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The Impact of Environmental Regulation and Carbon Emissions on Green Technology Innovation from the Perspective of Spatial Interaction: Empirical Evidence from Urban Agglomeration in China

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Abstract: As an important means of reducing carbon emissions, environmental regulation and green technology innovation have become a top research topic in academia in recent years. Existing studies have investigated the phenomenon of green technology innovation responses to carbon emissions, but there is less existing literature explaining this phenomenon from a spatial perspective and exploring the effect of the joint mechanism of carbon emissions and environmental regulation on green technology innovation. Based on the spatial econometric model, this study used the panel data of 41 cities in the Yangtze River Delta urban agglomeration from 2010 to 2019, to measure the impact of environmental regulation and carbon emissions on green technology innovation from the perspective of spatial interaction. The findings are as follows: green technology innovation in the Yangtze River Delta urban agglomeration shows a trend of "high in the east and low in the west" and has spatial autocorrelation; green technology innovation responds positively to changes in environmental regulations and carbon emissions and, by decomposing the spatial effects, it can be observed that there is a spatial spillover effect of environmental regulations and carbon emissions on green technology innovation in the surrounding areas; there is a substitution effect between environmental regulations and carbon emissions. This paper combines the above results and proposes the corresponding policy recommendations.

Keywords: carbon emissions; technology innovation; environmental regulation; spatial interaction

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1. Introduction

To reduce greenhouse gas emissions and improve the level of green development, the Chinese government proposed a "dual control" policy of energy consumption intensity and energy consumption quantity in 2015 and launched a specific implementation plan in 2019 [1], establishing stable and clear control targets for total energy consumption and intensity for each province and city, and supervised and evaluated the local governments at all levels on a quarterly basis [2]. In August 2021, the National Development and Reform Commission conducted statistics on the completion of the energy consumption "dual control" target in the first half of 2021 and found that some major industrial provinces made profits by expanding their production capacity in light of rising commodity prices, leading to their failure to achieve the required "dual control" target and an energy consumption intensity increase; therefore, nine provinces and regions were listed as first-level warning areas. Faced with the pressure of assessment, some provinces and regions began to prohibit the production of high energy-consuming enterprises strictly and even began to suddenly cut off electricity supplies. This mandatory environmental regulation policy has exerted obvious adverse effects on the production of industrial enterprises and the daily life of residents. This phenomenon reflects the dilemma of local authorities in facing the central government's environmental regulations. This phenomenon demonstrates the difficulty faced by local authorities in terms of the central government's environmental regulation, which is to maintain the long-term stable growth of regional GDP, on the one hand, and to achieve the central government's "double control" goal, on the other. This is an urgent development issue for many cities in the face of climate change.

There are many well-respected research findings on environmental regulation and urban economic development. Urban technological innovation is now seen as the key to achieving sustainable economic growth under environmental regulation. However, the impact of environmental regulation on urban technological innovation is non-linear [3], as government environmental regulation policies may constrain firms' abilities to innovate, which, in turn, affects their efficiency [4]. There are many ways for enterprises to control carbon emissions and energy consumption; they can promote emissions reduction by improving energy use efficiency and by increasing the scope of green energy use, but none of these approaches can be led by green technology innovation. In the context of green and sustainable development driven by innovation, exploring the response mechanism of green technology innovation to carbon emissions and environmental regulation can help accelerate the green transformation of the development model and promote a win-win situation of economic development and environmental protection.

In recent years, an increasing amount of the literature has studied carbon emissions, environmental regulation and green technology innovation, but most existing studies focus on how environmental regulation or green technology innovation can reduce carbon emissions; therefore, in contrast, is there a response mechanism of green technology innovation to carbon emissions levels and environmental regulation? Are there mechanisms for carbon emissions levels and environmental regulation in response to green innovation? Exploring this question from the opposite perspective can help fill the gap in the existing literature and provide insights for local governments to promote green economic development, which is of great practical significance to accelerate green low-carbon cycle development and promote the green transformation of the economy and society. In addition, there are many energy-consuming enterprises in dense urban areas; with the deepening of inter-regional interaction and open cooperation, the links between cities are getting closer and closer. As the spatial organization forms of cities at a mature stage of development, urban agglomerations are the most active and innovative areas in the economy, so it is more representative to choose urban agglomerations as the research object. There are certain spatial spillover effects concerning population levels, the economy and policies within urban agglomerations [5]. There are also the inter-regional circulation and transfer of greenhouse gases under the effects of atmospheric circulation. There are spatial spillover effects of carbon emissions, environmental regulations and green technology innovation. Nevertheless, the existing studies of spatial effects usually use provincial-level panel data, which have their own problems of a too-large sampling scale of geographical units and insufficient panel data. Therefore, this paper takes municipal-level data as the benchmark and explores the response mechanism of green technology innovation to carbon emissions and environmental regulation from the perspective of spatial interaction, so that the related research can be more relevant and accurate.

The rest of this paper is organized as follows: the second part reviews the relevant literature; the third part selects the spatial econometric model and explains the associated research variables; the fourth part analyzes the results of the study; the fifth part elaborates upon the conclusions and proposes relevant policies and recommendations.

2. Literature Review

Green technology innovation is an essential national policy to promote the development of the green economy [6]. Economic development at this stage is often related to national green technology investment and national economic innovation capacity [6]. In addition to green technology innovation, government regulation and the laws regarding water resources and waste and gas control are also essential parts that make up a green economy. Although many components make up the green economy, the indicators used to assess the green economy are heterogeneous and depend entirely on the specific context in which they are generated and used [7]; for example, Natalia Vukovic et al. [8] used Russia as a context, while proposing a "number of documents regulating the green economy" to reflect the strength of government regulation of the environment, but the authors also argue that legal and regulatory standards are more complex and the choice of specific indicators may vary from country to country, due to the existence of uncertainty. As research on differential environmental regulation progresses, researchers have found that different environmental regulations have a differential impact on the green economy [9]. Another area of focus for the green economy is the structure and efficiency of energy consumption and use, specifically in the form of reduced carbon emissions. Therefore, green technology innovation, carbon emissions and environmental regulation are important research areas of the green economy. It is the core scope of this paper to include all three areas in the same research framework and explore the spatial interaction effects and mechanisms of action among them.

2.1. Environmental Regulation and Green Technology Innovation

Existing studies suggest that environmental regulations may have both a facilitating effect of innovation compensation and a disincentive effect of crowding out R&D costs on green technology innovation. The positive impact of environmental regulation on green technology innovation stems from the "Porter effect" hypothesis, which proposes that appropriate environmental regulation can help guide and motivate enterprises to carry out technological innovation activities. These technological innovations can compensate for the costs generated by environmental regulation and can help improve business efficiency and market competitiveness [10]. Requate and Unold [11] confirmed the "Porter effect" hypothesis, arguing that environmental taxation can lead to investment in new technologies by enterprises; Testa [12] studied the construction industry in several EU regions and found that strict environmental regulations have a positive effect on high-tech equipment and innovative products; Mohnen [13] conducted a study on Dutch firms and concluded that environmental regulations have a positive impact on firms' innovative activities; Jiang and Wang [14] suggested that voluntary environmental regulation also has a significant positive impact on green technology innovation. Conversely, there are also views that environmental regulation will increase the operating costs of enterprises and have a certain crowding-out effect on investment into the R&D resources of enterprises, which hinders the implementation of green technology innovation activities. During their analysis of the impact of regional environmental regulation on the innovation capability and competitiveness of pollution-intensive enterprises, Bel et al. [15] studied 27 European countries and found that instead of promoting technological innovation, overly strict environmental regulations had some negative effects. Zhao and Sun [16] found that environmental regulation has a weak positive effect on enterprise innovation, but has a negative impact on enterprise competitiveness, which shows that although environmental regulation is beneficial to enterprise innovation, the profits contributed by this innovation cannot make up for the losses caused by environmental regulation. In recent years, it has been pointed out in the research of certain scholars that the impact of environmental regulation on green technology innovation is not a simple linear relationship, instead presenting a "U-shaped" relationship of inhibition, followed by promotion; that is, there is a threshold for the impact of environmental regulation on green technology innovation [17–19]. In addition, with the continuous deepening of the relevant research, scholars in the field believe that the impact of environmental regulation on green technology innovation will also be affected by spatial heterogeneity [20], industry heterogeneity [21], enterprise-scale benefits [22], R&D efficiency [23], willingness to innovate [24], environmental regulatory flexibility [25], etc.

2.2. Green Technology Innovation and Carbon Emissions

In the field of research on green technology innovation and carbon emissions, most studies focus on how green technology innovation affects energy consumption and carbon emissions. The majority of scholars affirmed the positive effect of green technology innovation on carbon emissions reduction. For example, in his study on the impact of energy technology development improvements in 28 OECT countries on GHG emissions from 1990 to 2014, Agustín Álvarez-Herránz [26] found that energy technology innovation helps reduce per capita greenhouse gas emissions, but it does take time to reach the full effect. Zhang [27] argued that the development of technological innovation can help reduce greenhouse gas emissions and achieve the goal of carbon neutrality in the long run. However, some scholars believe that there is an energy rebound effect, due to the reduction in energy consumption as a result of green technology progress [28–30]; that is, advances in green technology increase energy efficiency and also promote economic growth, which, in turn, increases the demand for energy use, offsetting some of the energy savings due to increased usage. In his study of how exogenous changes in energy efficiency affect the consumption choices of Swedish households, Brannlund [31] found that improvements in energy efficiency lead to a rebound effect on carbon emissions. Lin and Liu [32] suggested that energy consumption cannot be reduced in a way that is simply based on the development of technology innovation, and that economic means should also be adopted to achieve the emissions reduction target.

2.3. Environmental Regulation and Carbon Emissions

In the existing literature, the impact of environmental regulation on carbon emissions is mainly reflected in two aspects: "forced emission-reduction" and the "green paradox". The "forced emission-reduction" argument posits that environmental regulation by the government will encourage enterprises to improve energy efficiency and reduce the carbon emissions level [33]. Chen and Lei [34] argued that strict environmental control will help reduce pollution; after a study of the BRICS data from 1999 to 2015, Danish and Ulucak [35] found that environmental regulation has effectively improved the technical level and energy efficiency, playing a positive role in reducing the carbon emissions level. Hashmi and Alam [36] found a positive effect of environmental regulation on reducing carbon emissions in a study of OECD countries from 1999 to 2014. Since Sinn [37] proposed the "green paradox", there have been some doubts about the effectiveness of environmental regulation in academic circles. At present, the academic community believes that there are three main reasons for the "green paradox", namely, the "display effect" when the policy is announced [38], the "substitution effect" brought about by clean energy [39] and carbon leakage [40]. However, in recent years, some scholars have pointed out that there is an obvious "inverted U-shaped" relationship between the impact of environmental regulation on carbon emissions; that is, with stricter environmental regulation, the carbon emissions level shows a rise–fall trend, and the impact of environmental regulation changes from a "green paradox" to a "forced emission-reduction" [41,42].

2.4. Environmental Regulation, Green Technology Innovation and Carbon Emissions

At present, there are few studies on the relationship between environmental regulation, green technology innovation and carbon emissions. Most of the existing literature concludes that environmental regulation and technological progress can significantly reduce energy consumption. For example, after studying the panel data at the province-level in China from 2005 to 2016, Yang and Zha [43] found that technological innovation is an important intervening variable of the impact of environmental regulation on carbon intensity. Government environmental regulation can promote green technology innovation, thereby reducing carbon intensity. On the contrary, some scholars believe that technological innovation brought about by environmental regulation may increase carbon emissions due to the rebound effect; for example, Liu and Li [44] discussed the impact of environmental regulation on energy consumption through technological innovation based on the Chinese province-level panel data from 1997 to 2015; they suggested that the technological innovation brought about by environmental regulation makes the energy rebound effect greater than the energy consumption reduction by technological innovation.

In addition, the existing literature has explored the response of technological innovation to climate change, including government regulations in the analytical framework [45]. Nevertheless, the question of whether changes in climate-related technological innovation are due to climate change or environmental regulation to reduce carbon emissions and, thus, strengthen the requirements for technological innovation has not yet been answered. This is one of the issues that need to be addressed in this paper.

As can be seen from the above sections, there have been many studies on the relationship between green technology innovation, environmental regulations and carbon emissions levels. However, further research is still needed in certain areas:

(1) Most of the existing research only chooses two elements from green technology innovation, environmental regulations and carbon emissions levels to explore the correlation, while most of them use the classical measurement for research with less consideration of spatial factors, which easily causes model-setting bias.
(2) Spatial econometric studies on the relationship between the three elements are mostly based on province-level panel data. However, there are obvious disadvantages to the province-level panel data when a spatial econometric analysis is performed: first, since the scales of municipalities and provincial geographic units are different, placing them into the same model for research will result in the modifiable areal unit problem in spatial measurement; second, the province-level panel as a geographic unit is too large, which causes the change of support problem, resulting in unconvincing research results; third, in the existing studies, provinces with missing data are usually discarded, which results in the geographical discontinuity of the study samples. Therefore, the study results are unreliable.
(3) Although both carbon emissions and environmental regulations impact green technology innovation, the literature focusing on the interactive impact of carbon emissions and environmental regulations is limited. This paper explores the mechanisms of carbon emissions and environmental regulations in their effects on green technology innovation by introducing cross-terms in a spatial econometric model.

Compared with existing studies, this study will provide four academic contributions:

(1) This paper considers the problem of existing studies from an alternate perspective and explores the mechanism of green technology innovation responses to carbon emissions and environmental regulation from the perspective of spatial interaction, which enriches the existing studies.
(2) This paper uses municipal panel data to construct a spatial econometric model, which solves the problems of using provincial panel data in spatial econometric studies and makes the relevant research more rigorous.
(3) This paper explores the interaction between carbon emissions and environmental regulations on the impact of green technology innovation.
(4) The sample used in this paper is selected from the Yangtze River Delta city cluster in China to investigate the response mechanism of green technology innovation regarding carbon emissions and environmental regulation.

3. Methodology

3.1. Research Area Overview

The authors of this paper took 2010–2019 as the research period, with 41 prefecture-level cities in the Yangtze River Delta urban agglomeration (YRDUA) being selected as the research object; Schematic diagram of the provinces and municipalities directly under the jurisdiction of the Yangtze River Delta urban agglomeration is shown in Figure 1; the reasons for data selection are as follows:

(1) To date, China has planned dozens of national urban agglomerations, among which the Yangtze River Delta urban agglomeration is China's foremost world-class urban agglomeration, demonstrating the most substantial economic volume, population size, openness and innovation capability in China. Before promoting major reform projects, the Chinese government usually conducts pilot projects in critical regions, summarizes the drawbacks and difficulties arising during the process of piloting, summarizes the practical experiences and promotes the role of pilot regions as a model. The study will provide a good reference for developing urban clusters in China and other developing countries.

(2) Previous studies on carbon emissions levels, environmental regulation and green technology innovation have mainly focused on province-level data. However, the use of too large a geographic unit can easily lead to inaccurate estimation results. Therefore, the authors of this paper selected panel data from prefecture-level cities to obtain more accurate research results.

As the only world-class urban agglomeration under construction in China, the Yangtze River Delta urban agglomeration consists of 3 provinces (Jiangsu Province, Zhejiang Province and Anhui Province) and 1 municipality (Shanghai), comprising a total of 41 cities.

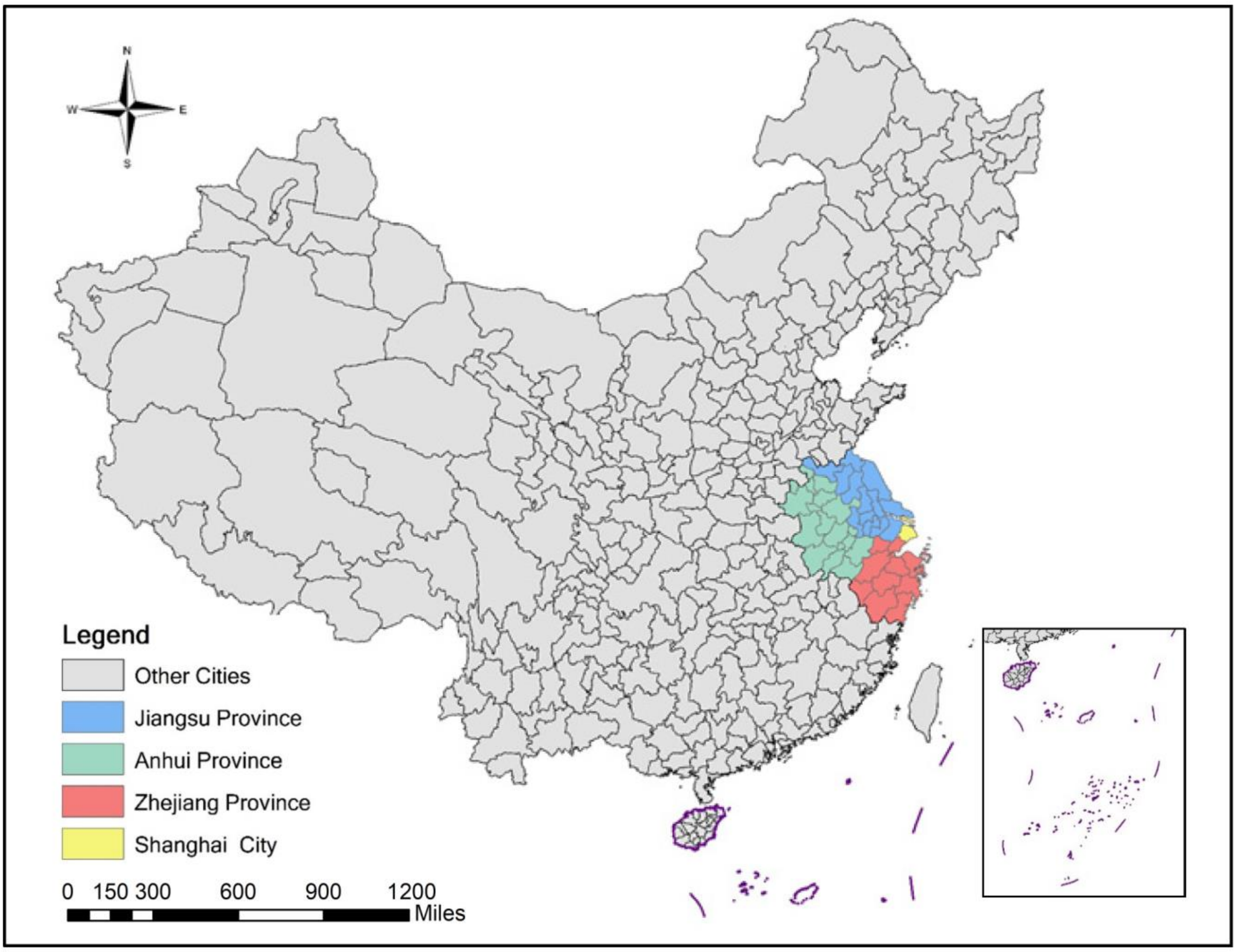

Figure 1. Schematic diagram of the provinces and municipalities directly under the jurisdiction of the Yangtze River Delta urban agglomeration.

As a municipality, Shanghai is a designated city that is directly under the jurisdiction of the Central People's Government, and its administrative level is the same as that of China's provinces, autonomous regions, and special administrative regions. Since the geographical scale of Shanghai is still essentially a prefecture-level city, this paper uses Shanghai and other 40 prefecture-level cities in the Yangtze River Delta urban agglomeration as the research object.

3.2. Calculation and Description of Each Variable

3.2.1. Explained Variable

The explained variable is green technology innovation (GTI), measured by the number of green patents granted in 41 prefecture-level cities in the Yangtze River Delta region. Multiple examples in the literature prove that patents are a reliable way to measure innovation [46,47].

3.2.2. Core Explanatory Variables

Carbon emissions (ln_CE): Su and Moaniba [45] suggested that the development of a country's climate change technology is affected by greenhouse gas emissions. Therefore, it is expected by the authors that the increase in carbon emissions levels will promote the development of green technology innovation. For this paper, the carbon emissions of the corresponding districts and counties of the cities in the Yangtze River Delta were calculated to obtain the carbon emissions levels of the prefecture-level cities in the Yangtze River Delta.

Environmental regulation (ln_ER): The government's environmental regulation policy will inevitably affect enterprises' innovation and production process. According to the "Porter effect" hypothesis, reasonable environmental regulation will guide the technological innovation activities of enterprises to a certain extent, enhancing their ability to achieve green technological innovation. As summarized in this literature review, the approach to environmental regulation differs among countries. By referring to the method of Zhou and Zhang [48], this paper used the urban sewage treatment rate, industrial comprehensive utilization rate and the proportion of days with good air quality to characterize the degree of environmental regulation. However, due to dimensional differences, the above three indicators could not be directly calculated. Therefore, this paper used the panel data entropy weight method for calculation. First, each indicator was standardized. The information entropy was then calculated, and the weight coefficient was adjusted. Finally, the environmental regulation intensity of the prefecture-level cities in the Yangtze River Delta region from 2010 to 2019 was calculated.

3.2.3. Control Variable

In addition to the impacts of carbon emissions levels and environmental regulation, green technology innovation is also constrained by economic development, industrial structure, government intervention, urbanization, etc. In order to exclude the influence of other variables on the analysis results, this paper introduced the following control variables:

(1) Economic development level: economic growth not only improves the consumption level of residents but also promotes the transformation of the modes of production and life. Due to the existence of spatial selection and spatial classification, cities with a higher level of economic development are more likely to attract enterprises with strong innovation capabilities, low pollution emissions and high production efficiency to agglomerate, thereby promoting green technology innovation. In this paper, local GDP (ln_GDP) and urban per capita disposable income (ln_DPI) were used to measure the economic development levels of the prefecture-level cities in the Yangtze River Delta region.

(2) Industrial structure (ln_IS): if the development level of the industrial structure is lower, this indicates that more R&D investment and human capital are concentrated in secondary industries with high pollution and high energy consumption, which is less conducive to the development of clean, green technology innovation. In this paper, the ratio of the GDP of the secondary industry to the GDP of the tertiary sector was used to characterize the industrial structure.

(3) Government intervention (ln_GI): the government can influence the development of technological innovation through fiscal and institutional policies; fiscal decentralization is an essential system for adjusting the fiscal power between the central and local governments, and fiscal decentralization was used here to represent government intervention in green technology innovation.
(4) Urbanization level (ln_UL): improvement in the urbanization level has brought about the agglomeration of resources and improvements in efficiency, which has promoted the development of green technology innovation to a certain extent. In this paper, the proportion of the permanent urban population of the cities in the Yangtze River Delta to the total population at the end of the year was used to measure the urbanization level.
(5) Demographic factor (ln_PR and ln_PD): the increase in the size and density of the population can promote the rapid exchange of knowledge and information, thereby accelerating the development of technological innovation activities in local enterprises. In this paper, the data regarding the permanent resident population (ln_PR) and population density (ln_PD) of the prefecture-level cities in the Yangtze River Delta region were selected to measure the impact of demographic factors on green technology innovation.
(6) Fixed asset investment (ln_FI): fixed asset investment is an important way to improve the basic capabilities of the technology industry; in this paper, the amount of fixed asset investment of the prefecture-level cities in the Yangtze River Delta was selected for measurement.

All data in this paper were obtained from the China Statistical Yearbook, China Statistical Yearbook on the Environment, China Energy Statistical Yearbook and the statistical yearbooks of prefecture-level cities in the Yangtze River Delta region. Some missing data were complemented by the linear interpolation method. In this paper, the relevant indicators, such as GDP, were adjusted by taking 2010 as the base period at a constant price, to eliminate the influence of inflation. In order to eliminate the effect of heteroscedasticity, all variables were logarithmically processed in this paper. Table 1 shows the results of the descriptive statistics of the main variables.

Table 1. Descriptive statistics for the variables.

Variable	Sample Size	Mean Value	Standard Deviation	Minimum Value	Maximum Value
Carbon Emissions (ln_CE)	410	3.36	0.75	1.76	5.44
Environmental Regulation (ln_ER)	410	4.33	0.11	4.01	4.67
Cross-sectional (ln _(CE × ER))	410	14.59	3.18	7.49	23.44
Gross Domestic Product (ln_GDP)	410	7.80	0.97	5.71	10.55
Disposable Income per Urban Resident (ln_DPI)	410	10.36	0.36	9.45	11.21
Industrial Structure (ln_IS)	410	4.49	0.33	3.44	5.60
Government Intervention (ln_GI)	410	2.72	0.37	2.03	3.57
Urbanization Level (ln_UL)	410	3.68	0.51	2.29	4.50
Resident Population (ln_RP)	410	6.09	0.65	4.28	7.82
Population Density (ln_PD)	410	7.75	0.45	6.51	8.77
Fixed Asset Investment (ln_FI)	410	6.71	1.01	4.13	8.98

3.3. Selection of Spatial Econometric Models

This paper aimed to study the impact of environmental regulation and carbon emissions on green technology innovation, from the perspective of spatial interaction. Therefore, this paper introduced a spatial econometric model to conduct an empirical analysis of 41 cities in the Yangtze River Delta urban agglomeration. According to the spatial econometric research paradigms of Anselin and Le Gallo [49] and Elhorst [50], in this paper, a specific spatial econometric model was first selected through the Lagrange Multiplier (LM) test. Meanwhile, the results of the LM test can also prove whether the spatial interaction effect of green technology innovation exists, which is shown in Table 2.

Table 2. Result of LM test for spatial econometric model selection.

	***t*-Statistic**	**Probability**
LM test—no spatial lag	28.4801	0.000
Robust LM test—no spatial lag	4.0177	0.045
LM test—no spatial error	16.5349	0.000
Robust LM test—no spatial error	0.0725	0.788
R^2	0.9647	
Conclusion	Since SLM is more significant than SEM, SLM is selected.	

The results showed that the fitting degree of the LM test was $R^2 = 0.9647$, which is good. The LM test results of the spatial lag model (SLM) and the spatial error model (SEM) were both significant at the 1% significance level, which means that the explained variables have a spatial autocorrelation, and the research sample can be studied using the spatial econometric model. However, at the same time, the results of the robust LM test showed that no spatial lag in the spatial lag model was significant at the 5% significance level; therefore, this paper failed to meet the conditions set by the spatial error model (SEM) and the spatial Durbin model (SDM), therefore, the spatial lag model was finally selected; see Formula (1) for the model design.

$$\begin{gathered} GTI_{i,t} = \rho \sum_{j=1}^{N} W_{ij} GTI_{j,t} + X_{i,t}\beta + u_{i,t} + v_{i,t} \\ X_{i,t} = \alpha_1 CE_{i,t} + \alpha_2 ER_{i,t} + \alpha_3 GDP_{i,t} + \alpha_4 DPI_{i,t} + \alpha_5 IS_{i,t} + \alpha_6 GI_{i,t} \\ +\alpha_7 UL_{i,t} + \alpha_8 PR_{i,t} + \alpha_9 PD_{i,t} + \alpha_{10} FI_{i,t} + \alpha_{11} CE * ER_{i,t} \\ u_{i,t} = c_i + \varphi_t \end{gathered} \quad (1)$$

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

$$W_{i,j} = \begin{bmatrix} 0 & \cdots & w_{1,j} \\ \vdots & \ddots & \vdots \\ w_{i,1} & \cdots & 0 \end{bmatrix} \quad (3)$$

where ρ represents the regression coefficient of the spatial lag term; i and j represent the first, second, ..., and n-th cities, respectively; t represents the year; $GTI_{i,t}$ represents the explained variable of the i-th city in the t year; and $X_{i,t}$ represents the explanatory variable of the i-th city in the t year. $u_{i,t}$ represents the individual fixed effect of the i-th city in the t year, where c_i is the spatial fixed effect and φ_t represents the time-fixed effect. $W_{i,j}$ is the geographic weight matrix between the i-th city and the j-th city, where $w_{i,j}$ is the spatial weight between two different cities, which is calculated according to the inverse square of the spatial distance. $\beta, \alpha_1, \alpha_2, \ldots, \alpha_{11}$ are parameters to be estimated. $v_{i,t}$ is the error term and $v_{i,t} \sim (0, \sigma^2)$.

After the specific spatial econometric model was determined, it was also necessary to test the specific effect of the model to determine whether $u_{i,t}$ exists in the model and whether c_i and φ_t exist at the same time. The Hausman test results of the spatial lag model (see Table 3) showed that the p-value was greater than 0.05, which indicated that $u_{i,t}$ is irrelevant to $X_{i,t}$, and the model should be a random effect model. Therefore, this paper selected the spatial lag model of random effect for testing.

Table 3. Result of the Hausman test for the spatial lag model.

Statistic	Degrees of Freedom	Probability
20.7519	12	0.0541

4. Results

4.1. Spatial–Temporal Differentiation Diagram of Environmental Regulation in the Yangtze River Delta Region

In order to explore the spatial distribution and evolution process of green technology innovation in the Yangtze River Delta urban agglomeration, this paper performed a visual analysis taking 2010, 2015 and 2019 as the time nodes, respectively; the results are shown in Figure 2. There are obvious differences in the spatial distribution of green technology innovation levels in the Yangtze River Delta urban agglomeration. In general, it shows the characteristics of being highest in the mid-east region, followed by the southeast, and is lowest in the northwest. In 2010, the provincial capital cities of Nanjing, Hangzhou, Hefei and Shanghai (a municipality directly under the Central Government), which are high-value areas for green technology innovation, showed a good momentum of innovation and development. Their excellent innovation ecology radiation and synergy capability have driven the development of the innovation levels of the surrounding cities. Most neighboring cities also show a relatively good level of green technology innovation, with a significant spatial spillover effect from core cities. In addition, the coastal city of Ningbo has a high degree of extroversion, with excellent green technology innovation level performance. With the continuous advancement of the concepts of green and low-carbon development, the level of green technology innovation in the Yangtze River Delta urban agglomeration has generally shown an upward trend, with high-value areas as the center. In 2019, by virtue of their strong comprehensive strength and the advantages of the agglomeration of innovative elements, Shanghai, Nanjing, Hangzhou, Hefei and other core cities played a prominent leading role in green technology innovation in the surrounding cities. The central urban agglomeration in the Yangtze River Delta region has achieved leapfrog development in terms of green technology innovation level. The green technology innovation level of the southern and northern urban agglomerations has also been improved to a certain extent.

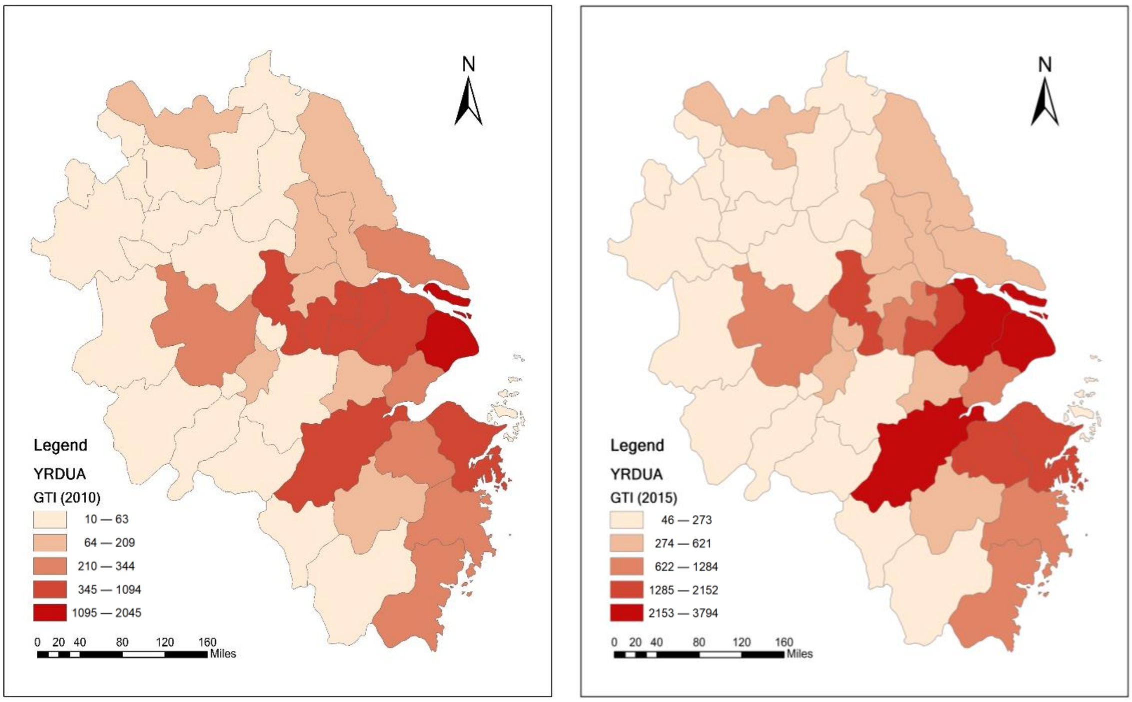

Figure 2. *Cont.*

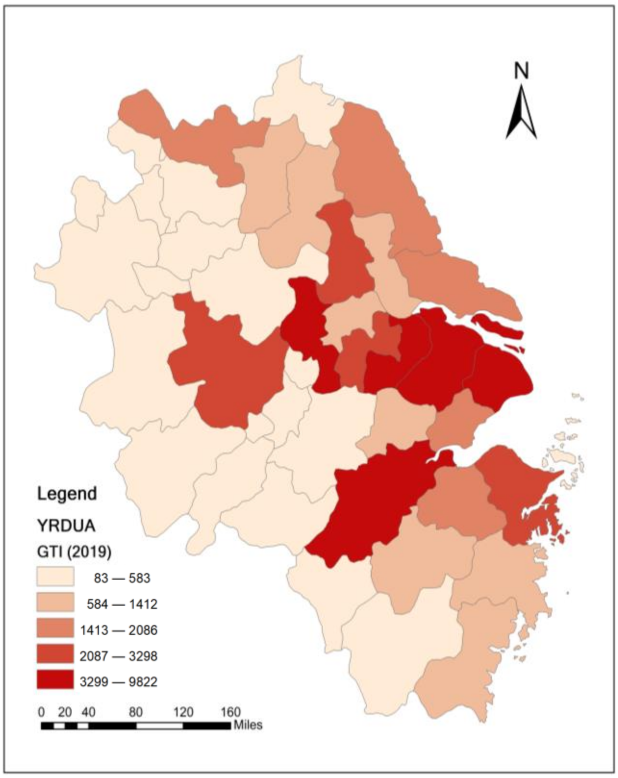

Figure 2. Spatial–temporal differentiation diagram of green technology innovation in the Yangtze River Delta urban agglomeration (2010, 2015 and 2019).

4.2. Model Results

Table 4 shows the SLM spatial econometrics results.

Table 4. SLM spatial econometrics results.

Variables	Random Effect Coefficient	*p*-Value
Carbon Emissions (ln_CE)	2.5032 **	0.0264
Environmental Regulation (ln_ER)	1.7970 **	0.0318
Cross-sectional (ln _(CE × ER))	−0.4388 *	0.0847
Gross Domestic Product (ln_GDP)	0.3168 *	0.0931
Disposable Income per Urban Resident (ln_DPI)	1.7653 ***	0.0000
Industrial Structure (ln_IS)	−0.2447 **	0.0240
Government Intervention (ln_GI)	−0.0815	0.4829
Urbanization Level (ln_UL)	0.2006 **	0.0181
Resident Population (ln_RP)	0.0657	0.1980
Population Density (ln_PD)	0.0547	0.5422
Fixed Asset Investment (ln_FI)	0.0413	0.4185

Note: ***, ** and * are significant at the 1%, 5% and 10% levels, respectively.

Core explanatory variables: the carbon emissions level (ln_CE) has a positive impact on green technology innovation and passed the 5% significance test, which shows that the increase in carbon emissions levels will stimulate the development of green technology innovation activities. This is the same view as that offered by Su and Moaniba (2017) [45] in a study of 70 countries regarding the drivers of innovation. This result shows that in the development process, the Yangtze River Delta region has begun to pay an increasing amount of attention to development quality and can actively promote the development of green technology to cope with changes in the environmental situation. Environmental regulation (ln_ER) plays a significant role in promoting green technology innovation, which further verifies the "Porter effect" hypothesis. It shows that with strengthened environmental supervision, the pollution control fees paid by enterprises in high-pollution industries will exceed the cost of green technology innovation, which will encourage enterprises to carry out innovation activities for energy conservation and emissions reduction [48,51]. Both the carbon emissions level and environmental regulation promote green technology innovation. Nevertheless, the coefficient of the cross-term of both is significantly negative, indicating that carbon emissions levels and environmental regulation have substitution effects on green technology innovation. This means that when the carbon emissions level tends to be stable, stricter environmental regulations can still promote green technology innovation; when the intensity of regional environmental regulations does not change, the increase in the carbon emissions level will promote the progress of green technology innovation. From another perspective, more stringent environmental regulation will prevent regional green technology innovation from being affected by local climate change because the environmental regulation has a greater impact on green technology innovation at this time; when the carbon emissions level is high, more climate-related green technology innovation will be created, even if the local government does not implement environmental regulation, which also confirms the accuracy of the existing related conclusions [52].

Control variables: economic development level (ln_GDP and ln_DPI), urbanization level (ln_UL), demographic factors (ln_PR and ln_PD) and fixed asset investment (ln_FI) have positive effects on green technology innovation, which supports the previous predictions. Among them, the highest impact of economic development levels represented by urban per capita disposable income (ln_DPI) passed the significance test, which implies that higher economic growth increases the public's demand for quality of life and makes the public pay more attention to energy conservation and sustainable development; this finding validates the view of Deng (2022) [53], in exploring the coupled and coordinated development of the environment and economy in the Yangtze River Delta region, that economic growth is essential for promoting sustainable development. People's concern for environmental protection further generates the need to encourage green technological innovation; therefore, the increase in the level of economic development contributes to the development of green technological innovation. In addition, the rise of urbanization levels (ln_UL) can also significantly drive the development of green technological innovation. The increase in this indicator can introduce many factors that are suitable for technological innovation development in the region through the agglomeration effect, which is similar to the findings of Calino (2007) [54] in a study of urbanization levels and technological innovation in the United States. Although demographic factors (ln_PR and ln_PD) and fixed asset investment (ln_FI) failed to pass the significance test, they also reflected a positive relationship with green technology innovation to a certain extent. This shows that with the growth of the population and fixed asset investment, the rapid flow of knowledge and the development of the technology industry will be promoted to some extent. Industrial structure (ln_IS) has a significant inhibiting effect on green technology innovation; the reasons for this may be that secondary industry, especially the manufacturing industry, aggregates in the Yangtze River Delta region and various resources are widely concentrated in the secondary industry, which is not conducive to the development of green technology innovation. With continuous improvement in the degree of specialization and diversification of the industrial structure, the industrial structure will promote technological innovation. This finding is the same as that suggested by Greunz (2004) when he studied the impact of industrial structure on innovation in 153 European regions [55]. The regression coefficient for government intervention (ln_GI) is -0.08. However, it fails to pass the significance test, which indicates that government intervention has a negative but not an obvious effect on green technology innovation [56]. This may be caused by the fact that against the background of fiscal decentralization, local officials pursue the maximization of political and economic interests during their term of office and fail to pay enough attention to the green technology innovation field, with its long investment cycle and a high degree of uncertainty.

4.3. Effect Decomposition Results

Since the SLM model contains a spatial lag term, the estimated coefficients of the SLM model in Table 4 cannot directly represent the marginal effect of the independent variables on the dependent variables. In this paper, the utility decomposition of the SLM model was performed, and the spatial effect of the independent variables on the dependent variables was reflected through the direct effect, indirect effect and gross effect of each parameter. Among them, the direct effect reflects the direct impact of independent variables on local green technology innovation. The indirect effect reflects the spatial spillover effect of independent variables on green technology innovation in adjacent areas. The effect decomposition results are shown in Table 5.

Table 5. SLM model effect decomposition.

Variables	Direct Effect	Indirect Effect	Total Effect
Carbon Emissions (ln_CE)	2.4795 **	0.4330	2.9126 **
	(2.2054)	(1.2896)	(2.1511)
Environmental Regulation (ln_ER)	1.7709 **	0.3063	2.0773 **
	(2.1235)	(1.2841)	(2.0872)
Cross-sectional $(\ln\_(CE \times ER))$	−0.4337 *	−0.0755	−0.5092
	(−1.6971)	(−1.1308)	(−1.6717)
Gross Domestic Product (ln_GDP)	0.3188 *	0.0556	0.3743
	(1.7018)	(1.1445)	(1.6734)
Disposable Income per Urban Resident (ln_DPI)	1.7623 ***	0.2913 *	2.0536 ***
	(7.0433)	(1.9294)	(8.6336)
Industrial Structure (ln_IS)	−0.2434 **	−0.0427	−0.2862 **
	(−2.2574)	(−1.3088)	(−2.1997)
Government Intervention (ln_GI)	−0.0773	−0.0156	−0.0928
	(−0.6504)	(−0.5741)	(−0.6520)
Urbanization Level (ln_UL)	0.2024 **	0.0349	0.2373 **
	(2.3238)	(1.3238)	(2.2723)
Resident Population (ln_RP)	0.0663	0.0118	0.0781
	(1.3145)	(0.9376)	(1.2940)
Population Density (ln_PD)	0.0505	0.0081	0.0586
	(0.5452)	(0.4409)	(0.5411)
Fixed Asset Investment (ln_FI)	0.0429	0.0066	0.0495
	(0.7988)	(0.6218)	(0.7943)

Note: ***, ** and * are significant at the 1%, 5% and 10% levels, respectively, and the *t*-value is in brackets.

The effect decomposition results are as follows.

Core explanatory variables: the carbon emissions level (ln_CE) had a significant promotion effect on local green technology innovation. Nevertheless, the promotion effect on the surrounding cities was relatively small and failed to pass the significance test. This showed that most of the promotion effect of carbon emissions levels on green technology innovation was local, and the spillover effect into the surrounding areas was not obvious. This result showed that although the city cluster in the Yangtze River Delta region was closely connected, the degree of coordination in pollution and carbon emissions reduction was not high enough. The investment in cooperation and innovation was not sufficient. The direct effect coefficient of environmental regulation (ln_ER) on green technology innovation was 1.7709. It passed the significance test at the 5% level, which shows that environmental regulation can significantly enhance the development of local green technology innovation. However, the spillover effect into the surrounding cities was not significant, which is inconsistent with the research conclusion of Dong and He [57]. This may be caused by the fact that to avoid the "transfer effect" of pollution between cities, the environmental policies adopted will be influenced by the policies of neighboring cities but local factors mainly determine it. Therefore, local environmental regulation has more of an effect on green technology innovation. The coefficient of the cross-term $(\ln\_(CE \times ER))$ of carbon emissions level and environmental regulation on green technology innovation was negative in terms of both direct and indirect effects. Nevertheless, the indirect effect was not significant, indicating that the substitution effect of the cross-term is more obvious in the local area and has less influence on the surrounding area.

Control variables: the direct and indirect effects of the representative factors of the two types of economic development levels (ln_GDP and ln_DPI) on green technology innovation were both positive, and the direct impact was relatively obvious, reaching 1.7663 and 0.3188, respectively; they passed the 10% significance test. The indirect effect of urban per capita disposable income was significant, indicating that the impact of economic development on green technology innovation has a certain degree of "diffusion effect", helping facilitate the progress and development of green technology in surrounding areas. The urbanization level (ln_UL) has a significant positive impact on local green technology innovation, and the coefficient of the indirect effect has an insignificant positive value. The results of this study show that the process of urbanization has brought about the agglomeration of capital, the improvement of the information exchange network and the improvement of the levels of science and education, which has created favorable conditions for the development of green technology innovation and can promote the development of green technology in the surrounding areas to a certain extent. Industrial structure (ln_IS) harmed both the direct and indirect effects, but the indirect impact was insignificant. The tertiary industry is usually featured as being knowledge- and technology-intensive and has led to many technical applications. The lower the proportion of tertiary industry in the economy, the slower the development of green technology innovation will be. The low-level industrial structure status hinders the development of local green technology innovation capabilities, but the industrial structure of the surrounding areas may not be the same. Therefore, the effect of industrial structure on green technology innovation in the surrounding regions is not strong. In addition, both demographic factors (ln_PR and ln_PD) and fixed asset investment (ln_FI) showed insignificant positive direct and indirect effects. Nevertheless, government intervention had an insignificant negative impact on green technology innovation in the local and surrounding areas.

4.4. Robustness Test

In order to test whether the conclusions of the study in this paper are robust, in this paper, a test was conducted by replacing the geographic weight matrix. The method adopted in this paper to calculate the geographic weight matrix calculated the inverse square of the distance between cities. However, the interaction between cities is related to the distance between cities and the economic development level of the province where each city is located. Therefore, this paper tested the model by replacing the economic geographic weight matrix. After the LM test and the Hausman test were performed, the model for the robustness test in this paper was changed to a spatial lag model with a time-fixed effect. The model and effect decomposition results showed no significant changes in the signs and significance of the coefficients of the core explanatory variables and cross-terms in this paper. The results were significant and the robustness results are shown in Table 6.

Table 6. Results of the robustness test.

Variable	SLM Model	Direct	Indirect	Total
ln _CE	3.7845 **	2.4418 ***	1.1312 *	3.5731 **
	(2.4641)	(3.4382)	(1.7732)	(2.1583)
ln _ ER	1.9851 **	1.0912 **	0.9278 *	1.9190 **
	(2.441)	(2.5819)	(1.9647)	(2.4954)
ln _(CE × ER)	−0.6181 **	−0.4150 **	−0.1348 **	−0.5498 **
	(−2.4688)	(−2.6784)	(−2.0774)	(−2.6106)
$Nobs = 410$			$R^2 = 0.9611$	

Note: ***, ** and * are significant at the 1%, 5% and 10% levels, respectively, and the t-value is in brackets.

5. Conclusions

Based on the panel data of 41 prefecture-level cities in the Yangtze River Delta urban agglomeration from 2010 to 2019, this paper adopted the spatial lag model (SLM) to analyze the mechanisms of green technology innovation in response to environmental regulation and changes in carbon emissions levels and examined the influence of the direct effect and indirect effect after decomposition. The research results are as follows:

(1) Environmental regulation and carbon emissions levels have a significant driving effect on local green technology innovation; that is, strict environmental regulation and higher carbon emissions levels will accelerate the progress of green technology innovation research and development and has a certain degree of spatial spillover effect on the surrounding areas, but this effect is not significant.
(2) Economic development level, urbanization level, demographic factors and fixed asset investment positively impact local green technology innovation and have a low level of spatial spillover to surrounding areas. An unreasonable industrial structure inhibits local green technology innovation, but it has no obvious impact on the surrounding areas. Government intervention has an insignificant negative impact on green technology innovation in local and surrounding areas.
(3) There is a significant substitution effect between carbon emissions and environmental regulations on green technology innovation, implying that carbon emissions and environmental regulations can replace each other as essential factors affecting green technology innovation. Nevertheless, the spillover effect of this phenomenon into neighboring regions is weak.

Based on the above conclusions, the following policies and recommendations are proposed in this paper:

(1) Policymakers should strengthen collaborative environmental governance and protection. The spatial spillover effect of inter-regional carbon emissions and environmental regulation on green technology innovation is not significant, which requires governments at all levels in the region to break through the administrative barriers, break the governance pattern of fragmentation and jointly plan and implement carbon emissions governance programs. Since the spatial scope of urban agglomerations is generally large and the development and emissions levels vary among regions, governments at all levels in urban agglomerations should implement a "demonstration-driven" governance approach and take the lead in solving environmental regulatory policies, such as cross-border environmental governance performance, cross-border ecological compensation standards and environmental system construction on a smaller spatial scale. Based on this approach, the government should give full play to the demonstration effect and gradually establish an institutional mechanism that is conducive to the synergy of pollution and carbon reduction in the whole region, to promote the continuous improvement of environmental quality and the sharing of results of carbon emissions management in urban clusters.
(2) Policymakers should guide the healthy and orderly development of the low-carbon economy. Research shows that the level of economic development has a positive impact on local green technology innovation but the spatial spillover effect on the surrounding areas is not obvious, which requires the governments in the region to continuously promote the economic growth of urban clusters, actively guide low-carbon and sustainable market demand and improve the policy environment for enhancing green technology innovation. In the central cities with greater economic and technological advantages that accelerate the development of the green economy, efforts should be made in terms of increasing the relevant scientific research investment, focusing on key green technology breakthroughs and strengthening the promotion and application of mature green technologies. At the same time, the focus should be directed toward strengthening the central cities to "feed" the surrounding areas, encouraging the release of green technology innovation dividends through green tech-

nology cooperation platforms, promoting coordinated development within the urban agglomerations and promoting the continuous "greening" of economic development within the urban agglomerations.

(3) Policymakers should improve the quality and level of urbanization. The level of urbanization can affect the development of local green technology innovation to a certain extent. Nevertheless, it has little impact on the surrounding areas, which requires the regional government to improve the level of urbanization further, give full play to the "agglomeration effect" of the central cities in the urban agglomeration and use the advanced elements brought about by the improvement of the urbanization level to realize the sustainable development of green technology innovation. At the same time, the urbanization process of non-central cities should be accelerated moderately to coordinate the urbanization development level within the whole urban agglomeration, to enhance the overall green technology innovation capability.

(4) Policymakers should accelerate the pace of industrial transformation and upgrading. An impractical industrial structure is not conducive to the development of green technological innovation, so the regional government needs to accelerate industrial transformation and upgrading in terms of two aspects. On the one hand, it should accelerate the transformation and upgrading of traditional industries with high energy consumption and high pollution, optimize the energy consumption structure, promote the transformation and upgrading of backward production capacity, promote the green transformation of traditional production capacity within the urban agglomeration, improve energy use efficiency and gradually eliminate the high energy consumption approaches of conventional industries. On the other hand, governments should actively cultivate new green production capacity that is safe, clean and efficient; focus on the research and application of new zero-carbon green energy; focus on building a technology system for the development of green emerging industries; and establish a long-term mechanism to promote the development of green technological innovation through industrial transformation.

(5) Policymakers should adopt a localized approach to environmental regulation. The interaction between carbon emissions and environmental regulation is significantly positive, proving a substitution effect between carbon emissions and environmental regulation. This situation requires governments at all levels in urban agglomerations to use environmental regulation tools reasonably, according to the level of carbon emissions in each region and formulate differentiated environmental regulation policies according to local conditions, avoiding being limited to a fixed standard. For regions with high carbon emissions levels, the intensity of environmental regulation should be increased, real-time supervision should be performed and policy implementation should be strictly promoted; for regions with low carbon emissions levels, the government should adopt moderate environmental regulation policies, encourage and guide enterprises to develop clean technologies and achieve collaborative and sustainable development within urban agglomerations through differentiated environmental regulation policies.

The study in this paper may have some limitations that can be addressed in future research. First, constrained, incentive and voluntary environmental regulations may have different impacts on green technology innovation. This paper failed to explore the effects of various environmental regulations on green technology innovation from a spatial perspective. Second, studies have suggested that there may be a non-linear relationship between environmental regulations and green technology innovation, while this paper only investigated the positive performance between them, failing to explore the threshold of different impacts of environmental regulations on green technology innovation from a spatial perspective. Therefore, in our future research, we will focus on the effects of different types of environmental regulations and carbon emissions levels on green technology innovation, using a threshold model to investigate the thresholds of the positive and negative impacts of environmental regulations on green technology innovation from a spatial perspective.

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