

The Impact of Environmental Regulation on Green Technology Innovation: Evidence from China's Core Economic Regions

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Abstract

Based on panel data from 20 provinces in China's three major economic regions from 2012 to 2021, this study explores the impact of environmental regulation on green technology innovation and its spillover effects. The results show differences in the impact of environmental regulation on green technology innovation in different economic regions, and the environmental regulation in the Pan-Pearl River Delta significantly promotes green technology innovation. In contrast, the impact of environmental regulation in the other two economic regions is not significant. The early green technology innovation in the three major economic regions has a significant impact on the future green technology innovation. Further using the spatial Durbin model, it is found that environmental regulation has a positive spillover effect on green technology innovation in the three major economic regions. There are spatiotemporal spillover effects in green technology innovation: there are negative temporal and spatiotemporal spillover effects in the Bohai Economic Rim, positive temporal and spatiotemporal spillover effects in the Yangtze River Delta, and only positive spatiotemporal spillover effects in the Pan-Pearl River Delta.

JEL classification numbers: C10, C87.

Keywords: Green technological innovation, Technological path dependence, Environmental regulation, Dynamic spatial Durbin model, Spatial spillover effect.

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1. Introduction

The ultimate goal of the global response to climate change is to ensure sustainable development through environmental protection measures, and governments and international organizations have developed laws, policies, and standards to constrain and guide enterprises and individuals to adopt more environmentally friendly technologies and production methods (Usman et al., 2024). Environmental regulation is an important tool of government management and plays an important role in promoting economic growth and achieving sustainable development (Ge et al., 2021). Environmental regulation is not only a restriction on pollution but also an incentive for green development, which plays an important role in promoting investment in environmental protection technology research and development (Fang, 2023). It plays an important role in promoting the innovation and development of green technology (Wang et al., 2024; Li et al., 2021).

As important engines of China's economy, the Bohai Economic Rim, the Yangtze River Delta, and the Pan-Pearl River Delta have a strong ability to absorb and regulate green innovation resources (Liu et al., 2021). In 2022, the total GDP of the three major economic regions accounted for nearly eighty percent of China's GDP, demonstrating the core position of these three regions in China's economic development. At the same time, environmental protection and technological innovation are regarded as the core driving forces of regional cooperation and sustainable development in their respective regions (Liu et al., 2021). The Bohai Economic Rim has achieved a significant improvement in ecological civilization, efficient utilization of resources, and regional scientific and technological innovation capabilities through joint prevention and control of the ecological environment, joint control of air pollution, and promotion of resource conservation and circular economy (Di et al., 2023). In the Pan-Pearl River Delta, the synergy between environmental protection and technological innovation has been strengthened, and the joint prevention and control of water and air pollution in cross-provincial basins has been deepened in the field of environmental protection, and ecological restoration and protection have been promoted (Peng et al., 2006). The Yangtze River Delta has focused on the organic combination of innovation-driven strategy and green development strategy (Zhu et al., 2022), especially in the protection of transboundary water bodies, pollution prevention and control, and ecological restoration (Tian et al., 2024), and has comprehensively improved the level of regional environmental quality and technological innovation through the construction of a smart supervision platform (Han et al., 2022).

From a regional perspective, this study takes the three economic regions of the Bohai Economic Rim, the Yangtze River Delta and the Pan-Pearl River Delta as the research objects, studies the regional differences of the impact mechanism of environmental regulation on green technology innovation, analyzes the spillover effect of green technology, and provides theoretical support and empirical basis for the formulation of scientific and effective environmental policies.

2. Literature Review

There are three main perspectives on the impact of environmental regulation on green technology innovation.

Most studies focus on Porter's hypothesis, which suggests that environmental regulation has a positive effect on green technology innovation. United States economist Michael E. Porter (1996) proposed that appropriate environmental regulations can stimulate innovation and thus improve the productivity and competitiveness of firms. Early in the study, scholars supported the rationality of Porter's hypothesis through empirical research. Jaffe et al. (1995) took the countries in the Organisation for Economic Co-operation and Development (OECD) as the research object and concluded that although environmental regulations do bring compliance costs to ecological protection and international competitiveness, they are usually small compared to the total costs of enterprises, and can be alleviated through technological innovation, and conclude that the existence of environmental regulations is inevitable and reasonable. With the deepening of research, Jaffe and Palmer (1997) further proposed that Porter's hypothesis is weak and strong: the "weak" hypothesis believes that environmental regulation stimulates certain types of innovation; The "strong" hypothesis suggests that environmental regulation will bring about a compensatory effect on innovation. Follow-up studies are based on the subdivision of Porter's hypothesis, and scholars conduct differentiated research based on different countries and regions. Yana Rubashkina et al. (2015) examines the positive effects of environmental regulation on the output of innovative activities in the European region, such as patent agency, in support of the "weak" hypothesis. Liu et al. (2020) proved that environmental regulation has an innovation compensation effect on green technology innovation in the case of large government subsidies, which supports the "strong" hypothesis. Piebswetter and Wackerbauer (2008) interviewed 14 manufacturing and service companies in the Munich region of southern Germany and found that environmental legislation stimulates innovation and has a "win-win" effect, i.e. reducing pollution and increasing productivity at the same time.

Based on classical economic theories, some scholars believe that environmental regulation has a negative impact on green technology innovation. Following the cost effect, before the implementation of environmental regulations, enterprises' R&D investment and R&D capabilities have tended to be relatively stable, while environmental regulations will occupy some enterprise resources, increase enterprise costs, and reduce enterprises' green innovation capabilities (Sinn, 2008). Tobias Stucki et al. (2018) explores the impact of energy-related regulations, taxes, voluntary agreements, and subsidies on the creation of green energy products through cross-sectional data of representative firms from Austria, Germany, and Switzerland, and finds that taxes and regulations are negatively correlated with green product innovation while controlling for demand-side effects.

In addition, with the help of moderating effect and threshold effect models, scholars find that the impact of environmental regulation on green technology innovation is

complex and diverse. Li et al. (2020) divided the innovation needs of resource-based industries into product innovation and industrial innovation and found that the impact of environmental regulation on product innovation and process innovation has a lag from the perspective of time. Wang et al. (2022) found that there is an inverted U-shaped relationship between environmental regulation and corporate green technology innovation at the firm level, and the impact of environmental regulation on green product innovation is greater than that of green process innovation. Based on the perspective of environmental administrative decentralization, Jiang et al. (2023) found that there is a U-shaped relationship between environmental regulation and green technology innovation, and with the gradual decentralization of administration and supervision, environmental regulation has a more significant role in promoting green technology innovation. The marginal contributions of this study are as follows: First, this study chooses to explore the regional heterogeneity of the direct impact of environmental regulation on green technology innovation from the perspective of China's three major economic regions, using static and dynamic panel models. Secondly, the dynamic spatial Durbin model is used to explore the spillover effect of green technology, analyze the impact of path dependence on green technology innovation, and put forward differentiated green technology innovation driving suggestions based on the different development models and directions of various economic regions.

3. Theoretical Mechanism Analysis

3.1 The influencing mechanism of environmental regulation on green technology innovation

Initially, environmental regulation was based on the government as the main body and enterprises as the object, and the government directly intervened in the use of environmental resources by enterprises by promulgating environmental policies and setting environmental standards (Song and Tong, 2022). Since the language of the query and the target language are the same, I cannot provide a translation (Fredriksson and Wollscheid, 2014; Yan et al., 2021).

Environmental regulation, as an institutional arrangement, has an impact on corporate behavior and decision-making in the region. Environmental regulation can be seen as an external incentive mechanism to encourage enterprises to increase investment in green technology innovation and improve their technological level and competitiveness (Eiadat et al., 2008). By stipulating environmental standards and incentives, regions can be guided to develop in a more environmentally friendly and sustainable direction (Hu, 2012). Although strict environmental regulations make enterprises face higher costs, they also turn pressure into innovation through subsidy policies, encouraging enterprises to seek more environmentally friendly and efficient technologies and production methods to reduce environmental pollution and resource consumption and improve production efficiency (Zong-hang et al., 2024; Liao et al., 2024). This means that environmental regulation can guide enterprises to increase investment in the research and development of green

technologies, and at the same time, because the environmental benefits and profit benefits brought by green technology innovation are greater than the costs and resources invested by enterprises, the innovation compensation effect is formed, and the green technology innovation is ultimately promoted (Zhong et al., 2023).

On the other hand, the cost-following theory based on classical economics argues that excessive environmental regulation increases the costs and resources invested by firms in pollution control, and firms need to adopt more expensive technologies and equipment to comply with regulations, which increases financial pressure and reduces the resources they invest in innovation, ultimately hindering innovation (Liu et al., 2022). Control imperative environmental regulation inhibits the motivation and efficiency of green innovation by imposing restrictions and requirements on the region, making it necessary for enterprises to consider environmental costs, and often has an inhibiting effect on local and surrounding green technology innovation (Fang and Shao, 2022).

In the process of green technology development, technology selection and development will be affected by environmental regulations at the same time, and also by the constraints of early technology. The green technologies in the early stage have laid the foundation for the innovation of green technologies in the current period and promoted sustainable development through experience accumulation, technology optimization, and ecosystem formation (Qu et al., 2023). Enterprises and research institutions accumulate data through experiments and practices in the early stage to reduce the risk of subsequent innovation (Sun et al., 2020). Policy support and market demand have promoted the popularization and application of green technologies, forming a favorable environment for innovation, and this positive cycle not only improves technology maturity, but also stimulates investment and R&D, and accelerates the iteration and upgrading of green technologies (Liu and Zhao, 2024). However, upfront green technology innovation may limit future innovation, resulting in technologies being locked into specific tracks and difficult to convert to more environmentally friendly emerging technologies (Stucki and Woerter, 2022). The popularization of existing technologies has become mainstream, which makes the transition to new green technologies require a lot of costs and resources, which limits the development of new technologies (Paroussos et al., 2020).

3.2 Spillover effects of green technology innovation

The spillover effect of green technology is mainly achieved through technology exchange and R&D cooperation, and the regions with more advanced green technologies will continue to expand their market influence through the application of new technologies, stimulating other regions to imitate these mature technologies and forming technological spillover effects. In addition, through cross-regional technical cooperation and the flow of technical talents, the knowledge and technology exchange between provinces is promoted, so that the provinces can efficiently invest resources in the exploration and development of cutting-edge

technologies based on existing technologies, reduce the difficulty and cost of independent research and development in other provinces, effectively promote the innovation efficiency of green technology cooperation and research and development, and promote the improvement of the level of green technology innovation in other provinces. The spillover effect of technological innovation is an important driver of economic growth and social progress, bringing long-term economic and social benefits to a wider range of interest groups through diffusion and application (Hall and Helmers, 2013).

The theoretical framework of this study is shown in Figure 1.

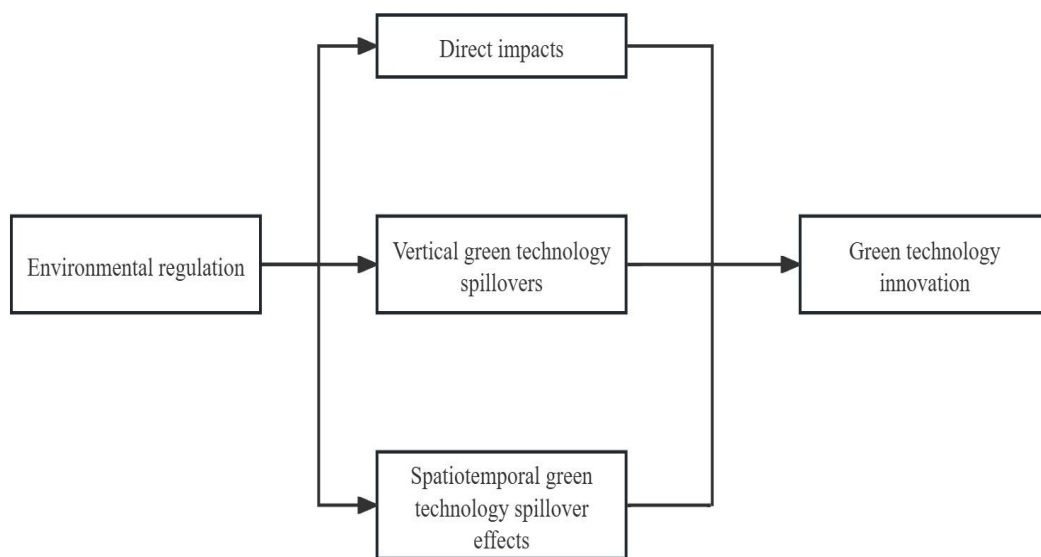


Figure 1: Theoretical framework

4. Research Design

4.1 Data sources and variable selection

This study selects data from 20 provinces in China's three major economic regions from 2012 to 2021. The Bohai Economic Rim includes Beijing, Tianjin, Hebei, Liaoning, Shandong, Shanxi and Inner Mongolia Autonomous Region; The Yangtze River Delta includes Shanghai, Jiangsu, Zhejiang and Anhui; The Pan-Pearl River Delta includes Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hunan, Jiangxi, Sichuan and Yunnan (Hong Kong and Macau S.A.R. are excluded due to missing data).

To ensure the rigor of the study, the data were processed as follows: (1) To avoid the impact of extreme values on the subsequent modeling and analysis process, the core explanatory variable Environmental Regulatory Intensity (*ERI*) was reduced by 1% at both ends; (2) To avoid the problem of "pseudo-regression" caused by the lack of data stationarity, the data of economic development level (*ED*) were

logarithmically processed. The data are all from the China Statistical Yearbook, the China Energy Statistical Yearbook, the CNRDS database, and the statistical yearbooks of various provinces. The empirical analysis part was completed using STATA 17.0.

4.2 Variable definitions

4.2.1 Dependent variable

Green Technology Innovation (*GTI*). Green technology innovation refers to a series of innovation activities, the core goal of which is to reduce the negative impact on the environment, improve the efficiency of resource utilization, and promote the protection and sustainable development of the ecological environment in the process of technology development and application. Combined with the current situation of intellectual property protection in China in recent years and the selection of green patent-related indicators by various scholars as a measure of green innovation ability, and referring to the practice of Chen et al. (2022), the number of green inventions applied for in that year was selected as a proxy variable for green technology innovation.

4.2.2 Explanatory variables

Environmental Regulatory Intensity (*ERI*). Industrial pollution is the main source of environmental problems. The investment data of industrial pollution control can reflect the efforts and investment of the government, enterprises and social parties in reducing industrial pollution and improving environmental quality. Combined with the availability of relevant policies and environment-related data in China, Zhao et al. (2021) and Gallagher et al. (2012) were selected as the proxy variable for the intensity of environmental regulation.

4.2.3 Control variables

Total Regional Population (*TP*). Since regional population growth can often bring talent to the region, it will bring about cultural and technological improvements. As the types of talent available will increase, so will the ability of the region to innovate in green technology. In this study, the total population of a region was measured using the number of resident residents in the region (Shao et al., 2022).

Degree of openness to the outside world (*ODI*). Through the introduction of foreign investment, technology and talents, opening up to the outside world can accelerate the transformation and upgrading of the industrial structure and promote high-quality economic development. Ultimately improves the level and efficiency of green technology innovation. In this study, the proportion of total imports and exports in the GDP of a region is selected to measure the degree of opening up to the outside world (Zhao et al., 2021).

Level of Economic Development (*ED*). GDP per capita is one of the important indicators to measure the level of economic development of a region or country. A high GDP per capita means a strong economy, which often boosts the region's

investment in green technology innovation, environmental protection, etc. Using the price deflator to measure GDP per capita eliminates differences in price levels between different regions, making comparisons more comparable. In this study, real per capita GDP expressed at constant prices in 2000 was used to measure the level of economic development (Wei et al., 2019).

4.3 Descriptive statistics

The descriptive statistical results of the variables are shown in Table 1. From Table 1, the mean values of green technology innovation variables in the three economic regions are 0.3606, 0.8368 and 0.2998, indicating that the overall level of green technology innovation in the Yangtze River Delta is relatively high, and the average level of green technology innovation in the Pan-Pearl River Delta is low. The minimum value of the green technology innovation variable is 0.0067 and the maximum value is 2.4072, which is in the Pan-Pearl River Delta, indicating that there is a large gap in the green technology innovation ability in the economic region. At the same time, the standard deviations of the environmental regulation variables in the three economic regions were 0.0035, 0.0013, and 0.0022, respectively, indicating that the environmental regulation intensity of the three economic regions was similar.

Table 1: Descriptive Statistics of Variables

Variables	The Bohai Economic Rim				The Yangtze River Delta				The Pan-Pearl River Delta			
	Mean	Std.	Min	Max	Mean	Std.	Min	Max	Mean	Std.	Min	Max
<i>GTI</i>	0.3606	0.4578	0.0082	2.1540	0.8368	0.5437	0.0929	2.0673	0.2998	0.4803	0.0067	2.4072
<i>ERI</i>	0.0042	0.0035	0.0001	0.1935	0.0023	0.0013	0.0002	0.0065	0.0024	0.0022	0.0001	0.0116
<i>TP</i>	0.4454	0.2911	0.1373	1.0170	0.5749	0.2145	0.2399	0.8505	0.5516	0.2976	0.0910	1.2684
<i>ODI</i>	0.3483	0.3099	0.0561	1.3541	0.5424	0.3308	0.1122	1.2935	0.2395	0.2345	0.0271	1.0896
<i>ED</i>	9.5682	0.5319	8.9002	10.7805	9.7841	0.5529	8.8641	10.5890	9.1519	0.3383	8.5984	9.8494

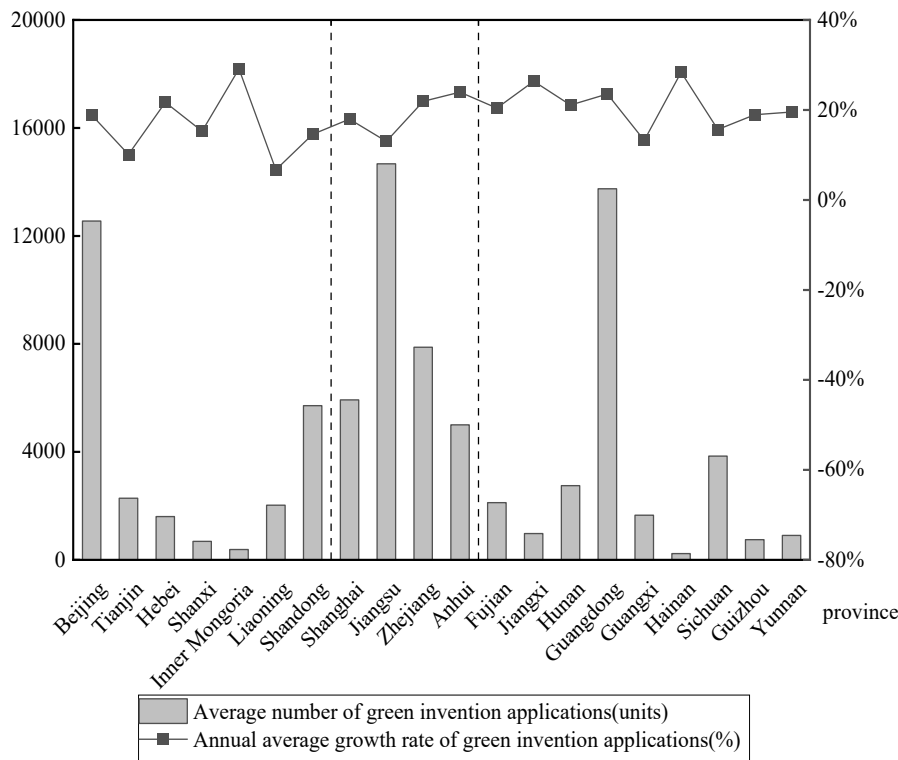


Figure 2: Average Number and Annual Growth Rate of Green Invention Applications in 20 Chinese Provinces (2012-2021)

Figure 2 shows the average number and average annual growth rate of green invention applications in 20 provinces in the three economic regions, and the average number of green invention applications in Jiangsu, Guangdong, and Beijing is 14,671.6, 13,743.4 and 12,549.4, respectively, ranking in the top three. The number of green invention applications in the economic region is highly concentrated, and the number of green invention applications in one province is much higher than the number of green invention applications in other provinces in each economic region, that is, there are "leaders" in green technology innovation in the economic region. The Inner Mongolia Autonomous Region had the highest average annual growth rate of 29.12% in the number of green invention applications, and the lowest in Liaoning Province at 6.72%.

4.4 Model specification

The impact of environmental regulation on green technology innovation in the three major economic zones is studied by constructing a two-way fixed-effect panel model, and the model construction is shown in Equation 1.

$$GTI_{it} = \lambda_i + \gamma_t + \beta_1 GTI_{it-1} + \beta_2 ERI_{it} + \sum_q \delta_q controls_{q,i,t} + \mu_{it} \quad (1)$$

Where GTI_{it} is the dependent variable representing green technology innovation. When $\beta_1 = 0$, the model is a static panel model; when $\beta_1 \neq 0$, the model includes the first-order lag of the dependent variable. ERI_{it} represents the explanatory variable for environmental regulation intensity, $controls_{q,i,t}$ are control variables (where $q = 1,2,3$; $i = 1,2, \dots, 20$; $t = 2012, \dots, 2021$), λ_i is the individual fixed intercept term, γ_t is the time fixed intercept term, and μ_{it} is the disturbance term, varying with individuals and time and uncorrelated with λ_i .

The dynamic spatial Durbin model is used to explore the spillover effects of green technology innovation between economic regions, as shown in Equation 2.

$$\begin{aligned} GTI_{it} = & \alpha + \beta_0 GTI_{it-1} + \rho \sum_{j \neq i} W_{ij} GTI_{it} + \varphi \sum_{j \neq i} W_{ij} WGTI_{it-1} \\ & + \beta_1 ERI_{it} + \gamma \sum_{j \neq i} W_{ij} ERI_{it} + \sum_q \delta_q controls_{q,i,t} \\ & + \sum_q \delta_q W_{ij} controls_{q,i,t} + \mu_i + \eta_t + \varepsilon_{it} \end{aligned} \quad (2)$$

Where GTI_{it} is the dependent variable representing green technology innovation. When $\beta_0 \neq 0$, $\varphi \neq 0$, the model is a dynamic spatial Durbin model including the first-order lag of green technology innovation. ERI_{it} is the environmental regulation intensity, W_{ij} is the spatial weight matrix, $controls_{q,i,t}$ are control variables (where $q = 1,2,3$; $i = 1,2, \dots, 20$; $t = 2012, \dots, 2021$), α is the constant term, μ_i and η_t represent individual and time effects, respectively, and ε_{it} is the disturbance term, varying with individuals and time.

5. Empirical Results and Analysis

5.1 The direct impact of environmental regulation on green technology in the three major economic regions

The three major economic regions have different development orientations in the early stage of establishment, and each region has different ways and ideas for sustainable development, and the results of the impact of environmental regulation on green technology innovation in the three major economic regions are shown in Table 2.

Table 2: The results of the panel regression of the three major economic regions

Variable	The Bohai Economic Rim		The Yangtze River Delta		The Pan-Pearl River Delta	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
<i>L.GTI1</i>		1.1012***		0.5065**		0.6566***
<i>ERI</i>	-3.2608	1.0949	-8.9514	-9.1283	22.8778***	10.4159**
<i>TP</i>	7.1144***	-1.3259	3.0759	2.4673	11.8621***	3.7893**
<i>ODI</i>	-1.0767***	0.2193**	-0.2386	-0.5849	-0.2603	-0.4018
<i>ED</i>	0.7637***	0.0062	-1.8558***	-0.8053	0.1732	0.1739
<i>_cons</i>	-9.7263***	0.4655	17.3764***	7.2863	-7.8205***	-3.4813
<i>Individual-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	70	63	40	36	90	81
<i>R²</i>	0.9472	0.9966	0.9696	0.9811	0.9684	0.9878

There are differences in the impact of environmental regulation on green technology innovation in the three major economic regions, and there is a significant positive impact of environmental regulation on regional green technology innovation in the Pan-Pearl River Delta. The impact of environmental regulation on regional green technology innovation in the Bohai Economic Rim and the Yangtze River Delta is not significant. For the Pan-Pearl River Delta, which has a higher level of urbanization and a more developed manufacturing and service industry, these industries have a more urgent need for environmental regulation and green technology innovation. To maintain a competitive advantage, enterprises are more inclined to adopt green technology innovation to reduce production costs and improve resource efficiency. In recent years, the Bohai Economic Rim has been more inclined to maintain the existing production model rather than invest in new technologies, due to the environmental demonstration effect of the Beijing center in the early stage, and green technology tends to mature. Although the Yangtze River Delta has the development orientation of "innovation lake area" and "happy city" and is guided by green and low-carbon cycles, the Yangtze River Delta has

accumulated rich experience in green technology innovation in the early development process.

The lag term added to the model of green technology innovation constitutes a dynamic panel model, and the lag terms of green technology innovation in the three economic regions are all significantly positive, and the results show that there is a certain continuity in green technology innovation in the three economic regions. The Pan-Pearl River Delta has a high level of economic development, rich experience, and technology accumulated in the early stage, and the current green technology innovation has a certain dependence on the early technology path. At the same time, the region is one of the regions with the most economic development vitality and potential in the country, and its sensitivity to new technologies and new ideas and rapid adaptability is strong, which enables the region to reform and upgrade old technologies more quickly. For the Bohai Economic Rim, the impact of green technology innovation in the early stage on the later stage is significantly positive. The strong economic strength and abundant innovative talents in the Bohai Economic Rim provide the necessary support for green technology innovation, which makes it easier to form the inertia of technological innovation and form a virtuous circle of green technology development. For the Yangtze River Delta, the early green technology innovation has a significant positive impact on the current green technology innovation, but the regression coefficient is small at 0.5065. The Yangtze River Delta has a long history of industrialization, with a well-established industrial chain and mature industrial clusters, so that enterprises in the region can use the existing supply chain and resources to make innovative breakthroughs and improve the current ability of green technology innovation.

5.2 Robustness test

In this study, the following methods were used to verify the robustness of the model: (a) provinces were excluded: individuals were randomly excluded for testing; (b) Shorten the sample time: shorten the sample time to 2012-2020 for testing. The robustness regression results in Tables 3 and 4 are consistent with panel regression, indicating that the model is robust.

Table 3: Robustness Test: Excluding Provinces

Variable	The Bohai Economic Rim		The Yangtze River Delta		The Pan-Pearl River Delta	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
<i>L.GTI</i>		1.1078***		0.4011** 9.8664		0.6361***
<i>ERI</i>	-0.3522	1.7864	-7.4938	9.8664	21.9998**	22.6094***
<i>TP</i>	7.4494***	-1.3278	0.8873	2.8028	12.1100***	3.7521*
<i>ODI</i>	-1.0992***	0.2327**	0.0038	-0.7938	-0.2171	-0.4487
<i>ED</i>	0.8489***	0.0121	-2.2827***	-1.0035*	0.1723	0.2178
<i>_cons</i>	-10.9101***	0.4361	22.5309***	8.5717	-8.0897**	-4.0623
<i>Individual-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	60	54	30	27	80	72
<i>R²</i>	0.9463	0.9966	0.9793	0.9933	0.9685	0.9887

Table 4: Robustness Test: Shortening Time

Variable	The Bohai Economic Rim		The Yangtze River Delta		The Pan-Pearl River Delta	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
<i>L.GTI</i>		1.1602***		0.5128*		0.6434***
<i>ERI</i>	-8.4792**	2.0821	-5.4434	-5.2500	22.1458***	11.2766**
<i>TP</i>	5.9117***	-0.8924	4.4780*	3.7549*	11.9349***	4.1444*
<i>ODI</i>	-0.9425***	0.2922***	-0.0723	-0.4334	-0.1655	-0.3528
<i>ED</i>	0.7759***	-0.0615	-1.7286***	-0.9188	0.0577	0.1363
<i>_cons</i>	-9.3480***	0.8748	15.1740**	7.5476	-6.8271**	-3.3404
<i>Individual-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	63	56	36	32	81	72
<i>R²</i>	0.9620	0.9963	0.9685	0.9820	0.9651	0.9846

5.3 Endogeneity test

Environmental regulations in various economic regions usually limit and manage different types of pollutant emissions, so there is a close correlation between pollutant emissions and environmental regulation, which can be used as a reasonable tool variable for environmental regulation. Considering the availability of data and the comprehensiveness of pollution emission measurement, the comprehensive pollution index (*PI*) constructed by the entropy method was used as the instrumental variable of the endogenous test. The instrumental variable regression method was used to estimate the impact of environmental regulation on green technology innovation and test its endogeneity. The test results are shown in Table 5.

Table 5: Results of instrumental variable regression estimation

Variable	The Bohai Economic Rim		The Yangtze River Delta		The Pan-Pearl River Delta	
	First	Second	First	Second	First	Second
	<i>ERI</i>	<i>GTI</i>	<i>ERI</i>	<i>GTI</i>	<i>ERI</i>	<i>GTI</i>
<i>PI</i>	0.0022***		0.0013**		0.0007	
	(3.74)		(2.20)		(0.62)	
<i>ERI</i>		-72.3394***		-532.5147**		-1,009.5228
		(-2.80)		(-2.34)		(-0.61)
<i>Control variables</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Weak identification test</i>	13.973***		4.831***		0.402	
<i>Under identification test</i>	12.385***		4.852**		0.382	
<i>N</i>	70	70	40	40	90	90
<i>Robust F</i>	11.5643		11.5643		11.5643	

The results of the Weak identification test showed that the Cragg-Donald Wald F-value was greater than the 10% horizontal threshold of Stock-Yogo. The LM statistic of the Underidentification test rejects the null hypothesis at the 1% significance level. After considering the endogeneity problem, the regression coefficient of the impact of environmental regulation on green technology innovation is significant at the 1% level, indicating that the benchmark model results have a certain degree of robustness.

6. Further Exploration

Based on the geographical distance between provinces and provincial capitals, the reciprocal of the geographical distance matrix was constructed as the weight matrix. Table 6 shows the results of the dynamic spatial Durbin model of the three major economic regions in China, and the spatial autocorrelation coefficient ρ of each region is positive and significant at the 1% level, indicating that there is a significant spatial spillover effect. Among them, the estimated coefficients of $W \times ERI$ are 5993.3070, 15262.4294, and 1263.2627, all of which are significant at the 1% level. The above results show that environmental regulation in each province in the three major economic regions has a positive spillover effect on green technology innovation.

Table 6: Results of the Durbin model of the dynamic space between the three major economic regions

Variable	(1) The Bohai Economic	(2) The Yangtze River Delta	(3) The Pan-Pearl River
<i>L.GTII</i>	-5.5625***	4.0936***	0.0692
	(-107.23)	(16.88)	(1.05)
<i>L.WGTII</i>	-20.8989***	15.4412***	1.4326***
	(-67.97)	(24.05)	(3.50)
<i>W×ERI</i>	5997.3070***	15262.4294***	1263.2627***
	(400.08)	(205.94)	(49.86)
<i>TP</i>	-59.0669***	-97.1481***	23.3334***
	(-99.00)	(-56.09)	(19.12)
<i>ODI</i>	1.9163***	15.7446***	2.2042***
	(26.35)	(53.12)	(9.98)
<i>ED</i>	-0.3793***	-23.3313***	-0.4342***
	(-8.03)	(-63.62)	(-2.71)
<i>Spatial rho</i>	3.8650***	2.5378***	2.5227***
	(14.90)	(10.64)	(7.71)
<i>N</i>	63	36	81
<i>R</i> ²	0.0128	0.1691	0.5290

For the Bohai Economic Rim, the time lag term and the spatiotemporal lag term of green technology innovation are negative, indicating that the technological

innovation in the early stage limits the development of new technologies at the current stage to a certain extent. At the same time, the level of green technology innovation in other provinces in the region in the early stage has a negative spillover effect on the green technology innovation of the province. Between neighboring provinces, companies may choose to adopt a more conservative strategy of technological renewal or imitate existing technologies in advanced technology regions, thus reducing the level of green technology innovation in the region. The estimation coefficient of $W \times ERI$ is significantly positive, which proves that environmental regulation in the Bohai Economic Rim has a positive spillover effect on green technology innovation. With Beijing as the center, the Bohai Economic Rim will form an environmental demonstration effect and encourage neighboring provinces to take similar measures, to enhance the R&D and innovation of green technologies in the whole region.

For the Yangtze River Delta, the coefficients of the time lag term and the time lag term are significantly positive, reflecting the accumulation and development of the experience and capabilities in the field of green technology in the Yangtze River Delta in the past. Through the advanced technological infrastructure, talent pool, and innovation policy environment in the region, a continuous innovation momentum has been formed, so that the previous innovation achievements can continue and promote current innovation activities. The estimation coefficient of $W \times ERI$ is positive, indicating that environmental regulation in the Yangtze River Delta has a positive spillover effect on green technology innovation. Due to the high concentration of technology-intensive industries in the region and the implementation of policies to promote industrial upgrading, the core provinces of regional innovation will share and exchange experience in green technology innovation with other provinces in the region as the center, to guide and stimulate the development of green technologies in the region.

For the Pan-Pearl River Delta, the coefficient of the spatiotemporal lag term of the model is significantly positive. The results show that the early green technology innovation in other provinces has promoted the development of new technologies in the current region to a certain extent. The Pan-Pearl River Delta is the core economic area with a strong manufacturing and high-tech industrial base, and the successful experience of green technology innovation R&D and application in the early stage can be adopted or imitated by enterprises in neighboring provinces, thereby driving the overall level of green technology innovation in the region and forming a positive spatial spillover effect. The estimation coefficient of $W \times ERI$ is positive, indicating that environmental regulation in the Pan-Pearl River Delta has a positive spillover effect on green technology innovation. The current environmental regulation policies can promote the development of green technologies between provinces in the Pan-Pearl River Delta, and the idea of regional collaborative innovation provides a good platform for innovation and stimulates enterprises and research institutions to invest in green technology innovation.

Table 7: The results of the decomposition of the spatial effects of the three major economic regions

Variable	Type of effect		(1) The Bohai	(2) The Yangtze	(3) The Pan-Pearl
<i>ERI</i>	Direct effects	ST	2264.5728	8397.9856	-170.2695
			(0.20)	(0.07)	(-0.26)
		LT	307.8568***	-1267.7195***	11.7451
			(12.24)	(-61.20)	(0.35)
	Indirect effects	ST	-794.2749	-2453.2126	572.4034
			(-0.07)	(-0.02)	(0.87)
		LT	-80.4891***	-44.6524	704.0034***
			(-3.45)	(-1.17)	(7.49)
	Total effect	ST	1470.2979***	5944.7729***	402.1340***
			(19.02)	(15.73)	(10.48)
		LT	227.3677***	-1312.3719***	715.7486***
			(119.29)	(-67.71)	(5.69)

As can be seen from Table 7, the direct effect coefficient of environmental regulation intensity in the Bohai Economic Rim is significantly positive in the long run, indicating that the increase in environmental regulation intensity has a positive and direct impact on green technology innovation in the Bohai Economic Rim in the long run. In addition, the indirect effect coefficient is significantly negative in the long run, that is, the environmental regulation of neighboring provinces has a negative spillover effect on the green technology innovation of the province in the long run. In the Yangtze River Delta, the direct effect coefficient of environmental regulation intensity is significantly negative in the long run, which confirms that environmental regulations in the region inhibit the development of green technology innovation. In the Pan-Pearl River Delta, the indirect effect coefficient of environmental regulation intensity is significantly positive in the long run, that is, the environmental regulation of neighboring provinces has a positive spillover effect on green technology innovation in the region.

7. Conclusion

Based on the annual data of 20 provinces in China's three major economic regions from 2012 to 2021, this study analyzes the impact of environmental regulation on green technology innovation and concludes as follows: (1) There are differences in the impact of environmental regulation on regional green technology innovation in different economic regions, but green technology innovation has a positive effect on regional green technology innovation in the early stage. (2) There is a positive spatial spillover effect of environmental regulation on green technology innovation in the three major economic regions. Due to regional differences, there are different spatiotemporal spillover effects of green technologies.

Green technology innovation is the key path to achieve China's sustainable development, and environmental regulation is an important guarantee in promoting the development path of green technology innovation, so environmental regulation is of great strategic significance to "adapt measures to local conditions". Based on the empirical conclusions of this study, the following policy recommendations are proposed:

First, form a legal system for environmental protection with regional characteristics, and strengthen the implementation and supervision of environmental regulations. Local governments should formulate differentiated environmental regulatory policies according to different regional development goals and make timely adjustments according to the implementation of environmental regulations to ensure the effective implementation of environmental regulatory policies. The Yangtze River Delta can focus on the integrated development of maritime affairs, strengthen the protection and management of water resources, promote the construction and upgrading of sewage treatment facilities, and ensure the cleanliness of water bodies and the sustainable use of water resources. The Bohai Economic Rim can give full play to the advantages of Beijing's science and technology innovation center, build a base for the transformation of scientific and technological achievements, and radiate the advantages of talent training.

Second, strengthen inter-regional cooperation, encourage diversified investment, and improve the continuity of talent training. Green technology and innovative talents have not formed a mutually beneficial cooperative relationship under the existing technological framework. In this regard, the establishment of cross-regional green technology innovation cooperation mechanisms should be encouraged, and research and development of multiple technology paths should be carried out to broaden the horizon of green technology development.

Third, make full use of the advantages of clusters to stimulate the vitality of green innovation from two aspects: rights and interests protection and government support. Improve the intellectual property protection system, ensure the legitimate rights and interests of innovation achievements, and enhance the stability and sustainability of innovation activities. Establish green innovation centers with regions as the main body to enhance the agglomeration effect of technology research and development capabilities and innovation activities.

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