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Exploring the Impact of Heterogeneous Environmental Regulations on Green Innovation Efficiency: Evidence from China's Yangtze River Economic Belt

Ruochan Xiong [1] and Da Gao [2,*]

[1] School of Economics, Huazhong University of Science and Technology, Wuhan 430070, China
[2] School of Law and Business, Wuhan Institute of Technology, Wuhan 430205, China
* Correspondence: gaoda@wit.edu.cn

Abstract: Enhancing environmental regulation (ER) is an effective way to improve the green innovation efficiency (GIE) of the Yangtze River Economic Belt (YREB) and the key to achieving the target of carbon peaking and neutrality. Using the data of 103 cities in YREB in 2013–2019, this paper explores the effect of heterogeneous ER on GIE. The results of the study are as follows: first, we categorize environmental regulations into formal and informal environmental regulations and explore their impact on green innovation efficiency separately. The results show that both formal and informal environmental regulations can effectively promote GIE in the YREB urban agglomeration. Second, the Spatial Durbin Model (SDM) model is used to analyze the spatial effect. The results show that there are spatial effects between heterogeneous environmental regulations and GIE, and environmental regulation can significantly strengthen GIE through positive spatial effects. Third, this paper uses the threshold model to explore the non-linear relationship between environmental regulation and green innovation efficiency. The results show that as ER increases, the positive effect on GIE increases, and this interesting finding holds for both formal and informal environmental regulations. Fourth, the mediating effect model is used to examine whether green technological innovation and industrial structure upgrading exert mediation effects on how environmental regulations affect GIE. The research results can provide effective policy recommendations to promote the green development of the cities in YREB.

Keywords: environmental regulations; green innovation efficiency; the YREB; spatial effects; nonlinear effect

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1. Introduction

The Yangtze River Economic Belt (YREB) is an innovation-driven belt leading China's transformation and development [1]. The proportion of the total economy of YREB in China has risen from 45.1% in 2015 to 46.5% in 2022. The sustainable development of the YREB is crucial to global environmental quality. However, the rapid development could lead to extensive resource consumption, resulting in significant ecological damage [2,3]. Thus, it is vital to look for solutions to harmonize the imbalance between the development of economic and environmental protection [4]. As an innovation mode that balances the environment and economic development, enhancing green innovation efficiency (GIE) is an effective way to promote the sustainable development of the green economy [5,6].

As a crucial means to promote GIE, environmental regulation (ER) is gradually receiving widespread academic attention. Effective ER can affect the GIE by balancing the negative and positive externalities generated by ecological pollution and innovative technologies, respectively. The influencing mechanisms of environmental regulation on GIE are completed through cost and technology diffusion. First, implementing ER increases the cost of pollution prevention, leading to a decline in enterprise competitiveness and innovation ability [7]. Meanwhile, the positive externality of knowledge spillover will reduce enthusiasm for technological innovation [8]. However, the "Porter Hypothesis" proposes that proper ER will encourage firms to carry on technological innovation, drive technology diffusion, and improve enterprise productivity [9,10], which will increase profits and offset costs [11]. Heterogeneous environmental regulations have disparate influencing mechanisms on the GIE. Government-led formal environmental regulation (Fer) has achieved remarkable achievements in promoting green innovation. ER is an important tool to incentivize firms' green innovation for the government due to the lack of specific economic incentives to promote technological innovation [12].

The invested capital of the Chinese government in emission control has increased from 449 billion yuan in 2008 to 10,638.9 billion yuan in 2020. To improve the ecological environment, China has put forward a flexible environmental regulation system according to different stages of national conditions [13]. The promulgation of the National Environmental Policy Act is an effective way to enforce ER and strengthen the supervision of enterprises [8]. The other type is public-led informal environmental regulation (Ier) [14]. With the increase in public concern about environmental pollution and the rapid development of electronic media, Ier has gradually become an effective auxiliary of Fer. As a value-realization mechanism for green products, public consumption of green innovative products motivates firms to carry out larger-scale green innovation, thus improving production efficiency. As a compulsory mechanism, public supervision of sewage discharge forces companies to improve green innovation to reduce pollution emissions and contribute to ecologically sustainable development. In addition to ER, a city's green technology innovation and industrial structure will also impact GIE, and there may be a mediating effect between them. Porter's hypothesis proposes that the innovation compensation generated by green technology innovation will improve GIE by enhancing resource utilization efficiency. Meanwhile, green technology innovation will attract resources to the tertiary industry. Moreover, with the transfer of resources from resource-intensive secondary industry to low-resource-intensive tertiary industry, environmental damage is reduced, and the economy can develop towards environmentally friendly practices, which can improve the level of GIE. Therefore, green technology innovation and industrial structure upgrading play potential mediating roles in these mechanisms. Meanwhile, the effects under different environmental regulation levels are varied, which requires deep analysis.

Therefore, can heterogeneous ER affect green innovation efficiency in the cities of YREB? What are the influence channels and pathways? Are there spatial effects and nonlinear relationships between ER and GIE? The in-depth study of these issues helps understand the internal influencing mechanisms. In view of these, using the data of 103 cities in the YREB in 2013–2019, we construct the SBM-DEA model to calculate GIE. Then we construct the spatial effect model, mediating effect model, and threshold model to test the spatial effect, mediating effect, and threshold effect of heterogeneous environmental regulations on GIE. The research results are helpful to accelerate the transformation of green innovation in YREB, enable the government to find a suitable path for developing green innovation and achieve coordinated development among regions.

The purpose of this paper is to find solutions to the imbalance between economic development and environmental protection in the YREB. As one of the regions with the strongest comprehensive strength and the greatest strategic support in China since the reform and opening up, the YREB has unique advantages and great development potential. Exploring whether environmental regulation can promote the improvement of GIE in the YREB can obtain an effective development mode that balances economic development and environmental protection, to promote the YREB to walk out of a road of ecological priority and green development. This paper not only explores the spatial effect and spatial spillover effect of environmental regulation on GIE but also verifies the nonlinear relationship between environmental regulation and GIE. At the same time, it explores a more complete influence mechanism of ER on green innovation efficiency.

The paper offers threefold contributions. Firstly, we construct the SBM-DEA model to measure the level of GIE in urban agglomerations in YREB and use spatial econometric methods to verify environmental regulation's spatial effect on GIE. Due to the close connection between different regions of the YREB, the spatial effect and the spatial spillover effect between urban agglomerations are prominent. However, most literature ignores it. Secondly, existing literature mainly studies the linear perspective and ignores the nonlinear relationship. This paper uses a threshold test to analyze the nonlinear effect. Thirdly, this paper carries out a mediating effect model to explore the influence channels of ER on green innovation efficiency and provide a more complete influence mechanism. The green development of the YREB can serve as a demonstration of ecological priority, leading to the construction of ecological civilization and economic development in various places and driving the whole of China to gradually move towards the road of green and sustainable development.

The structure of this paper is as follows: Section 2 presents the literature review. Section 3 discusses the theoretical analysis and research hypotheses. Section 4 provides an overview of the methodology and data. The empirical results are presented in Section 5. Finally, Section 6 presents the conclusions and policy recommendations.

2. Literature Review

We divide the existing literature into two categories. The first is the calculation methods of GIE and its influencing channels; the second is the relationship between ER and GIE.

Existing literature on green innovation efficiency is mainly developed from two aspects. The first is the measurement of GIE. Green innovation involves complex technologies that cross fields in economic and ecological systems [15]. Existing studies have proposed various calculation methods for GIE, including constructing single and composite indicators [16]. Meanwhile, most scholars adopt the DEA and SFA models to measure the level of GIE [17–19]. Since the traditional DEA model cannot interpret its internal operation rules, the super-efficiency network DEA-SBM calculates the effective decision-making units for SBM and compensates for the deficiency. Li et al. [20] used the undesirable-SBM model to measure the energy efficiency of 271 cities in China.

The second aspect is based on the influencing factors of GIE. Existing literature shows that various factors can affect GIE [21–24]. Porter's hypothesis shows that technological innovation can improve innovation efficiency by enhancing resource use efficiency through technological innovation [22]. Meanwhile, technological innovation can accelerate the transfer of resources to the tertiary industry [23]. With the transformation of industrial structure from secondary industry to tertiary industry, the environmental damage caused by economic development is reduced [24], and the economy can also develop into an environmentally friendly one. However, little literature take green technology innovation and industrial structure upgrading as mediating variables to explore whether they play a mediating role in the influence mechanisms.

The second type of literature studies the effect of ER on GIE. It has been proven that ER can potentially affect GIE. However, its influential effects and mechanisms are still under debate due to a series of uncertain factors. As for the influential effects, environmental regulation has dual effects on GIE [25]. Some scholars support the traditional neoclassical theory. They believe that ER will increase the cost of pollution reduction and squeeze the capital of enterprise technological innovation, which inhibits green innovation [26]. Thus, ER has a "crowding out effect" on investment in green innovation. Zhang et al. [27] proved that environmental regulation increases production costs and leads to the decline of firms' technological innovation.

On the other hand, Porter's hypothesis proposes that appropriate ER can create "innovation compensation" that realizes the double dividend of pollution prevention and enhances competitiveness [10]. The empirical results of some scholars support this view. Martínez et al. [28] found a positive impact, which verified the view of "innovation compensation". Cai and Ye [29] found that ER in China's heavily polluting industries can significantly promote GIE. Scholars have not reached a unified conclusion on whether environmental regulation "promotes" or "inhibits" GIE and the influential effect is still disputed.

As for the influencing mechanism, literature is generally researched from linear and nonlinear perspectives. Many scholars explore this aspect of the linear relationship. Qiao et al. [30] used the system-GMM model to explore the effect of ER on the innovation efficiency of 59 power enterprises in China. They pointed out a positive linear relationship between heterogeneous ER and innovation efficiency. Some scholars hold the view of a nonlinear relationship. Ouyang et al. [31] and Jiang et al. [32] proved a U-shaped trend between environmental regulation and GIE. However, compared with a few scholars who explored nonlinear relationships, more researchers supported the view of the linear relationship. Some scholars point out that environmental regulation can directly affect GIE. However, other researchers showed that there exist mediating effects between environmental regulation and GIE. Ning et al. [33] show that only the joint effect of environmental regulation and FDI can promote the innovation capacity of cities. Green technology innovation and industrial structure upgrading may also play a mediating role in this process [34].

In summary, although scholars have conducted extensive studies, there is still no unified conclusion. Previous studies focused on the national and provincial levels, and there were few in-depth analyses from the perspective of the YREB. Thus, we focus on the influencing factors in the urban agglomeration of the YREB. Secondly, few scholars have effectively divided environmental regulations from the perspective of heterogeneity. In addition, the ordinary panel model ignores the spatial effects between regions, leading to measurement errors. However, the spatial panel model considers the dual externalities of green innovation, which corresponds to the reality of the YREB. Most literature only explores from a linear perspective and ignores the nonlinear relationship. We add the mediating effect model and threshold model to analyze the multi-path influence factors and nonlinear influence path on GIE.

3. Background and Research Hypothesis

3.1. Background

As the most economically dense watershed belt and an innovation-driven belt leading the green transformation of China, it's of great strategic significance to explore the GIE in the YREB. Due to the resources in the YREB urban agglomeration flowing frequently among cities, an interaction effect exists among regions. The GIE also has obvious spatial-temporal heterogeneity. Based on the Miao et al. [35] model construction method, we use the SBM-DEA model and MaxDEA software to calculate the GIE through data from 103 cities in the YREB from 2013 to 2019. We divide the result of GIE into five equidistant intervals and draw a spatial distribution table.

From Table 1, we find that the average GIE in YREB increased from 0.1396 in 2013 to 0.2312 in 2019. Meanwhile, the number of cities in the first interval increases, while the number in the fifth interval decreases obviously, indicating that the overall GIE value of the YREB is improving. For example, the GIE of Chengdu, Sichuan Province, rose from the third interval in 2013 to the first interval in 2019, indicating that some cities, like Chengdu, have seized the opportunity of green development and improved their GIE significantly. However, from the overall perspective, the percentage of cities in the first interval is small, while more cities are in the fifth interval, indicating that the GIE of YREB is still in a low position. Although the Chinese government has been actively promoting the continuous optimization and upgrading of innovation-driven industries in the YREB, there are certain differences in innovation development among cities due to various factors, and the overall GIE of cities in the YREB needs to be further improved. In the spatial dimension, GIE exhibits regional unevenness. Dividing the YREB into upstream, midstream, and downstream, we find spatial variability in different regions. In contrast, the downstream cities are significantly higher than the upstream and midstream cities. In the process of green development, the downstream region has grasped various opportunities and made use of its resources and geographical advantages to vigorously develop technological innovation so that the economic development of the downstream cities is better than that of upstream and midstream cities, which drives the improvement of GIE. However, the upstream and midstream cities face pressure from environmental pollution and economic development, which negatively affects technological innovation and restrains the GIE.

Table 1. Spatial distribution of GIE.

Interval Distribution of GIE	Province	
	2013	2019
First interval (1, 1.25]	-	Shanghai, Jiangsu (1), Zhejiang (1), Sichuan (1)
Second interval (0.75, 1]	Shanghai	Jiangsu (1), Hubei (1), Hunan (1), Chongqing
Third interval (0.5, 0.75]	Jiangsu (2), Zhejiang (1), Anhui (1), Hubei (1), Hunan (1), Chongqing, Sichuan (1)	Jiangsu (2), Zhejiang (1), Anhui (1), Jiangxi (1), Guizhou (1)
Fourth interval (0.25, 0.5]	Jiangsu (4), Zhejiang (3), Jiangxi (1), Guizhou (1), Hubei (2), Sichuan (1)	Jiangsu (8), Zhejiang (4), Jiangxi (1), Hubei (3), Hunan (2), Sichuan (2), Guizhou (1), Yunnan (1)
Fifth interval (0, 0.25]	Jiangsu (8), Zhejiang (4), Anhui (15), Jiangxi (10), Hubei (9), Hunan (11), Sichuan (15), Guizhou (2), Yunnan (8)	Jiangsu (2), Zhejiang (2), Anhui (15), Jiangxi (9), Hubei (8), Hunan (9), Sichuan (14), Guizhou (1), Yunnan (7)

Note: () indicates the number of cities in the interval. The first interval is (1, 1.25], the second interval is (0.75, 1], the third interval is (0.5, 0.75], the fourth interval is (0.25, 0.5], and the fifth interval is (0, 0.25].

3.2. Theoretical Analysis and Research Hypothesis

The impact of environmental regulation on GIE is still uncertain, which involves some important theories in economics. Some scholars have proposed that ER has a dual effect on GIE [36–38], which has led to thinking about externalities and market failures in markets. However, whether this effect is "facilitating" or "inhibiting" is uncertain, which also relates to the theory of government intervention in the market. Referring to Liu et al. [39,40], we divide environmental regulation into government-led formal environmental regulation and public-led informal environmental regulation, which is related to institutional theory in institutional economics. The mechanism by which different types of ER affect GIE varies, reflecting differences in market structure and competition theory. At the same time, due to the frequent inter-city flow of resources in the urban agglomeration of the Yangtze River Economic Belt, the change in related factors in a city will not only affect itself but also affect the surrounding cities [41]. This involves the theory of spatial effects in regional economics, which examines the interaction between regions. Thus, ER may have a spatial effect that can both promote GIE and influence surrounding cities. Scholars have not reached a consensus conclusion on this unifying effect, which needs further research and empirical analysis. Therefore, we propose the following research hypothesis:

Hypothesis 1a. *Environmental regulations can improve GIE in the YREB urban agglomeration by positive spatial effects.*

Hypothesis 1b. *Environmental regulations can inhibit GIE in the YREB urban agglomeration by negative spatial effects.*

The impact of different levels of environmental regulation on GIE is significantly different, which involves the theory of marginal increase and nonlinear effect in economics. Studies have shown that the promotion effect of environmental regulation has a marginally increasing nonlinear effect on GIE [42], which changes significantly before and after the threshold. This leads us to think deeply about market behavior and government intervention. When the level of ER is low, the government's supervision of pollution is insufficient, and the public's concern about pollution and consumption of green innovative products is also relatively low. In this case, the driving force of green technology diffusion is not strong enough to provide sufficient incentives for enterprises to promote green innovation technologies to reduce pollution emissions. Although the "Porter hypothesis" may have been triggered, the driving force was not strong enough. Therefore, Porter incentivizes that the proposed 'compensation benefits' could not offset the 'cost losses' [26,43], nor could they lead to improvements in environmentally innovative firms. However, with the further improvement of ER, the government will strengthen the supervision of pollution prevention and control of enterprises, while the public has also participated in the supervision, increasing the consumption of green products [44]. These measures effectively stimulate enterprises to promote technology diffusion, trigger "Porter's hypothesis", create stronger "compensation benefits", improve the market competitiveness of enterprises, and effectively promote the development of green innovative enterprises.

Hypothesis 2. *A nonlinear relationship exists between environmental regulations and green innovation efficiency.*

Multiple factors have a complex influence on the development of GIE [21,45], and there may be a mediating effect between these factors, which involves several theories in the field of economics. First, the innovation compensation effect brought about by green technology innovation is an important mediating factor. This theoretical perspective shows that green technology innovation can improve the efficiency of resource use and thus effectively promote the development of GIE. This is based on the perspective of resource economics, where the efficient use of resources is essential for economic growth. In addition, green technology innovation will give birth to new industries, attract labor to the tertiary industry, and upgrade the industrial structure [46]. This is related to industrial economics and labor market theory in economics, which emphasize the impact of industrial structure change on employment and economic growth. This process not only increases the market opportunities of GIE but also increases the employment level and further promotes sustainable economic growth. The upgrading of industrial structures also means less environmental damage caused by economic development [47]. This reflects theories in environmental economics that emphasize the relationship between environmental sustainability and economic growth. When the industrial structure develops in a greener and more sustainable direction, the economy can achieve a better balance between environmental protection and economic growth, creating a virtuous circle [48–50]. Therefore, environmental regulations can indirectly affect the development of GIE in many ways, including promoting green technology innovation and guiding the upgrading of industrial structures. Based on the above theoretical foundation, we propose the following research hypotheses:

Hypothesis 3. *Green technological innovation and industrial structure upgrading play a mediating role in the influence mechanism of environmental regulation on GIE.*

As shown in Figure 1, due to the close connection among urban agglomerations in the YREB, environmental regulation can directly affect GIE by spatial effect. Meanwhile, green technology innovation and industrial structure upgrading may play potential mediating roles in the mechanisms. Environmental regulation will indirectly affect GIE through these two channels. In addition to these impact pathways, environmental regulation also has a threshold effect; the influential effect of ER on GIE is significantly disparate before and after the threshold.

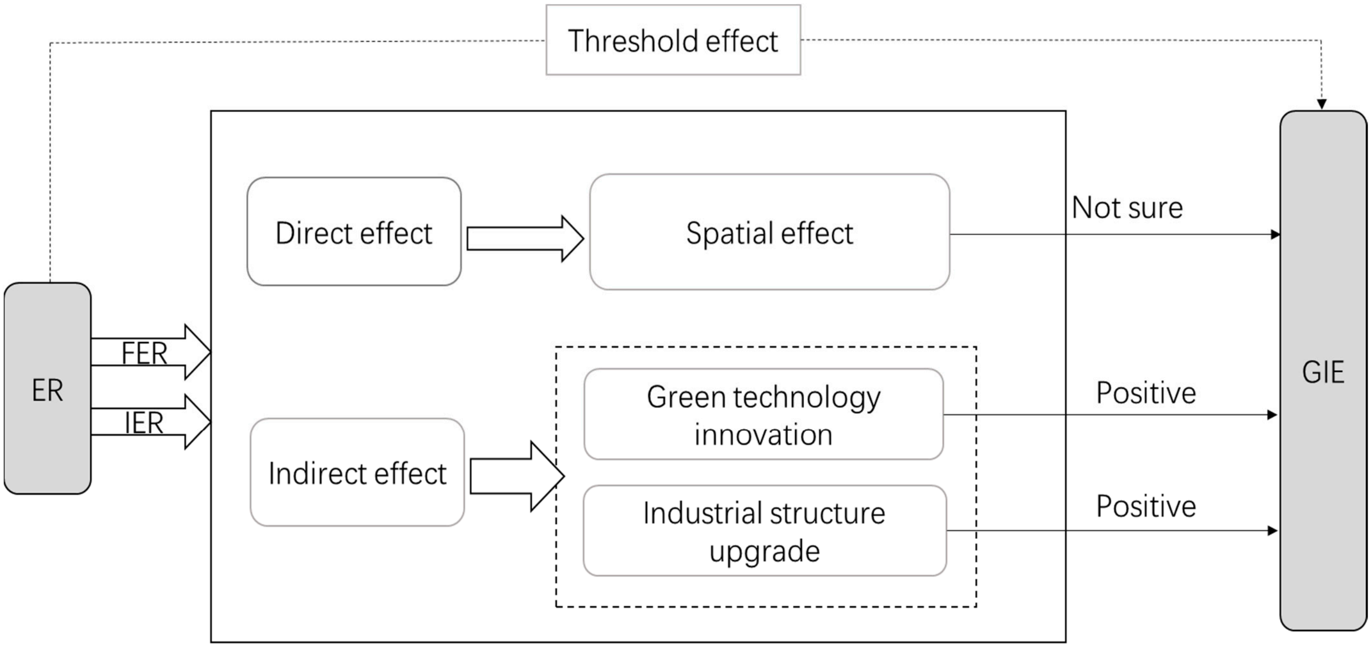

Figure 1. The mechanisms of direct and indirect effects of ER on GIE.

4. Methods and Data

4.1. Benchmark Regression Model

To test the direct effect of ER_{it} on GIE_{it}, we construct the following benchmark regression model:

$$GIE_{it} = \delta_0 + \delta_1 ER_{it} + \delta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{1}$$

In model (1), where i and t are city and year, respectively; GIE_{it} is the green innovation efficiency of city i in period t of YREB. ER_{it} represent the core explanatory variables Fer and Ier, respectively, X_{it} represent other variables that affect GIE_{it}, including economic development, degree of opening-up, living expenses, population size, human capital level, and so on. μ_i is the fixed effect of a city, and γ_t is the time-fixed effect, ε_{it} is the random error term.

4.2. Spatial Effect Model

Tobler's First Law of Geography pointed out that there is a spatial correlation between different cities' geographic and economic behavior [51]. Due to the externalities of environmental regulation, the urban agglomerations in the YREB are closely connected, and there is interaction among cities [52]. We use spatial econometric methods to verify environmental regulation's spatial effect on GIE in YREB, and we use LM, LR, and Wald tests to verify the accuracy of the model form. After a series of LM, LR, and Wald tests, the Spatial Durbin Model (SDM) is most suitable for our study because it can deal with the spatial correlations between the dependent variables and can also solve problems such as lack of spatial heterogeneity.

$$GIE_{it} = \delta_0 + \rho W \cdot GIE_{it} + \delta_1 ER_{it} + \delta_2 X_{it} + W X_{it} \theta + \mu_i + \gamma_t + \varepsilon_{it} \tag{2}$$

$$\varepsilon_{it} = \lambda M \cdot \varepsilon_t + \tau_{it} \tag{3}$$

where ρ stands for spatial regression coefficient, W represents the spatial weight matrix, and other variables are explained above. The geographical distance weight matrix W^g and the economic distance matrix W^e are used for the spatial weight matrix W.

4.3. Mediating Effect Model

Strict local environmental regulations promote enterprises to improve green technology innovation, thus effectively promoting GIE [22,53]. Meanwhile, strict environmental regulation will attract labor force flow to the tertiary industry of green environmental protection and promote industrial structure upgrading, which also accelerates the improvement of GIE [54]. Therefore, environmental regulation can indirectly affect GIE by improving green technology innovation and upgrading industrial structures. The three-step model of the mediating effect is one of the commonly used methods to test the mediating effect, which is simple, effective, and easy to operate. Compared with other testing methods, it has a clear structure and strong flexibility, which can timely and effectively test the influencing factors in the research as well as the causal relationship between the two variables to study the accuracy and substance of realistic problems. So we adopt a three-step mediating model to test whether green technological innovation and industrial structure upgrading exert mediation effects while implementing environmental regulations affecting cities' ER_{it} in the YREB.

$$MV_{it} = \delta_0 + \delta_1 ER_{it} + \delta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{4}$$

$$GIE_{it} = \theta_0 + \theta_1 MV_{it} + \theta_2 ER_{it} + \theta_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{5}$$

where the MV_{it} presents the mediating variables, the proxy of green technology innovation and industrial structure upgrading, respectively, GIE_{it} ER_{it} X_{it}, μ_i, γ_t, and ε_{it} have the same definition as above. The coefficient of models (4) and (5) is the indirect effects of the mediating variables on environmental regulation if they are both significantly positive, showing the existence of positive mediating effects. If the coefficient of the model (5) is not significant, it means MV is a full mediating effect; otherwise, it is a partial mediating effect.

4.4. Threshold Regression Model

Different levels of environmental regulation may have discrepant effects on GIE. When the level of ER is low, the supervision of the government is not strong enough to improve GIE. When environmental regulation is further improved, the government strengthens supervision, which effectively stimulates firms to carry out technological innovation and improve GIE. As the sample period of this paper is in the important period of the 12th and 13th Five-Year Plans of the National Economic and Social Development of China, the Chinese government is committed to environmental protection and has issued a series of environmental protection laws and regulations. These factors may affect environmental regulations and have a nonlinear impact on the GIE of cities in the YREB. To test the nonlinear relationship between ER and GIE, we use the method of the Hansen [55] panel threshold model to test the nonlinear mechanism, taking heterogeneous environmental regulations as the threshold variables and constructing the following model:

$$GIE_{it} = \delta_0 + \delta_1 ER_{it} \cdot I(q_{it} < \varphi) + \delta_2 ER_{it} \cdot I(q_{it} \geq \varphi) + \delta_i X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{6}$$

In model (6), q_{it} is the threshold variable. In this study, Fer and Ier are the threshold variables respectively. I (*) represents the indicator function, φ represents the specific threshold value. X_{it} represents other factors affecting green innovation efficiency, and δ_1 and δ_2 are the coefficients of different ER_{it} levels on GIE_{it}.

4.5. Variable Description

4.5.1. Dependent Variable

Green innovation efficiency. The most commonly used calculation methods for efficiency can be divided into the parametric method and the non-parametric method. However, when the parametric method is used to measure efficiency, the production function form of the efficiency boundary must be determined in advance, which makes the subject of the production boundary more subjective [56]. The non-parametric method not only does not need to set up a specific function but also can calculate the multiple input and output model, which has strong advantages in avoiding the subjectivity of model setting and reducing measurement errors [53]. This paper uses multiple input and output variables to construct a GIE index, and the DEA is more suitable for our work. However, the traditional DEA model cannot incorporate the slack variables of input and output into evaluation; the slack-based measure (SBM)-DEA model, a non-radial and non-angular DEA analysis method based on slack variable measurement proposed by Tone [57] with undesirable outputs, was adopted by our work. Meanwhile, in the actual situation, there are undesired outputs, such as environmental pollution, etc. This paper includes the undesired outputs in the model to improve the accuracy of efficiency assessment. Therefore, the non-radial and non-angular SBM-DEA model, which overcomes the defects of the traditional DEA model, is more suitable for the measurement of the GIE of 103 cities in this paper. Referring to [58], we choose the following indicators to measure input, expected output, and non-expected output, respectively. The specific selection of indicators and the construction of the GIE evaluation index are shown in Table 2.

Table 2. GIE evaluation index.

Targets	Category	Indicators
Green innovation Efficiency	Input	R&D personnel full-time equivalent
		Internal expenditure on R&D expenses
		Capital stock
	Desirable output	GDP
		Industrial output
		Number of patent applications
		Green products sales revenue
	Undesirable output	Industrial wastewater discharge
		Industrial sulfur dioxide emissions
		Industrial solid waste emissions

We choose R&D personnel full-time equivalent, internal expenditure on R&D expenses, and capital stock to measure innovation and green input. Noteworthy is the capital stock, which is calculated by the "permanent inventory method" by selecting the total fixed asset investment and fixed asset investment price index data of 103 cities in the YREB from 2013 to 2019, data from the China Statistical Yearbook. The specific formula is as follows:

$$K_{i,t} = (1-\delta)K_{i,t-1} + \frac{I_{i,t}}{P_{i,t}} \tag{7}$$

where K is the real capital stock, I is the nominal capital stock, δ is the annual capital depreciation rate, P is the price index, and the subscripts I and t represent the city and year, respectively. GDP and industrial output value are used to measure economic output, while patent applications and green product sales revenue measure desirable output. We select industrial wastewater discharge, industrial sulfur dioxide emissions, and industrial solid waste emissions to measure the undesired output.

4.5.2. Explanatory Variables

Environmental regulation. According to Wu et al. [59], we effectively divide environmental regulation into Fer and Ier. As a compulsory execution means of regulation, a single index is difficult to accurately measure Fer, so a composite indicator is needed. We select three one-way indicators of industrial wastewater emissions, industrial solid waste emissions, and industrial sulfur dioxide emissions to construct the Fer comprehensive index by entropy weight method. First, we forward and standardize the data: $R_{ij} = X_{max(j)} - X_{ij}/X_{max(j)} - X_{min(j)}$, R_{ij} is the index value; X_{ij} represents the initial value. The characteristic specific gravity P_{ij} is calculated based on R_{ij}: $P_{ij} = R_{ij}/\sum_{i=1}^{m} R_{ij}$, the entropy value of the index: $E_{ij} = -(1/lnm)\sum_{i=1}^{m} P_{ij}ln(P_{ij})$, and the difference coefficient:

$D_{ij} = 1 - E_{ij}$. Then the entropy weight of the index is determined: $W_{ij} = D_{ij} / \sum_{j=1}^{n} D_{ij}$, $j = 1, I, m, 0 \le W_{ij} \le 1$. Finally, the comprehensive value is calculated by the linear weighting method: $ERS_i = \sum_{j=1}^{m} W_{ij} P_{ij}$. The calculation results can be used as measurement values for Fer in YREB. For the measurement of Ier, we construct the index of the public's attention to environmental problems on the network. Based on [60], this study searches for the keyword "environmental pollution" in the Google index and selects the average search value as the proxy variable of Ier. The larger the search index for environmental pollution, the higher the attention of the public to the environment, and the greater the intensity of Ier. It can be shown from the data that the public pays the highest attention to environmental pollution in Shanghai among the cities in the YREB, followed by Chengdu, Hangzhou, Wuhan, Chongqing, Changsha, and Nanjing.

4.5.3. Relevant Variables

Green technology innovation (Gti). Scholars widely use the patent number to measure the level of technological innovation [61]. Referring to Liu et al. [2], we use the accepted green patent applications' number as a measurement.

Industrial structure upgrading (Isu). The Isu refers to the transformation of industrial structure into tertiary industry. Based on [41], the study uses the proportion of tertiary industry in GDP to indicate the Isu level in the YREB.

Control variables. According to Ren et al. [49], we introduce the following city-level control variables: economic development level (Pgdp), degree of openness (Fdi), living expenditure (Con), population size (Pop), and human capital level (Edu). A city's level of economic development determines its level of technological innovation. According to Grossman and Krueger [62], the economic development level (Pgdp) is calculated by the per capita GDP of each city. Foreign direct investment can accelerate a city's economic development and have an impact on environmental issues and technology [40]. The degree of openness (Fdi) is calculated through the amount of foreign capital utilized in the current year. The higher the urban population size and consumption capacity, the stronger the people's green consumption level. Therefore, a larger consumption market is more conducive to promoting the innovation of green technology, thus affecting the efficiency of urban innovation. Living expenditure (Con) is calculated by the total retail sales of consumer goods; population size (Pop) uses the total population of each city at the end of the year to represent. The level of human capital reflects the human cost of technological innovation in cities. Regions with a high level of human capital tend to have a strong ability to absorb advanced technologies [63], so the level of human capital will affect the efficiency of green innovation in a city. The human capital level (EDU) is calculated by employees' numbers in the tertiary industry. Table 3 shows the variable descriptive statistics.

Table 3. Descriptive statistics.

Variable	Variable Definition	Obs	Mean	Min	Max
Gie	Green innovation efficiency (the number of accepted green patent applications)	721	0.283	0.001	1.173
Fer	Formal environmental regulation (construct the Fer comprehensive index by entropy weight method)	721	0.045	0.014	0.205
Ier(log)	Informal environmental regulation (the index of the public's attention to environmental problems)	721	2.714	−2.303	5.011
Gti(log)	Green technology innovation (the number of accepted green patent applications)	721	5.152	0.000	9.322
Isu(log)	Industrial structure upgrading (the proportion of tertiary industry in GDP)	721	3.707	3.076	4.287
Pgdp(log)	Economic development level (per capita GDP of each city)	721	1.541	0.009	2.991
Fdi(log)	Foreign direct investment (the amount of foreign capital utilized in the current year)	721	1.269	−5.099	5.250
Con(log)	Living expenses (the total retail sales of consumer goods)	721	2.014	−0.290	5.066
Pop(log)	Population size (the total population of each city)	721	6.077	4.682	8.136
Edu(log)	Human capital level (the number of employees in the tertiary industry)	721	3.092	1.591	10.389

5. Empirical Result

5.1. Benchmark Regression Analysis

To reduce the influence of unobservable variables, we use the two-way fixed effect model to analyze the effect. Column (1) of Table 4 is the impact of Fer on GIE when control variables are not added, the coefficient of Fer is significantly positive at the 1% level. Column (2) is the result of informal environmental regulation on GIE without control variables. The coefficient of Ier is also significantly positive at the 1% level. For both the government and the public, implementing environmental regulations will significantly promote GIE in the YREB. Columns (3) and (4) show the regression results after adding control variables. The coefficients of Fer and Ier are still significantly positive, which verifies the previous conclusions and shows that both Fer and Ier can promote GIE alone. Compared with Ier, Fer has a stronger effect.

The economic implications of the results indicate that the improvement of formal and informal environmental regulation levels can significantly promote the improvement of urban green innovation efficiency at levels of 1% and 10%, respectively. The possible explanations are that the formal environmental regulations implemented by the government encourage firms to implement technological innovation, promote technology diffusion, and generate "compensation benefits". The generation of "compensation benefits" realizes the double dividend of pollution prevention and improvement of production efficiency, which can improve the GIE. Meanwhile, public scrutiny can incentivize firms to decrease pollution emissions by improving green innovation technologies, which can promote GIE and accelerate sustainable development. Meanwhile, because the government's environmental regulation is more authoritative than environmental regulation by non-governmental organizations, the formal environmental regulation led by the government has a stronger binding effect on urban pollution and a stronger promoting effect on the GIE of the Yangtze River Economic Belt than the informal environmental regulation led by the public and other non-governmental organizations. Therefore, the government can shift the focus of environmental governance toward formal environmental regulations.

Table 4. The results of Benchmark regression.

	(1)	**(2)**	**(3)**	**(4)**
Variables	**GIE**	**GIE**	**GIE**	**GIE**
Fer	5.820 ***		4.844 ***	
	(9.92)		(7.66)	
Ier		0.033 ***		0.001 *
		(3.85)		(1.94)
Constant	−0.077 ***	0.098 ***	−0.904 ***	−0.105 **
	(−2.89)	(4.20)	(−3.04)	(−2.15)
Control	No	No	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	721	721	721	721
R-squared	0.506	0.745	0.847	0.581

Note: () indicates the t-value. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively (The following table is the same).

5.2. Spatial Spillover Effect Analysis

5.2.1. Spatial Correlation Test

The premise of the spatial model is that the variables have spatial correlation, and the Moran index (Moran's I) can evaluate whether the variables have spatial correlations. We choose W^g and W^e as the spatial weight matrixes, and use Moran's I to measure the spatial correlation of GIE; the results are shown in Table 5. The results show that whether using the W^g or W^e, the Moran index is significantly positive each year, which shows that the GIE in the YREB has a spatial agglomeration phenomenon and significant spatial positive correlation. The improvement of GIE in a city may promote innovation efficiency in its surrounding cities. Therefore, spatial factors cannot be ignored.

Table 5. The results of Moran's I.

Year	W^g			W^e		
	I	**E(I)**	**sd(I)**	**I**	**E(I)**	**sd(I)**
2013	0.044 ***	−0.01	0.053	0.431 ***	−0.01	0.053
2014	0.044 ***	−0.01	0.053	0.416 ***	−0.01	0.053
2015	0.037 ***	−0.01	0.053	0.424 ***	−0.01	0.053
2016	0.045 ***	−0.01	0.053	0.404 ***	−0.01	0.053
2017	0.044 ***	−0.01	0.053	0.442 ***	−0.01	0.053
2018	0.041 ***	−0.01	0.053	0.467 ***	−0.01	0.053
2019	0.033 ***	−0.01	0.053	0.411 ***	−0.01	0.053

Note: *** indicate significance at the 1% level.

5.2.2. Testing Spatial Effect

We use the SDM model to further analyze the spatial effect after concluding the obvious spatial positive correlation of GIE among cities in the YREB. The columns (1) and (2) in Table 6 are based on the geographic distance matrix W^g, and (3) and (4) are the results based on the economic distance matrix W^e. We can find that whether it is based on the W^g or the W^e for regression, both Fer and Ier have significant positive effects on GIE, which shows that the implementation of heterogeneous environmental regulations can produce a significant positive spatial effect on the improvement of GIE, and compared with Ier, Fer has a more significant spatial effect.

Table 6. Test results of spatial spillover effect.

Variables	**(1)**	**(2)**	**(3)**	**(4)**
Fer	4.37 ***		4.07 ***	
	(16.89)		(15.92)	
Ier		0.002 **		0.004 *
		(1.98)		(1.80)
Control	Yes	Yes	Yes	Yes
rho	0.231 *	0.409 ***	0.205 **	0.420 ***
	(1.90)	(3.31)	(3.14)	(8.23)
sigma2_e	0.001 ***	0.002 ***	0.001 ***	0.002 ***
	(18.97)	(18.95)	(18.92)	(18.77)
Observations	721	721	721	721
R-squared	0.850	0.752	0.846	0.802
N	721	721	721	721

Note: Values in parentheses indicate t statistics. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The results show that when it is based on the W^g for regression, the improvement of formal and informal environmental regulation levels can significantly promote the GIE of YREB at the level of 1% and 5%, respectively; when it is based on the W^e for regression, this effect is significant at the 1% and 10% level, respectively. The possible explanations are as follows: due to the phenomenon of resource flow and mutual influence among cities in the YREB, changes in factors related to one city in the YREB will not only affect itself but also the surrounding cities. Meanwhile, there are externalities in ER and green technology innovation, and their externalities are stronger in issues such as transboundary pollution. Due to the openness of the economic system, green technology innovation activities in one city can spread to neighboring cities through technology transfer, making more neighboring cities use the same technology, which can promote neighboring cities to improve GIE together through spatial effects. Therefore, we can conclude that not only is there a significant spatial effect of environmental regulation but also that the improvement of GIE in a city may promote innovation efficiency in its surrounding cities. ER can incentivize firms to implement green technological innovation and significantly promote GIE in its city and neighboring cities through the spatial effects. In addition, the Fer is more authoritative than the Ier. Yangtze River Economic Belt is an innovation-driven belt leading the transformation and development of China, Fer is more suitable for the situation of the YREB and can play a more important role in pollution prevention and enhancing GIE. Therefore, compared with Ier, Fer is more efficient at promoting the improvement of GIE.

5.3. Mediating Effect Model

The results of the mediating effect are shown in Table 7. The columns (1)–(4) are the test results of the mediation role of technological innovation, and the columns (5)–(8) are the test results when referring to the industrial structure upgrading as the mediation. In Table 7, columns (1) and (2) show the effect of heterogeneous ER on green technological innovation (GTI), and the regression coefficient is found to be significantly positive at 1% level, denoting that ER can promote GTI. The coefficients of GTI in Columns (3) and (4) are significantly positive at 1% and 5% levels, respectively, which show the validity of the mediating effect of technological innovation no matter the implementation of formal environmental regulation or informal environmental regulation. Meanwhile, the coefficients of both Fer and Ier are significant at the 1% and 10% levels, respectively, indicating that GTI is an incomplete mediating effect. Similarly, Columns (5) and (6) in Table 7 show the effect of heterogeneous ER on industrial structure upgrading, and its regression coefficients are both significantly positive at the 1% level, indicating that ER can significantly promote industrial structure upgrading. Columns (7) and (8) show the regression results of adding ER and industrial structure upgrading simultaneously. The coefficients of industrial structure upgrading in Columns (3) and (4) are both significantly positive at 1% level, which shows the validity of the mediating effect of industrial structure upgrading. The coefficients of both Fer and Ier are significant at 1% and 5% levels, respectively, indicating the incomplete mediating role of industrial structure upgrading in the environmental regulations' impact process. Therefore, both green technological innovation and industrial structure upgrading have partial mediating effects.

Table 7. Mechanism analysis.

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
	Green Technological Innovation				***Industrial Structure Upgrading***			
Variables	**GTI**	**GTI**	**GIE**	**GIE.**	**ISU**	**ISU**	**GIE**	**GIE.**
Fer	0.757 ***		0.035 ***		0.023 ***		0.017 ***	
	(8.70)		(3.20)		(6.43)		(7.09)	
Ier		0.073 ***		0.012 *		0.003 ***		0.014 **
		(4.97)		(1.77)		(3.78)		
TI			0.002 ***	0.001 **				
			(5.36)	(2.31)				
STR							0.003 ***	0.001 ***
							(3.18)	(4.65)
Constant	0.697 ***	2.231 ***	0.450 ***	1.236 ***	0.597 ***	3.465 *	0.975 ***	2.982 **
	(12.04)	(11.25)	(9.32)	(4.87)	(12.04)	(1.79)	(12.04)	(2.06)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3822	3822	3822	3822	3822	3822	3822	3822
R-squared	0.121	0.258	0.225	0.341	0.223	0.265	0.421	0.393

Note: ***, **, and * indicate the significance at 1%, 5%, and 10% levels, respectively; *t* values are denoted in parentheses.

The possible explanations are as follows: appropriate environmental regulations can promote more innovative activities in cities, and as the level of green technological innovation in cities improves, the innovation compensation generated by green technological innovation will promote GIE in the YREB by improving the efficiency of resource utilization. At the same time, green technology innovation will create new industries, which will attract the labor force from the secondary industry to the tertiary industry, and the industrial structures can be effectively upgraded. The upgrading of industrial structure reduces the damage caused by development to the environment, and the economy can develop in the direction of environmental protection, forming a virtuous circle, thus improving the green innovation efficiency of the Yangtze River Economic Belt. Therefore, environmental regulation can promote green innovation efficiency by improving green technological innovation and upgrading industrial structure.

5.4. Threshold Effect Analysis

The test results of the threshold model are shown in Table 8; no matter whether Fer or Ier is chosen as the threshold variable, only a single threshold passes the significance level test, indicating that Fer and Ier have a single threshold effect on GIE. Therefore, this study adopts a single-threshold model. Table 9 shows the threshold estimate results and the confidence interval of the single threshold model with Fer and Ier as the threshold variables. It can be seen that the Fer threshold value is 0.037 and the Ier threshold value is 29. Before and after the threshold value, the impact of environmental regulations on green innovation efficiency is different.

Table 8. Results of threshold effects.

Threshold Variable	Model	F-Value	*p*-Value	BS
	Single Threshold	48.54 ***	0.000	300
Fer	Double Threshold	34.60	0.113	300
	Single Threshold	45.54 **	0.027	300
Ier	Double Threshold	11.88	0.257	300

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

Table 9. Threshold estimates and confidence interval.

Threshold Variable	Model	Threshold Estimate	95% Confidence Interval
Fer	Single Threshold	0.0899	[0.0616, 0.1435]
Ier	Single Threshold	4.7536	[4.7273, 4.7875]

Columns (1) and (2) of Table 10 are the results when Fer is the threshold variable, and columns (3) and (4) are the results when Ier is the threshold variable. It shows that when the level of Fer is less than the threshold value of 0.037, the influence coefficient on GIE is 1.4202 under the significance level of 5%; when the level of Fer is greater than the threshold value, the effect on GIE increases to 2.2162 under the significance level of 1%. When the level of Ier is less than the threshold value, it has no significant effect on GIE. When it exceeds the threshold, it promotes GIE at a significance level of 1%. The results find that in the regions with higher levels of formal and informal environmental regulation, ER has a more significant incentive effect on GIE. The results differ from previous study results. In the previous studies, when the level of ER is less than the threshold, the coefficient is negative, and it becomes positive when it exceeds the threshold value. However, this paper shows that the effect of ER on the GIE is positive both before and after the threshold; as the level of ER increases, its effect on the GIE also increases.

Table 10. Results of the panel threshold model.

Variables	Threshold Variable = Fer		Threshold Variable = Ier	
	Coefficient (1)	**T-Value (2)**	**Coefficient (3)**	**T-Value (4)**
Core variable(Er $\leq$ C1)	4.145 ***	14.59	0.004	1.51
Core variable (Er $>$ C1)	6.386 ***	17.97	0.026 ***	4.07
lnPgdp	0.028 ***	3.53	0.075 ***	4.04
lnCon	0.026 **	2.10	0.048 ***	3.21
lnFdi	0.002	1.01	0.004	0.97
lnPop	0.090 **	2.07	0.170 ***	3.18
lnEdu	0.013 **	2.39	0.013 *	1.93
Constant	−0.690 **	−2.46	−1.125 ***	−3.29
N	721		721	
R-squared	0.852		0.830	

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

The possible explanations are when the level of ER is low, the supervision of the government is inadequate, the public pays little attention to environmental pollution, and there is insufficient consumption power of green innovative products. The driving force of green technology diffusion is not strong, and the motivation to carry out green innovation is not enough to encourage enterprises to enhance green innovation technology to reduce pollution emissions, pollution prevention by primitive methods may increase the cost of prevention and production. Although a low level of ER can trigger the "Porter Hypothesis", the driving force is not strong, and the innovation compensation cannot offset the control and production costs, which is not conducive to improving GIE. When the level of environmental regulation further rises, the government completes environmental protection policies and strengthens supervision. The public increases its consumption of green products. These measures can better encourage enterprises to promote technological diffusion and promote technology diffusion, thus triggering the "Porter hypothesis" and generating a stronger "compensation benefit", improving enterprises' market competitiveness, and efficiently promoting green innovation efficiency.

5.5. Heterogeneity Analysis

To explore the spatial heterogeneity, we divide the YREB into three areas: upstream, midstream, and downstream, and decompose the spatial effect into an indirect effect, a direct effect, and a total effect to test the spatial spillover effect. The results are shown in Table 11. It shows that no matter whether the direct, indirect, or total effects are both significantly positive, at least at the 10% level, indicating that Fer has a significant positive spatial effect and a spatial spillover effect on GIE in the three areas. It means that no matter in which area, Fer will not only significantly promote the GIE of its city but also drive the surrounding cities. The total effect of the downstream is stronger than the upstream and midstream. The possible explanation is that the cities in downstream areas have better economic development; the more economically developed areas are, the more they can attract labor and technical resources. Therefore, due to the superior development conditions and stronger resource attraction, the environmental regulations implemented by the government have a stronger effect on the GIE downstream of the YREB than in the midstream and upstream. However, the total effect of Ier on the upstream areas is positive but not significant, and the total effect in the midstream and downstream is significantly negative, indicating that the implementation of Ier may hinder the development of the city's GIE in midstream and downstream. The possible explanation is that when the public supervises the environmental pollution discharge in midstream and downstream, it will increase the pollution control cost of the firm and inhibit the improvement of the enterprise's market competitiveness. Therefore, the investment funds for green innovation are squeezed out, which is not conducive to the improvement of urban green innovation efficiency in the Yangtze River Economic Belt.

Table 11. The results of heterogeneity analysis.

Variables	Upstream			Midstream			Downstream		
	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
Fer	4.308 ***	4.122 **	8.430 ***	3.873 ***	2.024 *	5.690 ***	4.863 ***	5.773 **	10.636 ***
	(8.51)	(2.08)	(4.14)	(9.52)	(1.82)	(5.47)	(10.73)	(2.35)	(4.39)
lnIer	−0.003	0.026	0.029	0.005 *	−0.057 ***	−0.062 ***	0.013	−0.017 *	−0.017 *
	(−0.49)	(1.32)	(1.48)	(1.62)	(−3.06)	(−3.59)	(1.23)	(−1.83)	(−1.59)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	203	203	203	252	252	252	266	266	266

Note: T value in (). ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

5.6. Robustness Test

We use two ways to test its robustness. First, green innovation efficiency may have a time correlation; the current green innovation efficiency will be affected by the previous period, so we construct a dynamic panel model by including the first-order lag term of GIE:

$$GIE_{it} = \delta_0 + \delta_1 GIE_{it-1} + \delta_2 ER_{it} + \delta_3 X_{it} + \mu_i + \gamma_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \tag{8}$$

The results in Table 12 are consistent with the benchmark regression results. After adding the first-order lag term of GIE, both Fer and Ier can significantly affect GIE, demonstrating the robustness of the results. However, after adding control variables, the effect of Ier is decreased, indicating that the first-order lag term of GIE weakens the effect of Ier, but the overall conclusion is still robust.

Table 12. The results of the dynamic panel model.

Variables	(1)	(2)	(3)	(4)
L.GIE	0.516 ***	0.815 ***	0.578 ***	0.890 ***
	(11.67)	(18.36)	(15.78)	(27.22)
Fer	2.408 ***		2.302 ***	
	(11.66)		(12.13)	
lnIer		0.005 ***		0.003 *
		(3.26)		(1.87)
Constant	−0.573 **	0.556 ***	−0.111 **	−0.026
	(−2.08)	(4.24)	(−2.23)	(−1.44)
Control	No	No	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	618	618	618	618
R-squared	0.741	0.655	0.767	0.656

Note: T value in (). ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Second, we change the measurement of GIE. Referring to Sun et al. [64], we use the single indicator of green invention patent applications to calculate the GIE. Controlling the measurement of other variables unchanged and carrying out benchmark regression again, the results are shown in Table 13. It shows that, compared with Table 4, when replacing the multi-indicator measurement of the GIE with a single indicator measurement of the GIE, whether implemented by Fer or Ier, the influence coefficients are significant at the 1% level. The conclusions are the same with benchmark regression results, verifying their robustness.

Table 13. The results of replacing the measurement of GIE.

Variables	(1)	(2)	(3)
Fer	3.010 ***	2.708 ***	
	(3.52)	(7.59)	
lnIer	0.003 ***		0.003 ***
	(5.03)		(5.83)
Constant	−3.057 ***	−3.251 ***	−3.701 ***
	(−4.19)	(−5.69)	(−3.24)
Control	Yes	Yes	Yes
City FE	Yes	Yes	Yes
year FE	Yes	Yes	Yes
N	721	721	721

Note: T value in (). *** indicates significance at the 1% level.

6. Conclusions and Policy Implications

Using the data of 103 cities in the YREB urban agglomeration in 2013–2019, this paper explores the linear relationship, spatial impact effect, and threshold effect of heterogeneous ER on GIE. The results are as follows: First, the formal environmental regulation implemented by the government is more authoritative than informal environmental regulations, and the effect of urban control on the Yangtze River Economic Belt is stronger, so compared with Ier, Fer has a stronger effect. Second, we use the Moran index to test whether the GIE in the YREB has a significant spatial positive correlation. Meanwhile, the SDM model further analyzes the spatial effect and finds that both Fer and Ier have significant positive spatial effects on GIE. Due to the phenomenon of resource flow and mutual influence among cities in the YREB, there are positive spatial effects of environmental regulation. Third, we use a meditating model to test the potential mechanisms. Environmental regulations can improve cities' GIE in YREB by promoting green technological innovation and industrial structure upgrading. Fourth, the nonlinear test shows that the effect of ER on the GIE is positive both before and after the threshold; as the level of ER increases, its effect on the GIE also increases. When the level of ER is low, the motivation to carry out green innovation is not enough to enhance green innovation technology to reduce pollution emissions. When the level of ER rises, it can better promote technology diffusion, efficiently promoting green innovation efficiency.

This paper conducts theoretical explorations and empirical analyses to investigate the study of heterogeneous environmental regulation on the innovation efficiency of YREB urban agglomerations from different perspectives. However, the research in this paper mainly focuses on the city level, and micro-level studies are lacking. The large amount of pollutant emissions generated by enterprises in the production process is the main source of productive pollutant emissions in developing countries. Therefore, the environmental behavior of enterprises also plays an important role in improving urban green technology innovation and industrial structure upgrading. In future research, we will further explore the impact of environmental regulations on the environmental behavior of enterprises and governments.

Based on the conclusions, we propose the following recommendations for policymakers: first, the local government should adjust the level of environmental regulation reasonably and try to control the ER at a level greater than the threshold value to play the effect on GIE better. At the same time, relevant departments should adopt diversified environmental regulation policies, with Fer as the main way and Ier as the auxiliary way. The conclusions show that, compared with the Ier led by the public, the Fer led by the government is more authoritative and effective. Relevant departments can appropriately focus on formal environmental regulation policies in resource allocation, and informal environmental regulation can be used as an effective supplement to realize the green economic support effect of the YREB at the optimal governance level. That is, the government should take the lead in environmental governance, actively issue environmental regulations and policies, and actively supervise the environmental protection behaviors of enterprises. Meanwhile, non-governmental organizations, such as the public, should assist the government in environmental governance and supervise the environmental protection behaviors of the government and enterprises to obtain higher environmental regulation efficiency.

Second, optimize the industrial structure and focus on developing green technological innovation. The government should effectively use the mediating effect, increase support for green industries, develop clean energy industries, energy conservation, and environmental protection industries, and accelerate the pace of industrial structure upgrading. Meanwhile, enterprises need to increase funding for green technology innovation and realize technical cooperation and resource sharing among enterprises to improve competitiveness and accelerate green transformation. That is, to increase investment in technological innovation while supporting the development of the tertiary industry, and to attract labor and resources to transfer to the tertiary industry.

Third, the government can implement the regional coordination strategy. The results show that environmental regulations have an obvious positive spatial effect on the improvement of GIE; resources can flow between cities, and environmental regulations can work both locally and in neighboring cities. Therefore, relevant departments can use the spatial effects of environmental regulation and work with other cities to establish a collaborative governance mechanism to govern the ecological environment. Also, they can implement the integrated development strategy of the YREB to ensure the coordinated development of the upstream, midstream, and downstream cities. At the same time, by leading downstream cities, the upstream and midstream cities can make use of the "backwardness advantage" to realize the policy linkage of environmental regulation and effectively improve GIE.

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