interaction between environmental regulations and GTFP, which rarely consider both economic and geographical factors. Third, existing studies mainly explore the role of environmental regulations and green technology innovation on GTFP at the provincial level and industry level. However, scholars have started to conduct insights into the relationship between the three at the prefectural level in recent years, while most of them focus on the impact of environmental regulations on the number of patents for innovative inventions, etc. A large number of studies confirm that environmental regulations can have some impact on green technology innovation, but no consistent conclusions have been reached. Scholars also less frequently explore the motivations of environmental regulations driving green technological innovation and consequently affecting GTFP at the prefecture-level cities, nor have they further investigated whether such motivations are consistent with macroeconomic phenotypes. For this purpose, this study quantifies the impact of environmental regulation on GTFP under green technological innovation using the spatial lag approach for 269 prefecture-level cities in China over the period 2004 to 2018. Our findings also contribute to providing useful policy insights and empirical evidence for achieving green development in China's economy.

Methodology

Economic strategies

Most of the available studies neglect the spatial impact of GTFP due to its spatial spillover characteristics (Ding et al., 2021). Referring to Zhang et al. (2021b) and Cheng et al. (2019), this study employs the spatial autoregressive model (SAR) to quantify the spatial association between environmental regulation, green technology innovation, and GTFP (Song et al. 2020). The SAR model was constructed as follows:

$$GTFP_{it} = \alpha_0 + \rho \sum_{j=1}^{n} W_{ijt} GTFP_{it} + \alpha_1 ER_{it} + \sum_{k=1}^{6} \beta_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{1}$$

Furthermore, to verify the mediation role generated by green technological innovation between environmental regulations affecting GTFP, following Baron and Kenny (1986) and Wu et al.(2021b), an econometric model is formulated as follows:

$$GTE_{it} = \beta_0 + \rho \sum_{j=1}^{n} W_{ijt} GTE_{it} + \beta_1 ER_{it} + \sum_{k=1}^{6} \beta_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{2}$$

$$GTFP_{it} = \theta_0 + \rho \sum_{j=1}^{n} W_{ijt} GTFP_{it} + \theta_1 ER_{it} + \theta_2 GTE_{it} + \sum_{k=1}^{6} \theta_k X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{3}$$

where $i$and$t$ denote the city and year, respectively. *GTFP* denotes green total factor productivity. *ER* denotes environmental regulation. *GTE* denotes the level of green technological innovation. X denotes a set of control variables that affect GTFP, including economic development level (*RGDP*), human capital (*HUM*), financial development level (*FIN*), foreign direct investment (*FDI*), industrial structure (*IND*), and informatization level (*INF*). μ_i denotes fixed effects, ν_t denotes time fixed effects, and ε_{it} denotes random disturbance terms. α , β, and θ_0 are the coefficients to be estimated.

Spatial weight matrix building

As for the building of the spatial weight matrix, there are three primary ways to build them as follows: the binary adjacency matrix based on whether or not there is a common boundary, the inverse distance square matrix based on the gravitational model, and the truncated distance matrix examined by distance range (Wang et al. 2021b). In order to take economic and distance factors into account, referring to Yang et al. (2021a), the following economic geographic weight matrix (W) is constructed in this study:

$$\mathrm{W}_a = \begin{cases} \frac{1}{\left|\overline{Y_i} - \overline{Y_j}\right| + 1}, i \neq j \\ 1, i = j \end{cases}$$

$$\mathrm{W}_b = \begin{cases} \frac{1}{d}, i \neq j \\ 0, i = j \end{cases}$$

$$\mathrm{W}_1 = W_a \times W_b$$

where $\overline{Y_i}$ ($\overline{Y_j}$) denotes the annual GDP per capita of city i (j) during the sample period. d_{ij} denotes the surface distance between two prefecture-level cities measured by latitude and longitude. Also, this study constructs a geographic inverse distance matrix for robustness testing, which is constructed as follows:

$$\mathrm{W}_1 = \begin{cases} \frac{1}{d^2}, i \neq j \\ 0, i = j \end{cases}$$

Spatial autocorrelation test

Spatial econometric approaches are applied on the premise that the existence of spatial autocorrelation of the quantified variables is required. To explore the spatial effects of GTFP and environmental regulation, referring to Yang et al (2021b), this study uses the global Moran$'$sI index to verify the spatial effects of the above indicators. The measurement is given as follows:

$$\text{Moran}'\text{s}I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\left(M_i - \overline{M}\right)\left(M_j - \overline{M}\right)}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \quad (4)$$

among them, $S^2 = \frac{1}{n}\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2$, $\overline{M} = \frac{1}{n}\sum_{i=1}^{j}M_i$, W_{ij} is the economic geography weight matrix. n is the number of cities, M_i and M_j are the observed values of city i and city j, respectively, and $\overline{M}$ is the average of the observed values. If $\text{Moran}'\text{s}I$ is significantly greater than 0, which indicates that the variables are spatially positively correlated. If $\text{Moran}'\text{s}I$ is significantly less than 0, it indicates that the variables have significant negative spatial correlation; if $\text{Moran}'\text{s}I$ is near to 0, it indicates that the variables do not have a spatial correlation.

Variable definition

Dependent variable

GTFP (GTFP). Following the calculation method of Wang et al. (2021a), the research framework of non-oriented epsilon-based measure (EBM) containing undesired outputs is applied to measure GTFP. The measurement of input factors, output factors (desired output as well as undesired output) is presented in Table 1. The efficiency values are measured by the super-efficiency EBM model of undesired output by the software MAXDEAPro and expressed by GTFP (Baloch et al. 2021).

Core explanatory variable

Environmental regulation (ER). Given the availability of original data, following Shen et al. (2017), the basic indicator for this study is the removal rate of sulfur dioxide and soot to measure environmental regulations. The specific measurement steps are as follows.

First, we standardize the sulfur dioxide and soot removal rates as follows:

$$PE_{ij}^{s} = \frac{\left[PE_{ij} - min\left(PE_{ij}\right)\right]}{\left[max\left(PE_{ij}\right) - min\left(PE_{ij}\right)\right]} \quad (5)$$

where PE_{ij} denotes the actual value of pollutant j removal rate index in city i. $\max\left(PE_{ij}\right)$ and $\min\left(PE_{ij}\right)$ are the maximum and minimum values of pollutant j removal rate in the city, respectively. PE_{ij}^{s} denotes the standardized value of pollutant j removal rate index in city i.

Second, we calculate the adjustment coefficients $\left(W_{ij}\right)$ for sulfur dioxide and soot separately, which are used to differentiate the pollutant emission coefficients of each city. The formula for measuring W_{ij} is shown below.

$$W_{ij} = \frac{P_{ij}}{\sum_{i}P_{ij}} / \frac{GDP_i}{\sum_{i}GDP_i} \quad (6)$$

where W_{ij} is the ratio of the share of pollutant j emitted by city i in the entire country to the share of its GDP. The logic of using W_{ij} for adjustment is that if a city has relatively high emissions of a certain pollutant, the same pollution removal rate implies a stronger degree of environmental regulation, thereby assigning a greater weight accordingly. Finally, the standardized values of two single indicators, industrial sulfur dioxide removal rate and industrial soot removal rate, and the adjustment factor W_{ij} are used to derive the environmental remediation level of city i.

$$ER_i = \sum_{j=1}^{2} W_{ij}PE_{ij}^{s}/2 \quad (7)$$

Table 1 Measurements of GTFP

Factors	Indicators	Measurement methods	References
Input factors	Labor input	urban unit employment	Wang et al. (2021a)
	Capital input	The capital stock is measured using the perpetual inventory method. The depreciation rate in the capital stock is chosen to be 9.6%, and treat the capital stock in the base period as the amount of fixed-asset investment in the base year multiplied by 10 times	Young (2003); Su et al. (2021)
	Energy input	Energy consumption is replaced by per capita urban electricity consumption	Wang et al. (2021a)
Output factors	Desired output	Desired output is the GDP of the prefecture-level city and is discounted to 2004 as the base period	Wang et al. (2021a)
	Undesired output	The undesired outputs are industrial wastewater emissions, industrial smoke and dust emissions, and industrial sulfur dioxide emissions at the prefecture-level	Wang et al. (2021a)

Mediation variable

Green technological innovation (GTE). Following the relationship between green technology fields and IPC classification according to the "Comparison Table of Technology Fields and IPC Classification Numbers" issued by OECD, we use the number of green patent applications granted to portray the green technology innovation level (Gao et al. 2021). We manually collected the green technology innovation data by comparing the green list of international patent classification developed by the International Patent Classification Expert Committee with the patent information service platform of the China Intellectual Property Office one by one.

Control variables

To control other factors interfering with the dependent variable, we introduced control variables including economic development level (*RGDP*), human capital (*HUM*), financial development level (*FIN*), foreign direct investment (*FDI*), informationization level (*INF*), and industrial structure (*IND*). Economic development level (*RGDP*) is expressed as GDP per capita in prefecture-level cities. Human capital (HUM) is defined as a ratio of overall city population to the number of students enrolled in general higher education schools. Financial development level (*FIN*) is represented by the ratio of total bank deposits and loans to GDP of prefecture-level cities. Foreign direct investment (FDI) is denoted by the ratio of actual foreign investment utilized to GDP of prefecture-level cities where US dollars are converted to RMB (in RMB). Industrial structure (*IND*) is characterized by the ratio of tertiary industry structure to secondary industry structure. Informationization level (*INF*) is reflected by the amount of post and telecommunications per capita.

Data

Panel data of 269 prefecture-level cities (prefecture-level cities with more missing data, such as Turpan, Korla, and Changji, are excluded, and the sample of cities with a few missing data are interpolated to make up for the missing data) are selected for this study from 2004 to 2018. The raw data of the above variables are collected from the China Environmental Statistical Yearbook, China Urban Statistical Yearbook, Wind database, EPS database, and the official website of the National Bureau of Statistics. Variable definitions are shown in Table 2 below.

Results and discussion

Spatial correlation result analysis

Moran's *I* approach was applied to examine the spatial dependencies of both GTFP and environmental regulation that were based on the economic geographic weight matrix, and each correlation test result is shown in Fig. 1 and Table 2 (Wang et al. 2021a, b, c, d, e). Table 2 reveals that the Moran's *I* value of GTFP is significantly positive at least 5% level, and Fig. 1 reflects that the scattered points gradually change over time toward the first and third quadrants, indicating that in the whole area, there are significant spatial positive interrelatedness and clustering characteristics of GTFP, and its development has contributed to the enhancement of GTFP in the neighboring areas. Therefore, the promotion of GTFP will form an interareavirtuous circle for sustainable economic development and area innovation environment improvement. Moreover, the Moran's *I* values of environmental regulation in Table 3, the positive spatial and temporal collinearity, and clustering characteristics of environmental regulations can be seen in Fig. 2, i.e., a clustering distribution between cities with high and low environmental regulation levels.

Spatial econometric model applicability test

To accurately select the spatial panel models that are mostly applicable in this paper, a series of tests are executed (Table 4). Table 4 reports both SEM and SAR pass the LM test and the spatial after model passes the robust LM test, but the SEM does not pass the robust LM test. Therefore, SAR is selected to verify the effect of environmental regulation on GTFP in this study.

Table 2 Variable definition

Variables	*N*	Mean	Sd	Min	Max
GTFP	4035	2.181	1.0860	0.2530	11.6300
ER	4035	0.375	0.0711	0.0097	0.6610
GTE	4035	0.749	0.2480	0.2430	10.0200
RGDP	4035	10.28	0.7890	4.5950	15.6800
HUM	4035	1.654	2.2500	0.0064	13.1100
FIN	4035	2.087	0.9910	0.5080	12.3900
FDI	4035	1.961	2.1100	0	21.8600
IND	4035	0.870	1.3390	0.0943	81.7200
INF	4035	1.014	1.7220	0.0441	31.4100

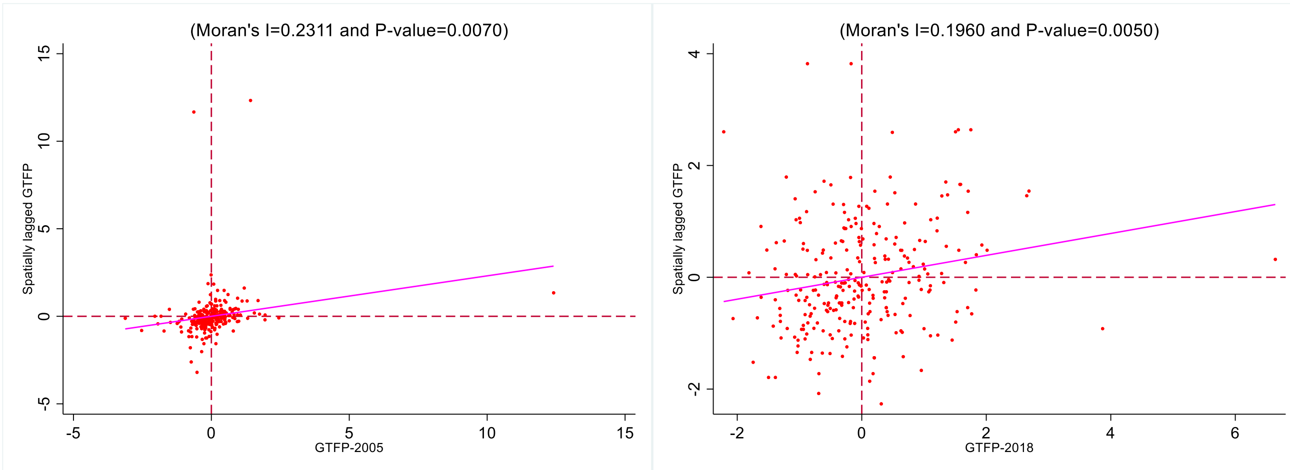

Fig. 1 Moran scatter plot of GTFP

Table 3 Moran's I index values for GTFP and environmental regulation

	GTFP		ER	
Year	Moran's *I*	*p*-value	Moran's *I*	*p*-value
2004	/	/	0.257	0.000
2005	0.231	0.000	0.271	0.000
2006	0.257	0.000	0.250	0.000
2007	0.219	0.001	0.369	0.000
2008	0.207	0.002	0.308	0.000
2009	0.152	0.016	0.443	0.000
2010	0.118	0.034	0.420	0.000
2011	0.143	0.016	0.296	0.000
2012	0.161	0.010	0.265	0.000
2013	0.278	0.000	0.221	0.001
2014	0.309	0.000	0.309	0.000
2015	0.286	0.000	0.211	0.002
2016	0.333	0.000	0.332	0.000
2017	0.217	0.001	0.231	0.001
2018	0.196	0.003	0.173	0.008

Benchmark regression results and discussion

Table 5 reflects the results of the empirical regression based on the SAR model. Further, in order to demonstrate that the findings are comparable, the OLS, RE, and FE models were included in the regressions, and the empirical regressions were conducted under two scenarios of no control variables and control variables, respectively (Li et al. 2021a, b, c). Judging from the estimated coefficients, the coefficients of *ER* are found to be positive and all pass the significance test at the 1% level, implying that environmental regulation can promote the growth of GTFP. Our results are in line with that of Peng et al. (2021), but significantly different from that of Li and Li (2021) and Qiu et al. (2021). One potential interpretation is that environmental regulation in China is implemented primarily through administrative means. Laws, regulations, and policies on environmental protection formulated through government departments or conservation agencies directly and effectively address the more prominent environmental problems. Environmental regulation, which is mainly characterized by mandatory treatment, is effective in dealing with environmental problems (Li and Lin 2016). In addition, under the pressure of environmental protection generated by environmental regulation, government departments use market-based instruments such as prices and fees to internalize the external costs of enterprises, so that enterprises themselves have an intrinsic motivation to reduce environmental resource damage and reduce environmental pollution, which eventually causes the improvement of the environmental pollution situation in society as a whole, thus increasing GTFP (Peng et al. 2021). In addition, since enterprises develop according to Porter's hypothesis, environmental regulations stimulate enterprises to further optimize the efficiency of resource allocation and improve the level of technology, resulting in the "innovation compensation" effect, which in turn improves enterprise productivity and product quality, gains competitive advantage and economic effect, and promotes GTFP.

To further investigate the spatial spillover effect of environmental regulation on GTFP, this study decomposes the spatial effect to obtain the direct effect and indirect and total impact of environmental regulation on GTFP (see Table 6). As can be seen from Table 6, judging from the direct effect, there will be a direct increase of 0.4543 units in local GTFP for every 1 unit increase in the level of local environmental regulations. From the indirect effect, when the level of environmental regulation in the city is increased by 1 unit, there will be a significant increase of 0.0450 units in GTFP

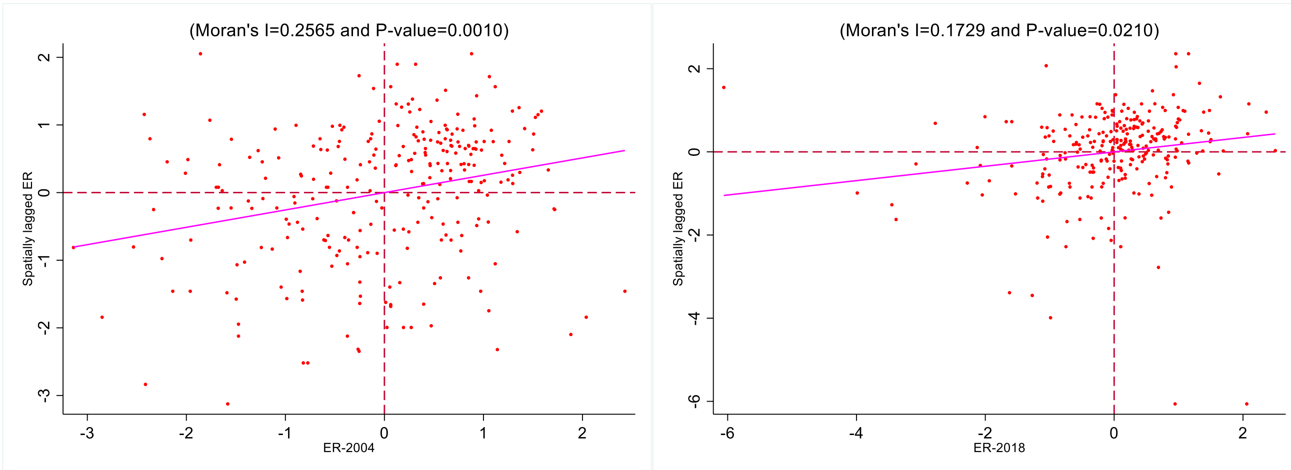

Fig. 2 Moran scatter plot of environmental regulation

Table 4 Spatial econometric model applicability test results

Spatial model applicability test	Statistical value	*p*-value
Spatial error		
Moran's *I*	20.570	0.000
Lagrange multiplier	421.185	0.000
Robust Lagrange multiplier	0.008	0.930
Spatial lag		
Lagrange multiplier	480.842	0.000
Robust Lagrange multiplier	59.665	0.000

in the neighboring cities, indicating that there is a spatial spillover characteristic of the enhancement effect of environmental regulation on GTFP. We can learn the answer from the following explanation. In the case where the effect of environmental regulation on GTFP is obvious, due to the existence of performance appraisal and official promotion mechanisms, surrounding cities will borrow and emulate local environmental regulation instruments, thus making the spatial spillover effect of local environmental regulation on GTFP growth (Li et al. 2013; Wang et al. 2021a, b, c, d, e).

Influence mechanism results and discussion

To validate additionally the influence environmental regulation on GTFP realized through the path of green technology innovation, this study employs mediation effects to verify the existence and significance of this path. The estimation results of the mediation effect result are indicated in Table 7. Column (1) denotes the role of ER on GTFP, and column (2) denotes the effect of environmental regulation on GTFP with green technology innovation as a mediation variable. Column (1) reveals that the coefficient of green technology innovation is positive and passes the significance test at the 1% level, indicating that environmental regulation can significantly enhance green technology innovation, which are consistent with those of Cai et al. (2020). A reasonable interpretation is that green technological innovation is a management innovation and technological innovation that takes into account both green and innovative concepts with the goal of saving resources and energy and avoiding, eliminating, or mitigating ecological pollution or damage (Cai et al. 2020). Environmental regulation coordinates the economy, resources, and the environment by establishing management models and regulatory mechanisms as a way to force producers to take into account the costs spent on environmental resource conservation into the production costs of the enterprise (Frondel et al. 2007). This not only makes the demand for cleaner production technologies and green technology equipment increase but also promotes in-depth research and development in related green fields (Abid et al. 2021a, b). Green technology innovation minimizes or eliminates the generation of pollutants in the production process, contributing to the "green" nature of economic operations. At the same time, green technology innovation, as an additional technology separate from production technology, has the potential to reduce the impact of undesired output on GTFP through the treatment, recovery, and recycling of pollutants. When it is the case that the gains from green technology innovation outweigh the increased production costs, enterprises will further increase their capital investment in green technology reform to improve production efficiency and the innovation effect brought by the change of production methods, thus realizing a higher level of environmental regulation to toward fostering green technology innovation (Guo et al. 2018).

Combining columns (2) and (3), we find that environmental regulation can enhance GTFP by promoting green technological innovation, i.e., the mediation effect of green

Table 5 Benchmark regression results

Variables	OLS		RE		FE		SAR	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ER	4.2957***	0.7810***	7.8125***	0.8876***	8.4230***	0.8662***	0.3565**	0.4460***
	(18.61)	(3.29)	(35.08)	(4.96)	(37.02)	(4.97)	(2.00)	(2.68)
RGDP		0.7333***		1.1118***		1.1104***		0.6330***
		(30.68)		(60.56)		(61.14)		(17.36)
HUM		−0.0089		0.1091***		0.2076***		0.1967***
		(-0.99)		(8.62)		(14.11)		(14.48)
FIN		0.1190***		0.0025		−0.0037		−0.1943***
		(6.24)		(0.14)		(−0.20)		(−9.54)
FDI		−0.0885***		−0.0202***		0.0032		0.0080
		(-12.29)		(−3.48)		(0.56)		(1.51)
IND		0.0239**		0.0092		0.0075		−0.0009
		(2.21)		(1.49)		(1.26)		(−0.16)
INF		−0.0805***		−0.0037		0.0172		−0.0108
		(−8.61)		(−0.35)		(1.55)		(−1.06)
_CONS	0.5704***	−5.6492***	−0.7482***	−9.7316***	−0.9771***	−9.9248***		
	(6.48)	(−26.27)	(−8.04)	(−61.13)	(−11.34)	(−66.16)		
ρ							0.1459***	0.0954***
							(11.33)	(7.54)
δ^2							0.2121***	0.1824***
							(44.73)	(44.84)
N	4035	4035	4035	4035	4035	4035	4035	4035
R^2	0.0789	0.3043			0.2145	0.6963	0.3090	0.6902

Z values are in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

technological innovation exists. It is not difficult to understand that under the condition of environmental regulation, the increase in production cost of regulated enterprises will reduce technological innovation to a certain extent (Jin et al. 2019; Shen et al. 2019; Zhao et al. 2018). However, green technology innovation takes the realization of green development as the core pursuit, and enterprises will seek green technology innovation to gain a competitive advantage in the market by considering long-term profit maximization (Jin et al. 2019; Wang et al. 2021a, b, c, d, e). The efficient production mode brought by this green technology innovation can provide new green products, processes, and services, which not only effectively make up for the defects of traditional technology innovation in neglecting natural resource consumption and ecological damage but also improve resource allocation efficiency in order to thus drive the industry to achieve green transformation and ultimately improve GTFP (Liu et al. 2020).

Table 6 Spatial spillover effect result

Variables	LR_Direct	LR_Indirect	LR_Total
ER	0.4543***	0.0450**	0.4993***
	(2.65)	(2.55)	(2.66)
RGDP	0.6346***	0.0632***	0.6979***
	(17.99)	(7.15)	(18.10)
HUM	0.1991***	0.0199***	0.2190***
	(15.28)	(6.66)	(15.03)
FIN	−0.1959***	−0.0196***	−0.2155***
	(−9.94)	(−5.69)	(−9.79)
FDI	0.0081	0.0008	0.0089
	(1.58)	(1.57)	(1.58)
IND	−0.0006	−0.0001	−0.0007
	(−0.11)	(−0.10)	(−0.11)
INF	−0.0111	−0.0011	−0.0121
	(−1.05)	(−1.02)	(−1.05)

Z values are in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Heterogeneity results and discussion

Since the level of environmental regulation and the level of green technology innovation may have some disparity due to the economic scale disparity and geographical location, this study analyzed the heterogeneous impact of environmental regulation and green technology innovation on the GTFP with reference to Li et al. (2021b) and Su et al. (2021) splitting the sample into eastern, central, and western areas

Table 7 Influence mechanism result

Variables	(1) GTE	(2) GTFP
ER	0.4768***	0.4350***
	(12.34)	(2.66)
GTE		0.4763***
		(12.34)
RGDP	0.5909***	0.5870***
	(16.41)	(16.30)
HUM	0.2078***	0.2111***
	(15.58)	(15.77)
FIN	−0.1768***	−0.1782***
	(−8.81)	(−8.89)
FDI	0.0037	0.0030
	(0.71)	(0.58)
IND	0.0007	0.0005
	(0.14)	(0.10)
INF	−0.0088	−0.0101
	(−0.88)	(−1.01)
_CONS	0.0907***	0.0880***
	(7.27)	(7.02)
ρ	0.0907***	0.0880***
	(7.27)	(7.02)
δ^2	0.1761***	0.1759***
	(44.85)	(44.85)
N	4035	4035
R^2	0.6835	0.6884

Z values are in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

(see Table 8). Columns (1) and (4) of Table 7 reflect that environmental regulations promote GTFP growth at the 5% significance level in the eastern and central regions, while the inhibitory effect on GTFP in the western region is not significant. It is likely that the reason is the inadequate market system in the western region, which is manifested by the high proportion of state-owned enterprises, government overreach, and market absence, ultimately leading to the failure of environmental regulations to stimulate economic agents to take the initiative to control the pollution of their own enterprises and do not take the initiative to carry out the energy-saving transformation, thus hindering GTFP increase to some extent. Columns (2) and (5) confirm the significant contribution of environmental regulations to green technology innovation in the eastern, central, and western regions at the level of 1%, indicating that the "reverse" effect and innovation effect exist significantly in different areas. Combining columns (3) and (6), the mediation channel of environmental regulation to enhance GTFP through contributing to green technology innovation in the east-central region is found to be significantly present, but not be found in the western region. The reason for this analysis may be that, compared to the east-central region, the majority of prefecture-level cities in the west are in the early stage of industrialization, and the problem of rapid economic growth through sacrificing resources and environment is very prominent. Thus, there is no dependence on the role of green technology innovation for the promotion of GTFP by environmental regulation.

Robustness test

To verify the robustness of the above results, the following three procedures are performed to test the full sample in this paper. (1) Replacement of spatial weight matrix: Referring to Yang et al. (2021c), we change the economic geography matrix to a geographic inverse distance matrix for further estimation of the results (see columns (1) and (2) in Table 9). (2) Replacement of the measures of the explanatory variables: Following Wang et al. (2021a, b, c, d, e), we use the SBM-GML index method to re-measure GTFP (shown in columns (3) and (4) in Table 9). (3) Endogeneity problem: The improvement in the level of environmental regulation will contribute to the increase in the level of GTFP. Therefore, considering the bidirectional causal relationship between environmental regulation and GTFP, reasonable instrumental variables need to be selected to solve the endogeneity problem existing in the model. We selected the number of word frequency related to environmental protection from the government work reports of previous years as an instrumental variable for environmental regulation. Among them, the environmental vocabulary includes 15 groups of words: emission reduction, green, pollution, low carbon, environmental protection, energy consumption, $PM_{2.5}$, sulfur dioxide, chemical oxygen demand, air, PM_{10}, carbon dioxide, environmental protection, emission, and ecology. Further, the 2SLS method was applied to re-regress the results (see column (5) in Table 9). The estimation results of all the above three techniques indicate that environmental regulation significantly contributes to GTFP and that the previous results are robust.

Conclusions and policy implications

Under the current scenario of economic development at the cost of environmental pollution and energy consumption, the government adopts environmental regulations to respond to the environmental problems brought about by industry and enhance GTFP through green technological innovation. Based on the perspective of green technology innovation, the impact of environmental regulation on GTFP is explored using a spatial lag model based on panel data of 269 prefecture-level cities in China from 2004 to 2018. The statistical findings indicate that a significant positive spatial dependence exists between GTFP and environmental regulation, i.e., GTFP and environmental regulation have

Table 8 Heterogeneity result

Variables	Eastern and central region			Western region		
	(1)	(2)	(3)	(4)	(5)	(6)
ER	0.4109**	0.3116***	0.3940**	−0.0176	2.4576***	0.3024
	(2.20)	(7.90)	(2.13)	(−0.05)	(19.31)	(1.00)
GTE			0.3106***			2.4646***
			(7.88)			(19.35)
RGDP	0.8503***	0.8146***	0.8106***	0.2945***	0.1580***	0.1573***
	(17.40)	(16.73)	(16.65)	(4.99)	(3.21)	(3.20)
HUM	0.2100***	0.2220***	0.2250***	0.1603***	0.1519***	0.1551***
	(13.43)	(14.28)	(14.42)	(5.76)	(6.68)	(6.76)
FIN	−0.1317***	−0.1175***	−0.1190***	−0.4037***	−0.3467***	−0.3447***
	(−5.86)	(−5.27)	(−5.33)	(−7.85)	(−8.15)	(−8.10)
FDI	0.0075	0.0051	0.0047	0.0076	0.0193	0.0176
	(1.42)	(0.96)	(0.89)	(0.30)	(0.93)	(0.85)
IND	0.0018	0.0028	0.0027	−0.1469*	−0.2478***	−0.2541***
	(0.34)	(0.54)	(0.51)	(−1.67)	(−3.42)	(−3.50)
INF	−0.0111	−0.0096	−0.0108	0.0814*	0.0564	0.0555
	(−1.09)	(−0.95)	(−1.07)	(1.76)	(1.47)	(1.45)
ρ	0.0719***	0.0702***	0.0678***	0.0479*	0.0238	0.0229
	(4.86)	(4.78)	(4.60)	(1.88)	(1.08)	(1.04)
δ^2	0.1701***	0.1671***	0.1669***	0.2091***	0.1423***	0.1422***
	(40.20)	(40.21)	(40.21)	(19.93)	(19.94)	(19.94)
N	3240	3240	3240	795	795	795
R^2	0.7138	0.7145	0.7158	0.3667	0.3279	0.3555

Z values are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

significant spatial spillover characteristics. Beside, a positive correlation is found between environmental regulation and GTFP. Environmental regulation also indirectly contributes to GTFP by improving green technological innovation, and an increase of environmental regulation level in the local region significantly contributes to GTFP growth in neighboring regions. Finally, the direct and indirect effects of environmental regulations on GTFP are significantly found in eastern and central regions, but insignificant in the western. To better enhance GTFP through a combination of environmental regulation as well as green technology innovation, some necessary policy measures should be implemented.

Although environmental regulation not only has a significant positive effect on GTFP, but also this effect is subject to significant regional heterogeneity. The “Porter hypothesis” is based on the premise of strict and reasonable environmental regulations, thus policy makers should tackle both the intensity of environmental regulations and the rationality of environmental regulations to facilitate the positive effect of environmental regulations on GTFP. In terms of the intensity of environmental regulations, although the intensity of environmental regulations is conducive to the improvement of GTFP, it must be noted that the enhancement of environmental regulations is a long-term process and must be done gradually to prevent the phenomenon of excessive overkill. For example, if environmental regulations are increased too quickly in a short period of time, it will trigger a significant increase in the cost of industrial enterprises as well as the elimination of a large number of enterprises. Therefore, the intensity of environmental regulations should be steadily increased in the future to achieve a win–win situation for both environmental performance and economic performance. Policy makers should not only actively revise and improve relevant regulations to provide a basis for the use of environmental regulation tools but also continuously refine the content of specific provisions involved in environmental regulation, such as pollution emission standards and penalties for non-compliance, to enhance the operability of environmental regulation tools.

In addition, policy makers need to adjust policies according to the actual development status of each region. For example, the eastern and central regions should emphasize maintaining the scale and strength of existing environmental regulations; improving the system of taxation, subsidies, and environmental property rights transactions; enhancing the effectiveness of environmental regulations; and strengthening the driving and radiating effect of GTFP on the western region. The western region should absorb and learn from the advanced experience of the eastern and central regions in implementing environmental regulations and formulate

Table 9 Robustness test result

Variables	Change the spatial weight matrix		Change the dependent variable		2SLS
	(1)	(2)	(3)	(4)	(5)
ER	0.3584**	0.4193**	0.8474***	0.8060***	9.5450*
	(2.05)	(2.54)	(3.08)	(3.11)	(1.65)
RGDP		0.5883***		0.9574***	0.3133
		(16.18)		(16.90)	(1.13)
HUM		0.1904***		0.1769***	0.0073
		(14.11)		(8.36)	(0.48)
FIN		−0.1913***		−0.3313***	0.1114***
		(−9.47)		(−10.44)	(4.77)
FDI		0.0063		0.0216***	−0.1260***
		(1.20)		(2.62)	(−4.87)
IND		0.0008		−0.0119	0.0255
		(0.14)		(−1.41)	(0.88)
INF		−0.0109		−0.0084	−0.0728***
		(−1.08)		(−0.53)	(−6.74)
_CONS					−4.5644***
					(−6.09)
ρ	0.8698***	0.7435***	0.0947***	0.0440***	
	(27.50)	(13.68)	(7.57)	(3.59)	
δ^2	0.2068***	0.1797***	0.5056***	0.4423***	
	(44.73)	(44.77)	(44.84)	(44.90)	
N	4035	4035	4035	4035	4035
R^2	0.6093	0.7018	0.2731	0.6179	0.0712

Z values are in parentheses; ***$p<0.01$, **$p<0.05$, *$p<0.1$

policies that are conducive to improving GTFP in accordance with the economic development of the region.

Policymakers should strengthen their policy support for green technology innovation. We find that green technology innovation can significantly contribute to GTFP growth, which indicates the importance of promoting green technology innovation to enhance GTFP. Therefore, in order to enhance GTFP, policy makers must continuously upgrade the research level of green technologies and vigorously develop energy-saving and emission reduction technologies so that the overall innovation capability of the industry can be improved. Moreover, policy makers should establish innovation consciousness, integrate with their actual situation, step up investment in research and development of green technologies, and improve green innovation capability. Meanwhile, policymakers should also develop the intellectual property rights and patent system, create a good market system environment, and protect green technology innovation achievements.

The judicious use of environmental regulation by policymakers to improve green technology innovation is an essential way to achieve GTFP growth. The study finds that there is a positive mediation effect of green technology innovation between environmental regulation and GTFP growth, and its main policy implication is to take green technology innovation as an important power source to promote GTFP growth. On the one hand, policymakers should use the constraints and incentives of environmental regulation to contribute to the emergence and invention and application of green technology innovation, appropriately reduce fines while ensuring environmental performance. On the other hand, policymakers should combine environmental regulation with other policies, such as green ecological compensation and government financial subsidies. At the same time, policymakers should strengthen R&D subsidies for enterprises related to green technology innovation and tax deductions for related enterprise R&D activities, in order to guide them toward green, clean, and ultimately enhance GTFP.

Although the nexus between environmental regulation, green technology innovation, and GTFP has been thoroughly investigated, there are some limitations that should be considered when a similar topic is being carried out. First, this study only uses industrial three wastes as undesired output when measuring GTFP. However, important environmental variables such as haze pollution and carbon emissions have been ignored. Second, this study only selects industrial three wastes as undesired output when measuring GTFP. However, important environmental variables such as haze pollution and carbon emissions may have been ignored. Therefore, it is likely that better results will be found when haze pollution and carbon emissions are incorporated into the undesired outputs in the future studies. Second, when conducting the heterogeneity analysis, this study examines the internal differences of the study subjects based on the geographical characteristics of China. However, there may also be heterogeneous effects of different environmental regulation levels and green technological innovations on GTFP. For example, there may be nonlinear effects of environmental regulation and green technological innovation on GTFP. Therefore, using a panel threshold model to analyze the effects of environmental regulation and green technology innovation on GTFP seems to be an interesting and meaningful direction.

Author contribution Ping Yang: conceptualization, project administration, writing—review and editing, writing—original draft, formal analysis, data curation, software, visualization. Min Fan: writing—original draft, writing—review and editing, formal analysis, validation, methodology, conceptualization, funding acquisition, supervision. Qing Li: writing—original draft, writing—review and editing.

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Data Availability The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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