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Impact of Environmental Regulatory Types and Green Technological Innovation on Green Total Factor Productivity in Polluted Areas of China

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Abstract: Compared to regions with lighter pollution, the areas heavily affected by pollution in China face more severe environmental problems due to rapid economic growth, which creates a greater urgency for government and corporate environmental requirements. This study innovatively applies mediation and threshold models to explore the potential correlation between green technology innovation, types of environmental regulation, and provincial-level green total factor productivity (GTFP). Additionally, it examines inter-regional differences, determines threshold effects, and introduces regional heterogeneity and mediator variables. The research findings demonstrate that progress in green technology innovation significantly impacts the improvement of provincial-level GTFP. Further mechanism analysis reveals the crucial role of environmental regulation in facilitating sustained enhancement of GTFP through green technology innovation. The promotion of GTFP is more pronounced in eastern and central provinces compared to western regions, and the positive influence of green technology innovation varies significantly among provinces. By investigating the regional differences of polluted areas and introducing mediating variables, this paper explores the environmental regulation mechanism, which has important guiding significance for formulating more effective environmental regulation policies, promoting green technology innovation, and improving GTFP.

Keywords: green technological innovation; environmental regulations; GTFP; panel threshold model

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1. Introduction

China has seen a dramatic surge in green innovation in recent times, transforming into a modern economic model with the most potential and energy in the economic sector. The 14th Five-Year Plan and the 2035 Vision Goals emphasize the importance of green development and the harmonious coexistence between humans and nature [1,2]. By 2025, the ecological environment is expected to continue to advance, with current advances in ecological progress. By the year 2035, the ecological landscape will be significantly enhanced, and the ambition of constructing a stunning China will be essentially accomplished. The rapid development and change speed, wide radiation range, and profound impact are unprecedented. They are quietly promoting a fresh round of profound changes in China's mode of production, life, and governance, and becoming a key force in reorganizing global resources, reshaping the global economic structure, and changing the global competition pattern. The transition of China's economy from a peak growth rate to a period of superior green growth is a strategic decision. This current stage of development is characterized by a significant level of green development. However, China's economic development is still heavily dependent on energy and the environment, and resource and environmental issues have become a major challenge to China's green transformation. The comprehensive enhancement of GTFP is the essential path to green growth. Based on this, the academic circle began to pay widespread attention to the ways and channels to promote the development of GTFP [3].

The primary approach to achieving total factor productivity is to concurrently promote economic growth and enhance production technology through scientific means while also reducing pollution emissions. In addition, the enhancement of urban residents' energy literacy can additionally expedite the energy transition and facilitate sustainable development [4]. Governmental initiatives to reduce pollution emissions due to economic development have been implemented at all levels, with environmental regulation policies being the most effective. In light of the ongoing advancement of green technology, environmental regulation has become a fundamental policy tool to advance GTFP. Therefore, in light of the opportunities presented by green innovation, the primary challenges confronting the government include how to facilitate the development of GTFP [5], effectively harness the functional mechanism of environmental regulation, and explore potential heterogeneity in the impact mechanism of green innovation on GTFP across different provinces. This research endeavors to thoroughly evaluate the influence of environmental regulations and green invention on the total factor productivity of green plants in polluted regions of China. We shall investigate the magnitude of the effects of various environmental regulations on GTFP and assess the part green invention plays in lessening environmental strain and augmenting production effectiveness through a thorough examination of pertinent literature and the formation of economic models. This study's outcomes will be a significant reference for the government to devise environmental regulations and businesses to pursue green innovation. At the same time, it will also provide a reference and inspiration for other countries or regions in the polluted areas and promote the sustainable development of the global environment [6].

The remainder of this paper is organized as follows. We present a literature review and the research hypotheses in Section 2. In Section 3, we discuss our materials and methods. Section 4 reports our analysis results, and Section 5 presents our conclusions and offers a discussion on the limitations of our results.

2. Literature Review and Research Hypotheses

The relationship between green innovation, environmental regulation, and GTFP has attracted increasing attention from scholars who are devoting themselves to studying this field [7,8]. According to the existing literature, environmental regulation and green innovation have a significant impact on the macro economy. In addition, green innovation has a positive impact on the development and environmental performance of SMEs and heavily polluting companies. The implementation of environmental regulations can compel SMEs and heavily polluting companies to mitigate solid waste, greenhouse gases, and other hazardous chemicals through the imposition of penalties [9,10]. Specifically, relevant research on the impact of green innovation on GTFP is concentrated in the following three areas: literature related to green innovation, literature related to GTFP, and literature related to the action mechanism of green innovation with respect to GTFP [11].

2.1. Green Innovation's Direct Influence on Total Factor Productivity of the Green Sector

Green innovation has become a potent tool that is not only able to drastically decrease energy consumption in the traditional industrial production process but also to advance the social economy to attain green and superior growth through energy conservation and emissions abatement [12]. The ongoing advancement of the scientific and technological revolution, coupled with the industrial transformation, has resulted in this phenomenon. In today's new era of industry, digitalization, transformation, and upgrading have emerged as prevailing trends. Relevant research shows that green innovation yields significant enhancements in GTFP while exhibiting a nonlinear relationship with increasing marginal effects [6]. Consequently, the development of green innovation is not merely a strategic choice but an indispensable approach to expediting the fulfillment of people's living requirements.

By considering the development of the digital economy as a metric for evaluating green innovation, Zhou et al. discovered that actively promoting the growth of the digital economy can effectively facilitate the digital transformation of traditional industries, enhance regional competitive advantages, and consequently drive industry-wide enhancements in GTFP [11]. Some scholars analyzed the influencing factors of green total factor yield in China's dairy industry and found that the achievement of such productivity relies on advancements in green technology innovation [13]. Xiao et al. pioneered the concept of green development, developed the Tobit model, and examined the impact and mechanism of regional GTFP with respect to green innovation development. It was discovered that such development contributes to the enhancement of regional GTFP [12]. Subsequent research revealed that the role of innovation in green innovation (such as energy conservation and technological advancement) is heterogeneous, while the level of green innovation in Chinese cities directly influences and has spillover effects in terms of improving GTFP [14]. This conclusion has been firmly upheld through years of historical data analysis and is still supported today. The continual advancement of green innovation in China has drastically decreased the impediments between different areas. By augmenting innovation proficiency and refining industrial structures, the social and economic advantages can be significantly augmented, and the regional GTFP can be enhanced. Therefore, this paper proposes the following hypothesis:

H1. *Green innovation advancement aids in advancing the regional GTFP.*

2.2. The Indirect Influence of Green Innovation on Total Factor Productivity of the Green Sector Is Evident

The construction of the green production mode of enterprises is advanced by the development of green innovation, digital technology is employed to strengthen the government's role in environmental oversight, and social environmental monitoring is improved. Through these means of environmental regulation, we can reduce the emissions of provincial environmental pollutants so as to realize the green development of the economy. The research conducted by Zhao Tao et al. revealed that the integration level of green innovation is progressively deepening across various sectors, emerging as a highly influential input factor that drives overall advancements in both the economy and society [15]. The promotion of green innovation has been found to not only significantly alleviate competitive pressure on enterprises but also reduce their environmental control burden, thereby enhancing the effectiveness of various control measures. The government should take steps to draw the public's attention to green innovation, such as by encouraging environmental protection, creating public environmental regulatory bodies, and utilizing multiple media outlets to spread the word to the public. At the same time, with the continuous progress of IT, various forms of social media will also bring great benefits to society. The utilization of diverse social media platforms enables individuals to access the most up-to-date news, seek expert advice, and facilitate the sharing of knowledge and experiences. Simultaneously, businesses across various industries can leverage social media channels to effectively promote their products and drive sales growth [16].

Environmental protection policy in China has undergone continuous changes over time. This process includes the transition from relying on the traditional planning and control mode to a modern market control mode, in addition to increasing support for social forces. In this process, China is also constantly exploring new ways to promote sustainable social governance. In this case, the government has adopted a means to control and improve the environment by command and supervision [17]. This approach seeks to motivate companies that consume considerable resources and generate considerable pollution to modify their operations and to motivate them to embrace sophisticated science and technology to enhance effectiveness [18]. In this way, we can promote sustainable economic development and help our society to move towards a more harmonious future. Incentives from the market, like environmental taxes and emission trading, can be used to effectively suppress and transform pollutants into sustainable economic growth drivers, thus encouraging businesses to reduce pollution, improve ecological conditions, foster economic growth, and bring long-term advantages to society. Informal environmental regulation, such as public participation, is often only superficial and has no substantive effect, so it is difficult to exert real effects [19].

In terms of the correlation between environmental regulation and GTFP, the Chinese government currently emphasizes command-controlled environmental regulation as the primary approach to address environmental pollution. However, some scholars argue that such regulation only provides limited incentives for enterprises' green innovation. Due to the upper limit of environmental pollution penalties, some enterprises are satisfied to meet the minimum requirements of green innovation activities; this situation will lead to a decline in the level of green innovation [20,21]. The "Porter hypothesis" theory of environmental regulation is generally accepted as the most influential, and most research results in China suggest that it is more influential than the "compliance cost theory". This is due to the fact that these two schools of thought fall into two distinct categories. There are three main types of viewpoints in the existing research. One is positive correlation, which holds that moderate environmental regulation can improve GTFP. The second is negative correlation, believing that environmental regulation will distort resource allocation and, thus, hinder the improvement of total factor productivity [22,23]. The third is a nonlinear relationship. Some scholars have proposed that there is a U-shaped relationship between environmental regulation and GTFP in manufacturing. With respect to the relationship between the three, some scholars have considered that the amalgamation of realistic elements, combining green and creative growth with suitable environmental regulations, can have a more powerful influence on GTFP promotion, and this is exemplified by the following two aspects: on the one hand, green invention as a novel form of commerce in the economic arena, with a more advanced development impetus than the conventional development model. The Internet's growth and popularity have enabled more economic entities and social organizations to partake in environmental governance, thus broadening the scope of governance [24]. This has had a beneficial effect on environmental regulation policies, as well as making the energy in production more productive and avoiding the waste of resources and environmental pollution issues. Therefore, this paper innovatively adopts the mediation and threshold models to study the potential correlation between green technology innovation, types of environmental regulation, and provincial-level GTFP. This paper proposes the following hypothesis:

H2. *Environmental regulation is a mediator of the effect of green innovation on GTFP.*

2.3. The Influence of Environmental Control on GTFP Is Determined by the Threshold Mechanism

GTFP is more likely to be successful in the presence of an enterprise with a strong innovation ability, which makes it easier to attract external investors, as well as more capable partners [25]. This type of enterprise has a clear resource advantage and a greater capacity to resist risk, thus making it more likely to succeed in innovation. The investment crowding-out effect is outweighed by the innovation compensation effect for enterprises with a strong technological innovation ability; however, for those with a weak ability to realize the difficulty of green transformation through technological innovation, more resources are needed, and energy is likely to be a successful area of innovation. However, such enterprises face difficulties in obtaining external financing, and it is difficult to cooperate with well-qualified enterprise research and development, leading to the possibility of low enterprise innovation. In addition, there is a threshold effect between environmental regulation and green technology innovation [26–29]. Therefore, the investment crowding-out effect of enterprises with low technological innovation ability is greater than the innovation compensation effect, and such enterprises may not be able to combine pollution prevention and productivity improvement. Based on the above analysis, the following assumptions are made:

H3. *The level of technological innovation of enterprises restricts the effect of environmental regulation on GTFP; only when enterprises surpass the threshold value can environmental regulation advance GTFP.*

The framework of this article is summarized as follows. First, the Introduction provides a literature review and introduces three hypotheses. Secondly, based on these hypotheses, empirical analyses are conducted using regression models, mediation effect models, and panel threshold models. Lastly, the conclusions are summarized, and policy recommendations are proposed (Figure 1).

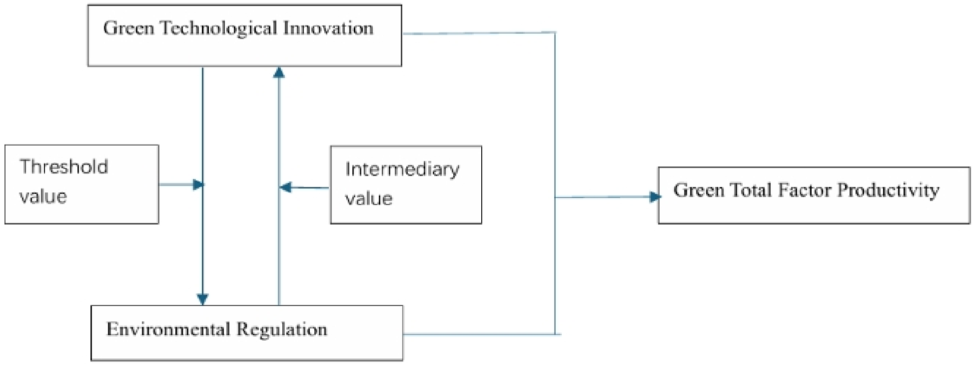

Figure 1. Research framework.

3. Materials and Methods

3.1. Measurement Model

Following Li's research [30], this paper constructs a benchmark model to explore how green innovation affects the results of GTFP.

$$GTFP_{i,t} = \vartheta_0 + \vartheta_1 Dig_{i,t} + \vartheta_2 C_{i,t} + \mu_i + \vartheta_i + \varepsilon_{i,t} \tag{1}$$

Subscripts i and t denote the province and year; $GTFP_{it}$ symbolizes the GTFP; $Dig_{i,t}$ denotes the level of green innovation development; C_{it} is the control variable; μ_i and ϑ_i symbolize the fixed effects of region and time, respectively; and $\varepsilon_{i,t}$ is the potential random error term.

According to the above analysis, environmental regulation is one of the important ways for green innovation to improve GTFP [31]. Therefore, following Wen's research [32], provincial environmental regulation (ER) variables are introduced, and the following intermediary effect model is constructed to analyze the mechanism principle of green innovation to promote provincial GTFP improvement:

$$ER_{i,t} = \partial_0 + \partial_1 Dig_{i,t} + \partial_2 C_{i,t} + \varepsilon_{i,t} \tag{2}$$

$$GTFP_{i,t} = \vartheta_0 + \vartheta_1 Dig_{i,t} + \vartheta_2 ER_{i,t} + \vartheta_3 C_{i,t} + \varepsilon_{i,t} \tag{3}$$

where $\mathrm{ER}_{\mathrm{it}}$ represents the environmental regulation of the intermediary variable. The level of green innovation development may produce nonlinearity, leading to a GTFP dynamic spillover effect. Therefore, based on existing research [33], the threshold regression model verifies this hypothesis as follows:

$$\begin{gathered} GTFP_{i,t} = \sigma_0 + \sigma_1 Dig_{i,t} \times I(Adj_{i,t} \leq Z_1) + \sigma_2 Dig_{i,t} \times I\left(Z_1 < Adgj_{i,t} \leq Z_2\right) + \sigma_3 Dig_{i,t} \times I(Adji,t > Z_2) \\ +\sigma_4 ER_{i,t} \times I(Adj_{i,t} \leq D) + \sigma_5 ER_{i,t} \times I(Adj_{i,t} > D) + \mu_i + \varepsilon_{i,t} \end{gathered} \tag{4}$$

3.2. Variable Measure

3.2.1. Core Explanatory Variables

Based on the research conducted by Wu Jing [12], this paper evaluates the progression of green innovation in China through an examination of the following three dimensions: the industrialization level, the digitalization extent, and infrastructure supporting green innovation. Subsequently, panel data are analyzed and processed to derive indicators that reflect the developmental stage of green innovation upgrading. Table 1 describes the green innovation level measurement system in China [34].

Table 1. Green innovation level measurement system in China.

Level 1 Indicators	Level 2 Indicators	Level 3 Indicators
	Environmental benefit indicators	Greenhouse gas emissions Energy consumption Green product sales volume
Level of green and innovative development	Economic benefit indicators Social benefit indicators	Market share of green products has increased Environmental health risk indicators Participation in the green economy

3.2.2. Interpreted Variable

A measure of GTFP is interpreted as a variable. An efficiency calculation technique based on the total factor productivity, taking into account the anticipated output, is known as GTFP. In the study of GTFP, many scholars have used the ML index for estimation, but this approach may lead to non-free and non-transitive problems of linear programming [35]. This paper proposes novel estimation techniques based on Li Bo et al.'s research [36], and data envelope analysis (DEA) can be used to determine the expected yield; unexpected output; and non-radial, non-angular relaxation directional time function (SBM). Additionally, the global Malmquist–Luenberger (GML) index can be employed to measure each province, as detailed in Table 2 for further information. We discovered, through the research of Cai Ling and Wang Ping, that the SBM-GML index can be employed to gauge the economic advancement of various areas [37]. We use the GTFP values for each year as a set of data; then, with reference to TONE's [38] research, we construct a super-efficient SBM model as follows:

$$\begin{gathered} \vec{R}(c, l, ed_y, d_o) = max\ a \\ s,t, \sum_{n=1}^{N} \lambda_n C_n \leq c' \sum_{n=1}^{N} \lambda_n l_n \leq l' \sum_{n=1}^{N} \lambda_n e_n \leq e' \sum_{n=1}^{N} \lambda_n y_n \leq y' + ad_y \\ \sum_{n=1}^{N} \lambda_n O_n \leq O' - \partial d1 \quad \sum_{n=1}^{N} \lambda_n = 1 \quad \lambda_n > 0\partial[0,1] \end{gathered} \tag{5}$$

Table 2. Measurement index of GTFP.

Level 1 Indicators	Level 2 Indicators	Level 3 Indicators
Put into	Capital input Labor input Energy input	Fixed capital stock Year-end employment personnel Regional standard coal consumption
	Expected output	Regional GDP
Output–input ratio	Undesired output	Industrial wastewater discharge volume Industrial soot emissions Industrial SO_2 emissions

According research to by Xia et al. [39], in this paper, we construct the Global Malmquist–Luenberger (GML) index as follows:

$$GML = \frac{1 + R^{\to c}\left(c^t \cdot l^t \cdot e^t \cdot \mathrm{y}^t \cdot \mathrm{o}^t\right)}{1 + R^{\to c}\left(c^{t+1} + l^{t+1} + e^{t+1} \cdot + y^{t+1} \cdot + o^{t+1}\right)} \tag{6}$$

The directional distance function R is represented by the output of the maximum, the input of the minimum, and the unexpected output of the minimum; y is the expected output; o stands for the undesired output; c, l, and e, are the capital input, labor input, and energy input, respectively; $d = (dy, do)$ is the directional vector; and the weight of the decision unit, denoted by λ_n, is summed to 1. The production function is a variable-scale return.

3.2.3. Intermediary Variable

The evaluation of environmental regulation (ER) is an important basis for realizing green development. Currently, there are many measurement methods used in the academic community, such as pollutant emissions, frequency of environmental measures, and timing of implementation. However, relying solely on these assessment methods often leads to a large bias. Employing Deng Rongrong and Zhang Aoxiang's three essential evaluation indices—industrial wastewater concentration, factory soot, and SO_2—we employ the entropy weight technique to ascertain the efficacy of environmental control, thus obtaining a thorough evaluation outcome [31].

3.2.4. The Data Source

To study the impact of environmental regulation types and green technology innovation on China's total factor productivity, a comprehensive assessment of economic performance, competitiveness, innovation capacity, and international trade dynamics must be conducted. This will provide a holistic view of the country's economic situation, enabling a relatively comprehensive analysis. It is essential to understand the level of foreign investment inflow and its impact on the national economy, reflecting foreign investors' confidence in the country's economic prospects and revealing the country's position in global trade dynamics, resource management, and market influence. Additionally, considering the allocation of resources to scientific research and innovation reflects the quality of human capital and the potential for sustainable development. After drawing on a large body of literature, the following indicators were selected:

Four main indicators are chosen in this article to assess the economic situation, namely the contribution of foreign direct investment to GDP;; the national foreign trade capacity (OPEC); and the GDP per capita of national research and the GDP per capita of innovation, which is determined by the amount of scientific research and innovation input. Other similar statements are referenced in [34].

This paper is the only one to provide pertinent data from the Tibet Autonomous Region, and the panel data of 30 provinces (autonomous regions and municipalities directly under the Central Government) from 2012 to 2021 are chosen for empirical analysis. This paper mainly draws its data from the *China Statistical Yearbook*, *China Statistical yearbook on Science and Technology*, *China Energy Statistical Yearbook* and the Peking University Digital Inclusive Financial Index. Table 3 provides descriptive data statistics, an interpolation supplement, and missing individual data [35].

Table 3 presents the descriptive statistics for the important variables. Among them, the average values of green invention and GTFP are 121.5 and 1.978, respectively. Moreover, environmental regulation has a mean and standard deviation of 0.745 and 0.176, respectively. The mean values of other control variables are 1.904, 59.57, 1.734, and 25.08.

Table 3. Data are descriptive statistics.

	Variable	Sample Capacity	Average Value	Standard Deviation	Least Value	Crest Value
Explained variable	GTFP	300	1.978	1.099	0.643	5.379
Core explanatory variables	Dig	300	121.5	35.72	0.183	212.5
Metavariable	ER	300	0.765	0.176	0.213	0.999
	OPEN	300	1.904	1.513	0.010	8.550
Controlled variable	URB	300	59.57	11.80	36.41	89.60
	RD	300	1.734	1.151	0.446	6.529
	GOV	300	25.08	10.26	10.66	64.30

4. Results

4.1. Empirical Analysis

4.1.1. Analysis of the Benchmark Regression Results

According to the study of GTFP, we found that the benchmark regression results of the random-effect (RE) model and the fixed-effect (FE) model have good consistency. Column (1) does not consider any factors, while column (2) considers factors, and column (3) considers factors, and the final regression coefficient is more than 1% significant [37] (Table 4).

Table 4. Benchmark regression results.

	(1)	(2)	(3)
Dig	0.288 *** (16.61)	0.302 *** (5.18)	0.119 *** (2.19)
OPEN			−0.198 ** (−2.08)
URB			0. 011 (0.34)
RD			1.793 *** (5.44)
GOV			−0.031 ** (−2.45)
Fixed effect	NO	YES	YES
R^2		0.519	0.744
F		69.40	33.63

Note: *** and ** indicate that the coefficients are significant at significance levels of 1% and 5%, respectively.

This study also considers the regional heterogeneity among different polluted areas and introduces mediator variables (such as green innovation, energy utilization efficiency, fiscal decentralization, and environmental decentralization) to investigate the mechanisms through which environmental regulation affects GTFP.

The results of the fixed-effect model are significantly better than those of the random-effect model, and after Hausman test, it is found that the fixed-effect model fits better and that its results are more robust. Through comparative analysis and based on recent research, we conclude that strengthening the application of green technology can not only greatly improve the overall environmental benefits between provinces but also bring more environmental benefits to society so as to better meet the current social needs. Hypothesis 1 is verified [40].

4.1.2. Mechanism Analysis

The intermediary effect model is employed to investigate the effect of green innovation development on GTFP, which is based on the theoretical mechanism analysis that unites green innovation, environmental regulation, and GTFP into a single research framework.

Table 5 reveals the regression results [41]. Following the introduction of environmental regulation, the Hausman test results demonstrate that the effect model of fixed individual and temporal factors is capable of accurately forecasting the alteration in GTFP. The results in column (1) demonstrate that the influence of environmental regulation on GTFP is 4.721, a result of considerable positive importance at 1%. This affirms the significance of environmental regulation in the green and high-quality growth of China's provincial economy. At the 10% level, the regression coefficient of green innovation with respect to environmental regulation is significantly positive, with a value of 0.411, indicating that green innovation has opened a channel for environmental regulation. We discover a positive correlation between green innovation and environmental regulation, with a correlation of 1% significance, in our analysis of the impact of environmental regulation in column (3) without taking into account the control variables [42]. This suggests that we can improve GTFP by increasing the implementation of environmental regulations. The control variable's addition yields item (4) as its outcome.

Table 5. Mechanistic analysis of the regression results.

VARIABLE	(1) GTFP	(2) ER	(3) GTFP	(4) GTFP
ER	4.721 *** (6.68)		1.433 *** (3.60)	0.438 *** (1.19)
Dig		0.411 *** (7.90)	2.642 *** (10.19)	0.811 ** (2.12)
OPEN				−0.262 *** (−5.98)
URB				0.020 ** (2.00)
RD				0.177 ** (2.41)
GOV				−0.043 *** (−6.06)
Cons	1.633 *** (3.02)	1.212 *** (4.84)	0.617 (5.45)	−2.170 (−1.45)
R^2	0.374	0.425	0.516	0.430
F	44.68	62.36	33.92	36.91

Note: ***, **, indicate that the coefficients are significant at significance levels of 1%, 5%, respectively.

The results show that when the external opening level (OPEN) reaches 1%, the increase in GTFP is significantly inhibited, which is consistent with the findings of Zhou Xiaohui and other scholars. The URB regression coefficient is significantly positive beneath the 10% mark, likely due to the enhancement of the urbanization level, which encourages the preservation of the environment for inhabitants and the intensification of green development, thus fostering its growth [43]. The government intervention (GOV) regression coefficient is also significantly negative at the 1% level; this may be the result of the role played by local government in economic construction and environmental management, resulting in higher costs. The law enforcement level is also higher, but in practice, the government's lax enforcement results in lawbreakers, thus hindering GTFP, consistent with Zhou et al. [41]. A significantly positive regression coefficient of government R&D investment (RD) with respect to GTFP beneath the 10% level implies that bolstering the backing of scientific and educational advancement is beneficial to the green transformation and enhancement of the economy, which is in agreement with the research findings of Cai Ling et al. [14]. The research results indicate that when the level of green technology innovation exceeds a certain threshold, both command-and-control environmental regulation and market-oriented environmental regulation have a promoting effect on GTFP. This provides a reference standard for the implementation of environmental regulation [44].

4.1.3. Analysis of Heterogeneity

According to the research experience reported in the existing literature, the development of interprovincial green innovation in China generally presents heterogeneous characteristics [45]. Therefore, in this section, we conduct heterogeneity analysis of the three regions of eastern, central, and western China to explore whether there are differences in the action mechanism of green innovation with respect to GTFP in different regions. Analyzing different regions and introducing inter-regional differences is also one of the innovations in this study. Table 6 reveals the results. Evident in the data is the disparity in the influence of GTFP across different regions. Columns (2), (4), and (6) demonstrate that green innovation development has a beneficial effect on GTFP enhancement in the eastern and central regions, while its effect on GTFP enhancement in the western regions is not as evident [46]. The central region's rapid development, digital infrastructure, and green innovation of GTFP promotion, as evidenced by the regression coefficient, may be due to the rise of central policy implementation, which has improved the unbalanced development of the region, given full play to its industrial base, and given it a market advantage in comparison to the western region. This has sped up the construction of green innovation and led to the development a new pattern of positive externalities, which provides more market space and the possibility of improving GTFP. The eastern region developed earlier and is now in the stage of stable development. In contrast, the policy dividends enjoyed by the western region are not fully effective, and the development space of digital industry and enterprises is relatively small; therefore, its green innovation has not played an important role in promoting GTFP [47]. The existing research findings in the academic community suggest that the relationship between green innovation development and GTFP is characterized by a nonlinear impact. After Hansen test and bootstrap self-service test, we find that the threshold of green innovation is clearly tested by double-threshold ACK, while environmental regulation is only tested by a single-threshold ACK, with threshold values of 1000 times and 1 time, respectively (see Table 7 for details). According to the data in Table 7, when the development of green technology reaches a certain level, at the same time, the government's environmental protection measures will also produce a positive, nonlinear marginal effect, which will greatly promote the improvement of interprovincial GTFP [48].

Table 6. Impact of green innovation on GTFP in different regions.

	East		**Middle**		**West**	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Variable	ER	GTFP	ER	GTFP	ER	GTFP
Dig	0.400 ***	1.307 ***	0.000	1.415 ***	0.001	0.091
	(3.13)	(1.44)	(0.36)	(4.28)	(0.84)	(0.28)
ER		2.823 ***		0.701		0.150
		(5.42)		(1.58)		(0.18)
OPEN	−0.002	−0.133	0.007	0.066	−0.011	−0.218
	(−0.15)	(−1.09)	(0.63)	(1.40)	(−0.57)	(−0.97)
URB	−0.006	−0.028	0.013 ***	0.047 ***	0.013 **	0.060 **
	(−1.57)	(−0.70)	(3.84)	(3.13)	(3.13)	(3.22)
RD	−0.000 *	2.094 ***	0.083 ***	0.553 ***	−0.109	0.850
	−1.86)	(5.12)	(3.18)	(4.92)	(−1.52)	(1.50)
GOV	−0.382 **	−0.126 ***	0.007 **	−0.035 ***	−0.004	−0.034 **
	(−2.05)	(−4.15)	(2.53)	(−3.11)	(−1.41)	(−2.51)
Cons	0.150	−2.929	−0.267 *	−8.232	0.370 *	−1.646
	(0.84)	(−1.54)	(−1.97)	(−7.27)	(2.17)	(−1.16)
R^2	0.300	0.786	0.549	0.769	0.629	0.851
F	9.817	50.27	20.46	46.15	44.34	36.59

Note: ***, **, and * indicate that the coefficients are significant at significance levels of 1%, 5%, and 10%, respectively.

Table 7. Regression results of green innovation affecting the GTFP promotion threshold model.

Variable	GTFP	Variable	GTFP
The threshold variable	Dig	The threshold variable	ER
First threshold value (Z1)	120.8163	Threshold value (D)	0.3664
Second threshold value (Z2)	181.3037		
Dig I (Adj ≤ Z1)	−0.257 (−0.67)		
Dig I (Z1 < Adj < Z2)	0.039 ** (0.12)	ER I (Adj ≤ D)	0.096 *** (3.45)
Dig I (Adj ≥ Z2)	0.783 *** (2.54)	ER I (Adj > D)	0.169 *** (5.89)
Controlled variable	YES	Controlled variable	YES
Goodness of fit	0.670	Goodness of fit	0.778
Sample capacity	300	Sample capacity	300

Note: ***, ** indicate that the coefficients are significant at significance levels of 1%, 5%, respectively.

4.1.4. Threshold Effect Test

Academic circles have concluded that the effect of green innovation development on GTFP is not linear. After Hansen and bootstrap self-service tests, the double-threshold test is found to clearly demonstrate the threshold of green innovation, while the single-threshold test only confirms environmental regulation, threshold values of 1000 times and 1 time, respectively (see Table 7 for further information) [49].

Table 7 demonstrates that as the green innovation level rises and environmental regulation intensifies, both green innovation and environmental regulation have a noteworthy nonlinear and positive effect on the enhancement of interprovincial GTFP [50].

The threshold test results presented in Table 8 demonstrate that single- and double-threshold tests are both significant at the 1% level, while the triple-threshold test is not; thus, technological innovation has a double-threshold effect in command environmental regulation, with threshold values of 14.652 and 14.950, respectively [51]. The 1% significance level of the single- and double-threshold tests of technological innovation in the regulation of the market environment is significant, while the triple-threshold test is not, thus indicating that technological innovation has a double-threshold effect under the regulation effect of the market environment, with threshold values of 14.759 and 14.950 respectively [52].

Table 8. Threshold test results.

Type of Environmental Regulation	The Threshold Variable	The Threshold Number	F Price	P Price	Bootstrap	1%	5%	10%	Threshold Value
LnCCER	LnTI	Single	166.492 ***	0.000	500	38.621	21.272	13.970	14.652
		Double	66.291 ***	0.000	500	13.871	7.102	4.753	14.950
		Triple	11.195	0.120	500	53.568	42.128	23.501	14.663
LnMBER	LnTI	Single	156.839 ***	0.000	500	33.976	17.766	11.726	14.759
		Double	61.799 ***	0.000	500	28.413	18.955	13.157	14.950
		Triple	18.503	0.157	500	39.456	32.710	13.837	15.502

Note: *** indicate that the coefficients are significant at significance levels of 1%.

The above empirical results verify the rationality of hypothesis H3, that is, that technological innovation does have a threshold effect on the relationship between environmental regulation and GTFP. As the level of technological innovation of businesses surpasses the threshold, the impact of environmental regulations on GTFP will gradually become evident. This is because when the industrial enterprise technology innovation ability is low, constrained by the restriction of technical barriers, it is difficult for enterprise R&D investment to bring considerable benefits. This makes the compensation effect of environmental regulation-driven innovation not significant; therefore, the improvement of GTFP becomes more dependent on the adjustment of energy structure and industrial structure. With the continuous improvement of the level of technological innovation of enterprises, their capacity for innovation has grown significantly. Research and development investments can surmount technical impediments, thus inspiring enterprises to take part in green innovation and clean production. Ultimately, this innovation is impacted by environmental regulation compensation [53].

4.2. Robustness Test

4.2.1. Handling of Endogenous Problems

To reduce the issue of endogeneity, this paper uses the number of Internet users per year and the number of fixed-line telephone users in 1984 as the instrumental variable of green innovation in the province [43]. By comparing the results in column (1) of Table 8, we find that green innovation significantly increases GTFP levels, leading to fairly reliable conclusions.

4.2.2. Excluding the Municipality

The results of columns (2) and (3) in Table 9 demonstrate that despite the municipality's considerable disparities relative to other provinces in terms of economics and politics, the enhancement effect of green innovation on GTFP remains intact, even after the municipality is excluded from the sample [54].

Table 9. The robustness tests.

VARIABLE	(1) GTFP	(2) GTFP	(3) GTFP	(4) GTFP
ER		2.365 *** (3.75)	0.375 (1.13)	1.473 ** (2.35)
Dig	1.195 ** (2.19)	0.017 *** (7.38)	0.884 *** (2.61)	0.012 ** (2.36)
OPEN	−0.198 ** (−2.08)		−0.142 *** (−3.30)	−0.144 * (−1.87)
URB	0.011 (0.34)		0.004 (0.34)	−0.029 (−0.90)
RD	1.793 *** (5.44)		0.716 *** (7.05)	1.655 *** (6.93)
GOV	−0.031 ** (−2.45)		−0.017 ** (−2.45)	−0.047 *** (−3.28)
Cons	−2.104 (−1.68)	0.466 *** (4.76)	−0.081 (−0.18)	−0.589 (−0.47)
R^2	0.744	0.625	0.494	0.730
F	33.63	45.90	41.21	22.93

Note: ***, **, and * indicate that the coefficients are significant at the significance levels of 1%, 5%, and 10%, respectively.

4.2.3. Lag of One Phase

The GTFP index obtained by SBM-GML measurement is dynamic. Therefore, we adopt a lag phase I method and conduct a regression analysis. Column (4) of Table 9 demonstrates that green innovation is still of great importance and contributes to the enhancement of GTFP [55].

5. Conclusions and Policy Recommendations

5.1. Conclusions

This paper focuses on the green effects of green innovation. Based on panel data, it empirically explores the mechanism of green innovation with respect to the GTFP of different provinces using the mediation effect model. Furthermore, it examines the marginal spillover effects of green innovation on GTFP enhancement using the threshold model. The main research conclusions are as follows:

1. Strengthening the application of green technology can significantly enhance the overall environmental benefits among provinces and bring more environmental welfare to society, better meeting current social needs.
2. Environmental regulation plays an intermediary role in the impact of green innovation on GTFP.
3. Technological innovation exhibits a threshold effect in the relationship between environmental regulation and GTFP. Only when the technological innovation level of an enterprise surpasses the threshold value will the promoting effect of environmental regulation on GTFP gradually become evident.

5.2. Policy Recommendations

To further enable each province to seize historical opportunities and promote high-quality regional economic development through green innovation, the following policy recommendations are proposed:

1. We recommend the formulation and promotion of the "Priority Development of Green Technology" policy, including tax incentives and financial support, providing tax incentives to enterprises engaged in green technology research and application to reduce production costs and encourage investment in the field; the establishment of special funds to support green technology innovation and demonstration projects to promote research on and the application of green technology [56]; the establishment of a green technology promotion platform, setting up a government-led green technology promotion platform to provide technical consulting, policy interpretation, and market connection services to promote the widespread application of green technology; the establishment of a mechanism for interdepartmental and cross-industry cooperation and exchange of green technology to achieve resource sharing and complementarity of strengths; the establishment of standards and certification systems, strengthening the construction of green technology standards and formulating relevant certification standards to regulate market access to green technology products and services; and support and encouragement of enterprises to apply for certification of green technology products to enhance their competitiveness and recognition in the market [57].
2. We recommend the formulation and promotion of the "Synergetic Development of Environmental Regulation and Green Innovation" policy, including the establishment of incentive mechanisms, establishing an award system for environmentally friendly enterprises to reward those who have achieved outstanding results in green technology innovation and environmental protection, stimulating their enthusiasm in environmental protection [58]; the promotion and establishment of a list of environmentally friendly innovative enterprises, providing tax reductions or financial support to listed enterprises and encouraging enterprises to increase investment in environmental protection; the improvement of environmental standards and supervision, strengthening the strict and scientific nature of environmental regulation, promoting the formulation of stricter environmental emission standards to encourage enterprises to increase investment in green technology innovation to meet more stringent environmental requirements [59,60]; the establishment of a sound environmental supervision system, increasing the penalties for environmental violations, raising enterprise environmental costs, and encouraging enterprises to strengthen environmental protection and promote green innovation [61]; support of policy-oriented green innovation projects, including financial subsidies, special funds, etc., to encourage enterprises to explore and experiment with green technology innovation; and encouragement of enterprises to participate in government-led environmental technology projects to promote the rapid development of green innovation through win–win cooperation [58,62].

3. We recommend the formulation and promotion of the "Reducing the Threshold of Technological Innovation to Promote GTFP Enhancement" policy, including the establishment a technology innovation support platform for small and medium-sized enterprises, providing technical consulting, guidance on the application of green technology, and services for the transformation of innovative achievements to reduce the information asymmetry and costs of technological innovation; the establishment of a project docking platform for technological innovation to promote cooperation and exchange between enterprises, research institutes, and universities, accelerating the research and application of green technology [63,64]; the promotion of in-depth cooperation between industry, academia, and research, encouraging enterprises to collaborate deeply with universities and research institutes to jointly establish green technology innovation joint laboratories and engineering centers, improving technological innovation levels, and reducing the threshold of technological innovation; and the establishment of a green technology innovation talent cultivation base to promote the integration of talent cultivation and research innovation, providing more talent support for enterprise technological innovation [61,65].

5.3. Contribution and Limitations

The findings of this study hold practical significance, as they emphasize the importance of strengthening the application of green technology to enhance environmental benefits and societal welfare. Additionally, the identification of the intermediary role of environmental regulation and the threshold effect of technological innovation on GTFP provides practical insights for policymakers and industry stakeholders in promoting sustainable development and green innovation.

This paper contributes to the theoretical research by empirically exploring the impact of green innovation on GTFP using mediation effect and threshold models. It identifies the significant role of green technology innovation and environmental regulation in influencing GTFP, shedding light on the mechanisms underlying the relationships between these variables.

Limitation: One potential limitation of this study could be the specific focus on the Chinese context, which may limit the generalizability of the findings to other countries or regions. Additionally, the study's reliance on panel data and empirical models may have certain limitations in capturing the full complexity of the relationships between green innovation, environmental regulation, and GTFP. The conclusions drawn from this study may have limited generalizability to other countries due to the specific contextual factors at play in the Chinese economic and regulatory environment. The intricacies of environmental policies, technological innovation landscapes, and industrial structures in other countries may lead to varied impacts and relationships between green innovation, environmental regulation, and productivity. Therefore, while the insights provided by this study are valuable, caution should be exercised in directly applying the conclusions to different national or regional contexts without considering the specific contextual factors at play.

By addressing these aspects, this study could offer a more comprehensive and nuanced understanding of the impact of green innovation and environmental regulation on productivity while also providing valuable insights for policymakers, researchers, and industry practitioners in the field of sustainable development and green technology innovation.

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