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DOES ENVIRONMENTAL DECENTRALIZATION PROMOTE GREEN TECHNOLOGY INNOVATION? —EMPIRICAL EVIDENCE BASED ON RIVER CHIEF SYSTEM

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Highlights:
- studied the impact of environmental decentralization on technological innovation;
- we used a basic regression model to examine the influence of driving factors;
- the spatial spillover effect was tested using a spatial double difference model;
- green technology innovation determines the direction of technological progress.

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Abstract. Based on the River Chief System policy characterized by Environmental Decentralization, a double difference model was used to empirically test the impact of Environmental Decentralization on Green Technology Innovation using panel data from 283 cities in China from 2005 to 2022. Research has found that there is a significant positive impact between Environmental Decentralization and Green Technology Innovation. Furthermore, the introduction of the spatial double difference model verifies the significant positive spatial spillover effect of Green Technology Innovation. Robustness testing is also conducted through a series of methods, such as replacing explanatory variables, to confirm the robustness and credibility of the results.

Keywords: River Chief System, green innovation, Environmental Decentralization, difference-in-differences models.

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1. Introduction

In recent years, the global economy has shifted focus from rapid growth to high-quality development, as nations face the dual challenge of improving both economic efficiency and overall quality. This transition is particularly pressing for developing countries, many of which have endured rapid industrialization, leading to significant challenges such as resource depletion, environmental pollution, and ecological degradation. Amid this global context, the need for a green transformation to ensure sustainable development has become more urgent than ever. As the world's second-largest economy, China is undergoing this transition. While recent improvements in its ecological environment signal progress, it remains at the critical juncture of the "Environmental Kuznets Curve." High levels of pollution emissions and challenges in resources and technological development persist, highlighting the complexities of balancing growth with ecological sustainability. Thus, addressing these challenges is not only critical for China but also for other countries facing similar dilemmas. A central theme of this study is the role of green technological innovation (GTI) in facilitating this transition. Green technology is recognized globally as a key driver of environmental transformation, helping reduce the costs of environmental governance and mitigate the negative externalities of economic activities (Andreoni & Levinson, 2001).

For developing regions, the establishment of a Green Technology Innovation system is inherently tied to effective regional environmental governance. The success of such governance efforts depends on their capacity to foster innovation, with the dual goals of ecological sustainability and technological advancement guiding the process (Lin & Zhang, 2023). Given these considerations, this study aims to explore how regional governments can enhance environmental governance by strengthening incentives for local green innovation. The ability of local governments to design and implement policies that support green technology development will be pivotal in driving broader environmental goals. Understanding how these factors interact will be essential for crafting effective strategies to foster sustainable development and improve environmental outcomes (Wang et al., 2023).

Oates (1972) proposes that under the decentralization model, local governments have the opportunity to leverage their unique informational advantages to enhance the

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efficiency of environmental systems and policies. By doing so, they can assume a proactive role in environmental governance within the framework of local development. while the central government is responsible for coordinating, supervising, and managing national environmental affairs.

(Aronsson, 2010). The central government, on the other hand, is only responsible for coordinating and supervising the national environmental affairs, giving full play to the synergies between the central and local governments, and enhancing the overall effectiveness of pollution control and environmental services (Ahmad & Satrovic, 2023). From the perspective of our national environmental management system reform practice, the connotation of Chinese decentralization is not only the choice between centralization and decentralization, but also reflects how the central and local governments can solve the environmental problems through coordination and cooperation, and truly maximize the efficiency of environmental governance (Hao et al., 2021). Consequently, a moderate degree of Environmental Decentralization enhances the capacity of local governments to provide subsidies for Green Technology Innovation, promotes the promotion of environmental protection technologies and reinforces the implementation of cleaner production methods as well as end-of-pipe treatment technologies.

Previous studies demonstrate that Environmental Decentralization improves enterprise productivity and innovation by strengthening the enforcement of environmental regulations (Zhang et al., 2023). It has been shown that Environmental Decentralization can improve the productivity and innovation of enterprises by improving the intensity of environmental regulation, effectively reducing pollution emissions and improving environmental quality, and realizing both environmental and economic effects (Hao et al., 2022). Environmental Decentralization signifies the distribution of management authority over environmental matters between central and local governments. However, there is currently no consensus on the measurement methods for Environmental Decentralization (Tiebout, 1956). Given the unique characteristics of environmental management, three distinct approaches will be utilized for measurement. First, both fiscal decentralization and Environmental Decentralization illustrate the distribution of management authority between central and local governments (Sun et al., 2023), and considering that environmental affairs may involve fiscal transfers, fiscal decentralization has been used as a substitute for Environmental Decentralization in a few previous studies, but fiscal decentralization focuses more on economic and political benefits (Satrovic et al., 2024). Second, Environmental Decentralization is measured using the number of staff in the environmental protection system at different levels of government, reflecting the changes in the management system of environmental affairs in different sectors (Qi et al., 2014). However, confined to data availability and the fact that environmental management affairs involve the joint role of multiple departments such as environmental protection and water conservancy, using a single number of environmental protection system staff is biased. Third, using the proportion of local laws and regulations, constructing dummy variables and constructing a multi-indicator evaluation system to characterize Environmental Decentralization, a more systematic approach is to use the local environmental governance policy "River Chief System" to reflect the autonomy of local governments in the management of rivers under their jurisdiction, and in this way, reflecting the process of decentralization of environmental governance to the local government (Grooms, 2015).

Research on Green Technology Innovation originated in the 1950s and 1960s, when the concept of green technology was introduced in the socio-ecological movement in the industrialization of Western countries, and is considered to be a general term for technologies, processes or products that reduce environmental pollution and energy consumption (Chen et al., 2023). However, the intricate nature of the characteristics associated with Green Technology Innovation has resulted in a lack of consensus within the academic community regarding its precise definition (Wang & Ahmad, 2024). In the long run, only by relying on green technology-oriented technological progress can we truly and effectively solve the problem of environmental pollution and realize resource conservation and ecological protection (Grégoire-Zawilski & Popp, 2024). The measurement methods of existing studies on green technological innovation can be categorized into two main groups (Chang et al., 2023). One is the directly adoptable data represented by green R&D investment, new product sales, number of green patents, etc. Most of them are directly characterized using absolute amounts, in particular, the metrics concerning green patent applications, the volume of patents awarded, and the patent conversion rates, all derived from the catalog of green technologies, align with the regional and corporate green development objectives. These metrics serve as clear indicators that can effectively illustrate the outcomes of innovations in green technology (Hu et al., 2023). The second is the green technological innovation efficiency indicator characterized using parametric and non-parametric methods, such as green total factor productivity and comprehensive indicator evaluation system. Considering the relativity of the indicator of green technological innovation efficiency, it cannot better explain the absolute changes in the level of innovation (Dou & Gao, 2023). For this reason, this paper utilizes the volume of green patent applications from each prefecture-level city as an indicator to gauge the capacity for urban green technological innovation. Green patents serve as a clear and direct reflection of the tangible outcomes produced by activities related to green technological innovation.

A review of existing literature reveals that existing studies lack a description of Environmental Decentralization as an exogenous environmental policy and a systematic assessment of its impact on Green Technology Innovation (Ren et al., 2023). Therefore, this paper utilizes the River Chief System as a quasi-natural experiment, analyzing panel data from 283 prefecture-level cities and higher, spanning the years 2005 to 2022. It investigates the dynamic effects of this system on Green Technology Innovation, drawing on theories from environmental and institutional economics. The marginal contributions of this paper are: (1) The use of the quasi-natural experiment of the River Chief System to measure Environmental Decentralization. Unlike conventional regulatory approaches documented in existing scholarship, this hierarchical accountability mechanism enables novel insights into how territorially segmented yet vertically integrated governance structures mediate technological responses. The RCS's unique institutional design, combining centralized target-setting with decentralized implementation, offers an unprecedented context to disentangle the paradox of Environmental Decentralization's dual effects on innovation incentives.

(2) The spatial difference-in-differences (SDID) framework advance spatial econometric rigor, which systematically quantifies inter-regional knowledge spillovers often neglected in policy evaluations. By incorporating spatial weight matrices and spatial autoregressive terms, we reveal significant cross-jurisdictional GTI diffusion patterns where conventional DID models would erroneously assume geographical independence. This methodological innovation addresses critical limitations in environmental policy analysis that traditionally treats administrative boundaries as impermeable barriers to knowledge transfer.

(3) We develop a dual-path analytical framework that reconciles competing theoretical perspectives on decentralization's innovation impacts. Through mechanism decomposition, we demonstrate how the RCS simultaneously activates "innovation environment effects" (via top-by-top political competition and bottom-by-bottom public scrutiny) and "technology R&D effects" (through input augmentation and expenditure crowding-out). This nuanced differentiation explains previously contradictory findings by revealing how Environmental Decentralization creates simultaneous enabling and constraining conditions for GTI – a critical advancement beyond unidimensional analyses dominating current literature.

Therefore, in order to systematically investigate how environmental decentralization affects green technology innovation, this paper next develops a theoretical framework. The following section provides a comprehensive analysis of the transmission mechanisms and dual effects of decentralization policies on regional green innovation outcomes.

2. Theoretical analysis

This paper analyzes the transmission mechanism of Environmental Decentralization on green technological innovation and its combined effects, which can be divided into positive promotion, negative hindrance and uncertainty.

1. Promoting Effect of Environmental Decentralization on Green Technological Innovation

Environmental decentralization clarifies the distribution of responsibilities between central and local governments, empowering local authorities to manage environmental affairs more effectively. This clear allocation of authority curtails local inaction and encourages stronger efforts to address pollution and protect the environment. As local governments have better knowledge of regional conditions, they are better positioned to balance economic development with environmental objectives, thereby improving resource allocation efficiency. Additionally, local governments, by raising environmental standards, create incentives for businesses to innovate, particularly in pollution control technologies. Increased government R&D expenditure further supports green technological innovation by offsetting the costs enterprises incur when adopting green technologies (Wang et al., 2022).

2. Negative Hindrance of Environmental Decentralization on Green Technological Innovation

Under the political promotion system, local government officials may prioritize short-term, high-return projects to secure career advancement, while neglecting long-term, high-risk green technological innovations (Xiao et al., 2025). Decentralization can also lead to "competition by the bottom," where local governments lower environmental standards to attract investment, undermining green technological innovation. This competition between local governments can cause market fragmentation, reducing the resources available for technological innovation and diminishing the quality of environmental public goods and services (Yuan et al., 2025). Furthermore, local governments may adopt merely symbolic compliance with central government policies or maintain a passive, wait-and-see attitude, which does not foster a supportive environment for green technological innovation.

3. Comprehensive Mechanism Analysis

(1) Top-by-Top Competition Mechanism. This mechanism occurs when local governments, motivated by the need to protect their environmental and economic performance, strictly implement environmental protection policies (Zeng et al., 2020). By clarifying their responsibilities in environmental governance, local authorities are incentivized to pursue green innovation to enhance their performance indicators, such as pollutant emissions reductions or green GDP. This proactive approach encourages businesses to invest in cleaner technologies, creating a synergistic relationship between governance and innovation, which ultimately drives regional sustainable development.

(2) Bottom-by-Bottom Competition Mechanism. In contrast, the bottom-by-bottom competition mechanism arises when local governments, under pressure to achieve economic growth and secure political promotions, prioritize short-term projects with quicker returns. This focus on immediate economic results often comes at the expense of long-term green technological innovation. As local governments engage in "race-to-the-bottom" behaviors—such as lowering environmental standards to attract investment—green innovation is stifled. This type of competition can lead to market fragmentation and hinder

the creation of a supportive innovation ecosystem (Abam et al., 2023).

(3) Increased Investment Mechanism. Environmental Decentralization often leads to higher costs for enterprises in terms of pollution control and compliance with local environmental standards. To offset these costs, businesses are more likely to invest in green technologies that improve their overall environmental efficiency. This mechanism encourages innovation, as companies seek to develop more sustainable production methods to reduce their regulatory burdens. Studies show that such incentives, like green fiscal expenditures, significantly promote the adoption of energy-efficient technologies and innovation in industrial processes (Fang et al., 2024). By encouraging businesses to invest in R&D, local governments can stimulate green innovation and enhance regional sustainability.

(4) Crowding Out Expenditure Mechanism. Under stringent environmental regulations, enterprises may face increased financial pressures to meet compliance standards. This can lead to a phenomenon known as "crowding out," where resources that could have been invested in technological innovation are instead used to comply with environmental regulations. This diversion of resources reduces the capacity of enterprises to invest in research and development for green technologies, hindering innovation in the long run (Farza et al., 2021). As local governments set high environmental protection standards, the cost burden on businesses may reduce the overall efficiency of green innovation, particularly for smaller companies with limited resources (Fang et al., 2022).

Among them, the top-by-top and bottom-by-bottom competition mechanisms form the innovation environment effect, while the mechanism of increasing inputs and crowding out funds forms the technology research and development effect, and the transmission mechanism of Environmental Decentralization affecting Green Technology Innovation is shown in the Figure 1.

Figure 1 illustrates the mechanisms through which Environmental Decentralization affects green technological innovation. These mechanisms involve two key effects: the **innovation environment effect**, influenced by top-by-top and bottom-by-bottom competition mechanisms, and the **technology R&D effect**, shaped by mechanisms for increasing inputs and crowding out expenditures. Both effects result in three potential outcomes—positive, negative, or neutral—leading to five possible scenarios. First, when both effects are positive or negative, they directly promote or hinder green technological innovation. Secondly, if one effect is positive and the other negative, the overall impact depends on their relative strengths. Thirdly, when both effects are neutral, no significant influence on green technological innovation is observed.

Environmental Decentralization's impact on green innovation depends on balancing compensatory and offsetting effects. In the context of environmental degradation and resource scarcity, stronger governance intensifies this balance. However, the relationship between China's Environmental Decentralization policies and regional green technological innovation remains complex, making it challenging to definitively determine whether decentralization promotes or hinders innovation through theoretical analysis alone. Therefore, this study aims to empirically investigate the specific impacts of Environmental Decentralization within China.

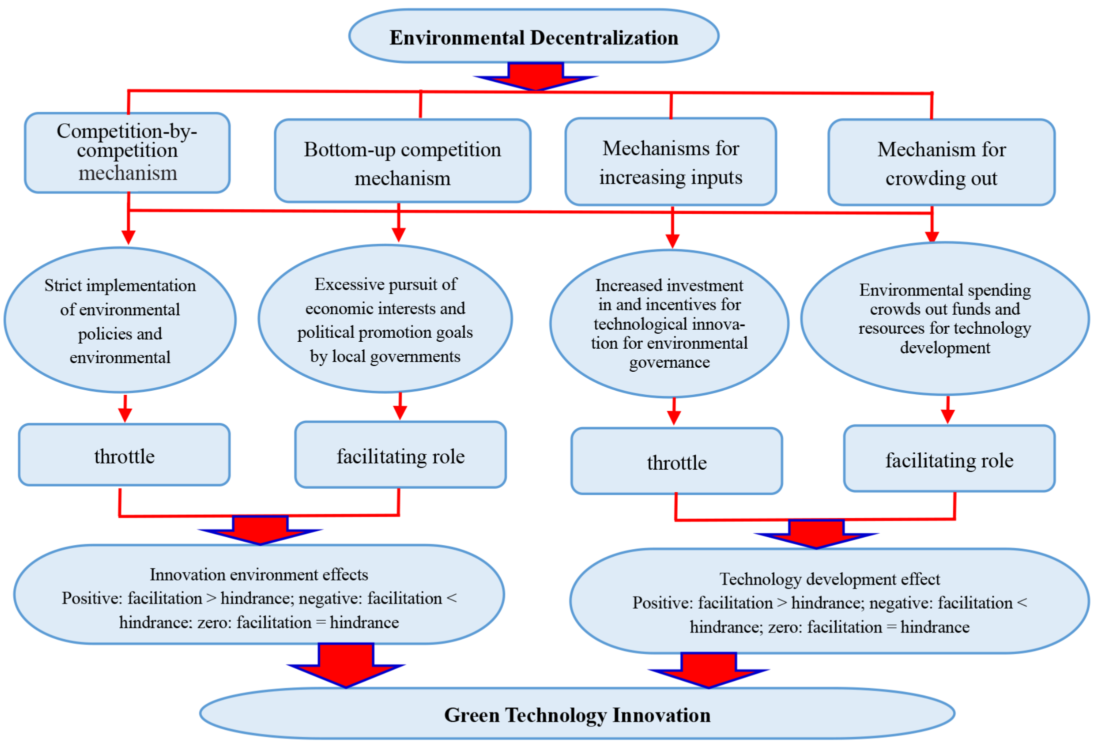


Figure 1. Transmission mechanism of Environmental Decentralization affecting Green Technology Innovation

Based on the theoretical framework and Figure 1, the following hypotheses are proposed: Green technological innovation exhibits spatial spillover effects. Regional green innovation generates spillover benefits, enabling knowledge sharing and policy synergy among neighboring areas, amplifying its overall impact; Environmental Decentralization policies enhance green technological innovation. By empowering local governments to manage environmental affairs, decentralization encourages stricter governance and incentive enterprises to invest in green R&D, fostering innovation and regional sustainability.

According to the analysis presented in Figure 1, the mechanism through which Environmental Decentralization influences green technological innovation is elucidated, through the promotion of the top-by-top competition mechanism and the size of the hindering effect of the bottom-by-bottom competition mechanism, we can derive three kinds of positive and negative innovation environment effect and zero effect; through the promotion of the mechanism of increasing inputs and the size of the hindering effect of the mechanism of crowding out expenditures we can derive three kinds of positive and negative innovation R&D effect and zero effect, and we can derive a total of five kinds of cases, from this It can be concluded that the sign of the technological innovation environment and technology R&D effect of positive and negative and the size of the role determines the impact of Environmental Decentralization on green technological innovation, which in turn can determine the comprehensive role of the effect. First, when both the innovation environment effect and the technology R&D effect are either positive or negative, they exert a direct influence on Green Technology Innovation, either promoting or hindering it. Secondly, when one of these effects is positive while the other is negative, the overall impact on Green Technology Innovation hinges on the relative strength of these two effects. Finally, when both the innovation environment effect and the technology R&D effect are nonexistent, their respective influence mechanisms do not affect Green Technology Innovation.

According to the theoretical analysis above, in the case of environmental degradation and resource scarcity, the intensity of environmental governance will continue to increase, the influence of Environmental Decentralization on regional green technological innovation is contingent upon the balance struck between the compensatory effects and the offsetting effects. However, the influence mechanism between China's Environmental Decentralization system and regional green technological innovation poses challenges in determining its ultimate impact—whether it serves to promote or inhibit such innovation—through theoretical analysis alone. Consequently, this study aims to investigate the impact of Environmental Decentralization as a policy instrument within the specific framework of China, focusing particularly on how Environmental Decentralization influences green technological innovation in the country.

3. Study design

Building upon the conceptual mechanisms discussed earlier, this section outlines the empirical strategy employed to test the proposed hypotheses. We specify the model selection, data sources, and identification strategies used to assess the causal relationship between environmental decentralization and green technology innovation.

3.1. Modeling

After investigation, it was found that the vast majority of environmental policies were gradually introduced after 2005, so this paper takes 2005 as the starting year, and the longer research study period can provide enough control groups for the experimental group of the double-difference model (Dubé et al., 2014). In this paper, the double difference model is set up based on the relevant data obtained as follows:

$$GTI_{it} = \alpha_0 + \alpha_1 \times did_{it} + \alpha_2 \times Z_{it} + \mu_i + \sigma_t + \varepsilon_{it}, \qquad (1)$$

where GTI_{it} denotes the total number of green patent applications of city i in period t; the interaction term *did* is a dummy variable for the River Chief System policy, with the city implementing the policy taking the value of 1 and the rest taking 0, which is used for estimating the impact of Environmental Decentralization on green technological innovation; Z_{it} denotes the control variable of the model; μ_i is a city fixed effect; σ_t is a time fixed effect; and ε_{it} is a random error term.

The spatial weight matrix is introduced on the basis of the traditional DID model and the model form is set as follows:

$$GTI_{it} = \rho \times W \times GTI_{it} + \alpha_1 \times did_{it} + \alpha_2 \times W \times treat_t \times post_{it} + \alpha_3 \times Z_{it} + \alpha_4 \times W \times Z_{it} + \mu_i + \sigma_t + (1-\lambda W)^{-1}\varepsilon_{it}, \qquad (2)$$

where W denotes the spatial weight matrix; r is the spatial correlation coefficient of the dependent variable; α_2 is the policy spillover effect; α_4 is the spillover effect of the control variable; and λ is the spatial auto correlation coefficient of the random error, which is further tested to select the appropriate model in a later section.

In order to objectively and comprehensively reflect the regional spatial spillover effect, this paper constructs four weight matrices, the latitude and longitude data of each region comes from the national basic geographic information system, and the four matrices constructed in this paper are standardized when used for parameter estimation: Firstly, a geographic adjacency matrix is constructed based on the binary adjacency relationship of the regions (W_{01}), and W_{01} is a 0–1 matrix, and if the region i is spatially adjacency to the region j, then W_{01} = 1, otherwise it is equal to 0. Second, the inter-area distance is calculated based on the latitude and longitude of the area, and the geographic distance matrix (W_{xy}) is constructed from this. ith row and jth column elements in W_{xy}, $W_{ij}^{xy} = 1/d_{ij}^2,\ i \neq j$. *dij* represent the straight-line distance between region i

and region j. Third, using the absolute value of the difference between the per capita GDP of the regions during the study period ($\overline{pgdp}$) difference of the absolute value of the difference between the regions to calculate the economic distance of each region (W_{pgdp}). The formula is calculated as $W_{ij}^{pgdp} = 1/|\overline{pgdp_i} - \overline{pgdp_j}|$. Fourth, to overcome the bias of a single measurement criterion, a Geo-economic nested spatial weight matrix in the form of a weighting that simultaneously takes into account geographic and economic distances is constructed with the elements of $W^{kj} = \omega W^{xy} + (1-\omega)W^{pgdp}$, where φ is between 0 and 1. For simplicity of analysis, ω takes the value of 0.5.

3.2. Description of variables

Explained variable: green technological innovation (*GTI*). As the academic community has not yet formed a unified metric for green technological innovation, combined with the dual characteristics of green technological innovation, the number of green patents implies the connotation of technological upgrading and invention progress, which can directly reflect the innovation output of green sustainable development. Among them, green patents include green invention patents and green utility model patents. Green invention patents refer to the original function of the product that is different from the original function of the product, and constantly innovate to develop new performance and use of the product. Green utility model patents refer to the secondary improvement and innovation under the original skills of the product, aiming at skill enhancement and technical improvement under energy saving and emission reduction. In order to objectively evaluate the actual impact effect of Environmental Decentralization on green technological innovation, this paper measures green technological innovation by the output indicator of the total number of green patent applications in prefecture-level cities. Compared with the amount of patent authorization, the patent application data is more stable and reliable, and it takes a long time from the beginning of the enterprise to apply for a patent to the approval of the patent authority, and the length of the approval period of the patent authorization is also related to many factors, which is easy to confuse the influence of other factors, and it will be difficult to measure the impact of the impact of the external event shocks on the behavior of green technological innovation.

Explanatory variable: Environmental Decentralization (*ED*). The River Chief System is a typical bottom-up environmental governance policy implemented by local governments, which fully embodies local governments' access to environmental autonomy, can fully clarify the relationship between rights and responsibilities in environmental governance, and has been implemented nationwide in an asymptotic manner, becoming an important initiative in local environmental governance. This paper adopts the River Chief System to characterize Environmental Decentralization, and takes the implementation of the River Chief System in 283 cities in the sample interval of 2005–2022 as a dummy variable for Environmental Decentralization.

Control variables: The level of regional development (*Pgdp*) is measured using the logarithm of real GDP per capita. The industrial structure (*Struc*) is expressed using the proportion (%) of the output value of the tertiary industry to the output value of the secondary industry. Financial development (*Finan*) is measured by the year-end loan balance of financial institutions in each prefecture-level city. The level of human capital (*Human*) is expressed by the proportion (%) of students enrolled in general colleges and universities to the total number of students at the end of the year. *Culture* is measured by the number of books in public libraries per 100 people in each region.

3.3. Description of data

The time frame of the sample data extends from 2005 to 2022, with the primary sources of the raw data being the China Statistical Yearbook, the China Environmental Yearbook, the China Environmental Statistical Yearbook, the China Urban Statistical Yearbook, and the Wind database from prior years. In this paper, in order to improve the accuracy of the manually organized data, specific samples of the river length system were collected and cross-checked through three ways. First, by directly using Baidu Encyclopedia to search for the official text of the river length system issued by each local government in China, second, by manually reviewing the documents issued by the relevant governments compiled by the Legal and Regulatory Center of Peking University, and third, by searching for documents related to the keyword "river length system" (or "river chief") on the China Knowledge Network related documents. And all the acquired data were manually organized to determine whether the River Chief System was implemented in each prefecture-level city and the specific time of implementation, counting the policy implementation before June into the current year, and the policy implementation time after June into the next year. Green patents are obtained based on the green technology fields specified by the World Intellectual Property Office and the green patent list issued by the World Intellectual Property Organization. This is done by first determining the green patent code (IPC), then obtaining patent data at different levels through the patent type, IPC classification code and address of the inventing unit (individual) at the State Patent and Property Office, and finally organizing and forming the number of green patents in each prefecture-level city. The article adjusts the variable indicators involving the price index to improve the comparability of data, and analyzes the descriptive statistics of each variable as shown in Table 1.

4. Results and discussions

Based on the empirical strategy outlined above, we now proceed to present and interpret the regression results, focusing on the impacts of Environmental Decentralization on Green Technology Innovation.

Table 1. Descriptive statistics of main variables

Variable		Variable definition	Average	Standard error
Explanatory variable	Green Patent Applications	Number of green patents filed per year for intellectual property rights	4.013	1.650
Explanatory variable	Environmental Decentralization	Virtual variable	0.053	0.227
Control variable	Level of economic development	GDP per capita	8.952	0.694
	Industrial structure	Ratio of tertiary sector output to secondary sector output	1.009	0.626
	Regional cultural level	Public library holdings per 100 inhabitants by region	0.334	0.224
	Level of financial development	Deposit and loan balances of financial institutions as a percentage of GDP	2.284	1.985
	Level of human capital	Students enrolled in general higher education as a proportion of the total number of students at the end of the year	1.035	1.172
Intermediary variable	R&D investment intensity	Expenditure on science and technology as a percentage of GDP	9.525	1.624
	Degree of fiscal decentralization	Ratio of regional per capita fiscal expenditure to national per capita fiscal expenditure	0.622	0.375

4.1. Benchmark regression

In order to avoid obvious differences between urban control variables in the treatment and control groups before the implementation of Environmental Decentralization, this paper firstly carries out the estimation of the double difference model to obtain the coefficients of Environmental Decentralization in the baseline regression, based on which the propensity score-matching double difference model is used as a control method to enhance the persuasiveness and validity of the results of the baseline regression (Table 2).

The findings indicate that the coefficient for the interaction term is both positive and statistically significant at the 1% level, irrespective of whether control variables are included. This suggests that Environmental Decentralization plays a vital role in fostering green technological innovation. Notably, upon the incorporation of control variables, the coefficients of the interaction term exhibit an upward trajectory, implying that the effect of Environmental Decentralization on regional Green Technology Innovation significantly intensifies when accounting for various factors, such as the level of regional economic development and industrial structure. Additionally, the coefficient estimates for regional economic development (*Pgdp*) and cultural human capital (*Human*) display a significantly positive relationship. This indicates that as regional economic development becomes more advanced, and the levels of cultural and human capital rise, the capacity for enterprises to engage in green technological innovation or demonstrate proactive behavior in this domain increases. Conversely, the coefficient estimates for industrial structure (*Struc*) and financial development (*Finan*) reveal significant negative relationships. This suggests that a greater proportion of value added by the tertiary industry relative to the secondary industry, or an elevated level of financial development, tends to diminish enterprises' enthusiasm

Table 2. Baseline regression result

Variable	DID		PSM-DID	
Did	0.145***(0.030)	0.148***(0.030)	0.147***(0.044)	0.153***(0.044)
Control variable	Yes	Yes	Yes	Yes
Pgdp		0.160***(0.048)		0.210**(0.094)
Struc		–0.155***(0.022)		–0.110***(0.036)
Culture		0.645***(0.134)		0.600**(0.280)
Finan		–0.025***(0.008)		–0.020(0.017)
Human		0.027*(0.012)		0.030(0.020)
Cons	4.399***(0.009)	3.050***(0.450)	5.201***(0.024)	3.257***(0.900)
Fixed city	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes
N	5094	4245	1564	1564
R^2	0.951	0.951	0.969	0.969

Note: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$; standard errors in parentheses.

for pursuing Green Technology Innovation. In summary, the influence of Environmental Decentralization on green technological innovation may be evidenced through both the enhancement of the technological innovation environment and supportive research and development initiatives. It appears that when the positive effects of these dimensions outweigh any negative repercussions, Environmental Decentralization empowers local governments to intensify environmental oversight and incentivize enterprises to refine and upgrade their production methodologies. This, in turn, encourages enterprises to engage actively in research and development activities, mitigates sewage treatment costs, and catalyzes efforts toward green technological innovation.

4.2. Analysis of spatial spillover effects

Before using the spatial econometric model, the spatial effect of green technological innovation is tested, and it is concluded that both global and local Moran's indexes are significantly positive at the 1% level, indicating that there is a significant positive spatial correlation and certain spatial cluster distribution characteristics of green technological innovation in the whole domain. Further, the article uses LM, robust LM test for testing, this analysis suggests that the hypothesis of no spatial correlation is indeed rejected. Furthermore, it is confirmed that SDM-DID cannot be simplified to SLM-DID or SEM-DID. Additionally, the study concludes that the spatial correlation of green technological innovations can be effectively quantified using the spatial Durbin model, as evidenced by the results of the LR test and the Wald test. Moreover, the findings from the Hausman test indicate that the fixed effects model provides a superior estimation compared to the random effects model. Columns (3) to (6) in Table 2 show the estimation results of the spatial Durbin model using four spatial weight matrices. It can be found that the estimated coefficients of Environmental Decentralization are significantly positive at the 1% level under the influence of either kind of weight matrix, indicating that Environmental Decentralization in general helps to increase the number of green patents and positively affects green technological innovation. This conclusion is completely consistent with the theoretical analysis in the previous section, and is also in line with the reality of China in recent years. In recent years, as China's ecological and environmental problems continue to intensify, the central government has gradually increased the authority of local environmental management, encouraging local governments to combine the actual situation of their jurisdictions to formulate and improve the standards and management policies of environmental pollution control in accordance with local conditions, and to fully increase the autonomy of local environmental governance, with a view to improving the relevance and effectiveness of environmental policies. As the Environmental Decentralization system continues to be improved, local governments will have the discretionary power to participate directly in environmental governance, and will be able to actively implement environmental policies under the overall supervision of the central government, and to promote green technological innovations by enterprises in the region on their own, and to increase their efforts to improve their production processes and research and development of advanced science and technology.

To analyze the overall benefits resulting from Environmental Decentralization on Green Technology Innovation, it is necessary to further decompose the effects as outlined in model (2). Table 3 presents the findings, where the direct effect represents the impact of Environmental Decentralization within a region on the enhancement of Green Technology Innovation in that same region. Conversely, the indirect effect, or spatial spillover, quantifies the average influence that improvements in Green Technology Innovation in a given region have on its neighboring regions. The total effect combines both the direct and indirect effects. The results indicate that when accounting for the spatial spillover effect, the coefficient of Environmental

Table 3. Spatial double difference model estimation results

Variable	W^{01}	W^{xy}	W^{pgdp}	W^{kj}
Did	0.125***(0.032)	0.108***(0.033)	0.212***(0.034)	0.111***(0.032)
*W*Did*	0.170***(0.038)	–0.010(0.046)	0.060(0.043)	–0.025(0.044)
Control	Yes	Yes	Yes	Yes
Cons	–3.950***(0.350)	–2.700***(0.365)	–3.100***(0.370)	–2.680***(0.360)
Rho	0.735***(0.011)	0.920***(0.010)	0.795***(0.012)	0.915***(0.010)
Direct effect	0.205***(0.032)	0.100***(0.033)	0.245***(0.034)	0.112***(0.032)
Indirect effect	0.915***(0.081)	0.880***(0.325)	1.075***(0.135)	0.870***(0.320)
Aggregate effect	1.120***(0.087)	0.980***(0.330)	1.320***(0.138)	0.985***(0.320)
Fixed city	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes
R^2	0.530	0.569	0.645	0.590
N	5094	5094	5094	5094

*Note:****p* < 0.01; standard errors in parentheses.

Decentralization on Green Technology Innovation is substantially higher, suggesting that the positive impact of Environmental Decentralization on green technological innovation has been underestimated. In addition, from the test results it can also be concluded that there are differences in the empirical results under the influence of different spatial relationships, indicating that the use of spatial double-difference models should choose the appropriate spatial relationship basis. Combined with the results of the spatial effect decomposition, the Environmental Decentralization affects the green technological innovation with the largest change in the policy spillover range measured by the economic distance spatial weight matrix, that is, the green technological innovation effect generated by the Environmental Decentralization reaches the maximum in this spatial measurement relationship.

From the results of the overall effect decomposition, the indirect effect of the policy impact under the spatial spillover effect is much larger than the direct effect, which may be due to the fact that the cities in the treatment group selected in this paper for the implementation of Environmental Decentralization have obvious urban agglomeration effect in spatial characteristics, this approach facilitates the transformation of scientific and technological achievements within the region, thereby fostering green technological innovation. In the context of green technological innovation, the outcomes associated with adopting a strategy of regional coordinated development frequently surpass those achieved through the implementation of policies in isolated regions. Due to the spatial correlation between technological innovation and environmental pollution, the spatial spillover effect brought about by constructing a pattern of regional synergistic co-development can accelerate the level of green technological innovation.

While the spatial spillover effects provide a deeper understanding of the geographical influence of Environmental Decentralization, it is essential to ensure the robustness of our findings through a series of rigorous tests.

4.3. Discussion on robustness testing

4.3.1. Discussion on parallel trend test

Environmental Decentralization is the result of the development of Chinese-style environmental federalism, with a certain degree of unpredictability. Since 2005, in order to prevent and control environmental pollution and improve the ecological environment, the Chinese government has continuously strengthened and improved the construction of Environmental Decentralization. The implementation of the river chief policy has been expanding to all prefectural-level cities, bringing Environmental Decentralization in China to a climax. In order to further discuss the stochasticity problem of the implementation time of Environmental Decentralization, before constructing the estimation of the framework double-difference model, the possible existence of the expected effect is examined to test whether the identification condition of the method is satisfied, i.e., to determine whether the green technological innovations in the regions prior to Environmental Decentralization satisfy the parallel trend test, it is crucial to ensure that the two groups of samples are comparable before the policy implementation, as any pre-existing differences could lead to biased estimates. This comparability is assessed through the presence of parallel trends. Figure 2 illustrates the outcomes of the parallel trend test, with the horizontal axis representing the years leading up to and following the implementation of Environmental Decentralization, while the vertical axis captures the effects of this policy. The dotted lines, positioned above and below each scatter point, indicate the 95% confidence intervals. The findings reveal that prior to the implementation of the River Chief System policy, there is no significant difference between the treatment group and the control group. This outcome suggests that urban Green Technology Innovation levels were comparable before the Environmental Decentralization initiative was clarified. Furthermore, following the policy's implementation, the urban Green Technology Innovation levels in the 0th and 1st periods exhibited positive but statistically insignificant growth. In contrast, the 2nd period displayed a significant upward trend, indicating that the impact of urban Green Technology Innovation manifests over time. Overall, the results affirm that the parallel trend test has been passed, highlighting that the decentralization of local environmental management powers has played a positive role in incentivizing regional green technological innovation. This supports the benchmark regression results, demonstrating that the decentralization process effectively stimulates green technological advancements at the regional level.

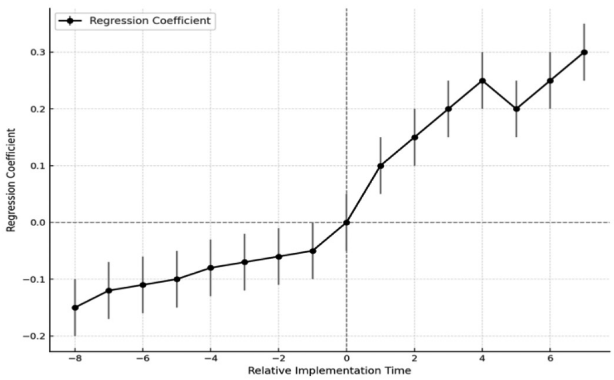


Figure 2. Plot of parallel trend test (95% confidence interval)

4.3.2. Discussion on substitution of explanatory variables

This article uses virtual variables of local environmental legislative power to characterize Environmental Decentralization. It is worth noting that the research object of using this method to characterize Environmental Decentralization has changed, according to the content of the new Legislative Law promulgated in 2015, the local legislative power has been expanded to the level of all prefectural municipalities, so that the localities can formulate relevant laws and regulations in accordance with the local actualities, and can carry out environmental governance in a more targeted way, which also marks a new starting point of Environmental Decentralization system in China. In order to meet the real and effective data, cities that already had legislative power before the new law came into effect were excluded from the analysis. The final selection of the research object is 231 prefecture-level cities. With the decentralization of environmental legislation, local governments have become more actively involved in local environmental governance, clarified local environmental quality objectives in the form of environmental protection laws and regulations, filled the blind spots in national environmental legislation, addressed the challenges related to authority and responsibility for environmental protection across various levels of government, while enhancing the efficiency of decentralized governance, thereby fostering the sustainable development of both the environment and the economy.

Table 4 reports the effect of Environmental Decentralization variables, characterized by local environmental legislative power, on Green Technology Innovation, where column (2) reports the results of the double-difference test using model 1, and columns (3)–columns (6) are the results of coefficient estimation when spatial spillover effects are considered. Further validation using the spatial double difference model is performed from the spatial autocorrelation test. The results show that the spatial correlation coefficient (*Rho*) is significantly positive, and the coefficient of Environmental Decentralization also passes the 1% significance level test, which further supports that Environmental Decentralization not only helps to promote the increase of green patent applications in local cities, but also may lead to the neighboring regions to pay attention to green products and environmentally friendly production.

4.3.3. Discussion on exclusion of other competing hypotheses

To ensure that the empirical results are robust and reliable, this paper further adds other relevant policies that may affect green technological innovation into the empirical regression to exclude the influence of other factors. If the regression coefficient for the policy of Environmental Decentralization becomes insignificant after accounting for other policy events, this suggests that the findings of this paper regarding the influence of Environmental Decentralization on green technological innovation are robust. Conversely, if the regression analysis indicates that the coefficient for Environmental Decentralization remains significant after introducing other policies into the model, albeit with a reduced magnitude, this would imply that the earlier estimates of the impact of Environmental Decentralization may have been overly optimistic. Nonetheless, such an overestimation is often an unavoidable aspect of empirical research. It further suggests that the estimated results presented in this study retain a degree of robustness. To examine this, this paper will focus on three specific policies that could concurrently affect green technological innovation. The first of these is the influence of the central environmental protection inspection. The Environmental Protection Inspection Program was considered and passed in 2015, which makes it clear that within the period of 2015–2018, the central government organizes a group of environmental protection inspectors in batches to carry out ecological environmental protection inspections of various regions to ensure local motivation to protect the environment. Second, the impact of the emissions trading system. The emissions trading system clarifies the choice of enterprises based on marginal environmental governance of their own emissions behavior, and under the influence of the continuous reduction of emissions reduction costs, enterprises will be incentivized to continue to carry out green technological innovation. Third, the impact of innovative city pilot policies. These systems may have a certain promotional effect on regional green innovation.

In this paper, in order to identify the possible effects of the environmental protection inspection and emissions trading policies, the environmental protection inspection dummy variable (*Inspection*), the emissions trading dummy variable (*Pollution*) and the innovative city dummy variable (*Innovation*) are controlled for generating an interaction term with Environmental Decentralization in order to exclude the interference of other policies from a similar period (Table 5). From the results of the benchmark DID test, it can be found that the regression coefficients of

Table 4. Robustness tests: replacing explanatory variables

Variable	DID	SDID			
		(1)	(2)	(3)	(4)
Did	0.605***(0.135)	0.172***(0.052)	0.036(0.046)	0.056(0.049)	0.056(0.049)
*W*Did*		0.175**(0.083)	0.127(0.149)	0.935***(0.112)	0.935***(0.112)
Control	Yes	Yes	Yes	Yes	Yes
Rho		0.695*** (0.010)	0.935*** (0.014)	0.760*** (0.014)	0.760*** (0.014)
Cons	–16.450*** (3.450)	–4.910*** (0.425)	–2.340*** (0.425)	–3.565*** (0.475)	–3.560*** (0.475)
N	4158	4158	4158	4158	4158
R^2	0.575	0.445	0.540	0.510	0.510

Note: $^{**}p < 0.05$, $^{***}p < 0.01$; standard errors in parentheses.

Table 5. Robustness tests: excluding other competing hypotheses

Variable	Pollution-did		Innovation-did		Inspection-did	
	(1)	(2)	(3)	(4)	(5)	(6)
Did	0.150*** (0.034)	0.125*** (0.033)	0.152*** (0.033)	0.121*** (0.033)	0.156*** (0.034)	0.127*** (0.033)
*W*Did*		0.182*** (0.038)		0.178*** (0.038)		0.183*** (0.039)
Rho		0.723*** (0.010)		0.733*** (0.010)		0.734*** (0.010)
Pollution-did	–0.008 (0.030)	0.130*** (0.027)				
Innovation-did			–0.013 (0.036)	0.086*** (0.033)		
Inspection-did					0.047 (0.037)	–0.026 (0.033)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Cons	3.010*** (0.465)	–3.790*** (0.342)	3.020*** (0.466)	–3.960*** (0.342)	3.020*** (0.466)	–3.970*** (0.343)
Fixed city	Yes	Yes	Yes	Yes	Yes	Yes
Fixed time	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.953	0.545	0.953	0.535	0.953	0.530
N	5094	5094	5094	5094	5094	5094

Note: ***p < 0.01; standard errors in parentheses.

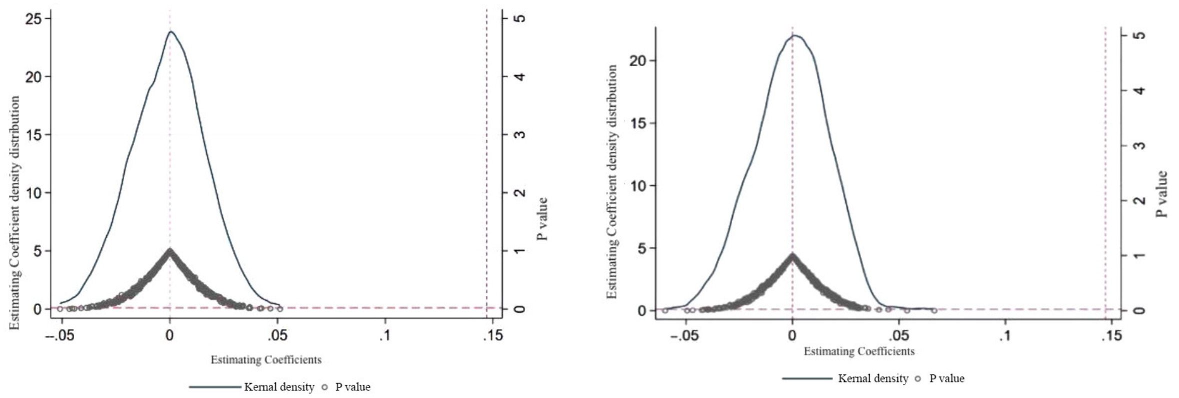
Environmental Decentralization after adding the dummy variables of the three policies are always positive and significant, with the coefficient size increased compared to the benchmark regression, and the regression coefficients of competitive policies themselves are not significant. This means that the significance of the competitive policy on the benchmark regression results have been enhanced, while the Environmental Decentralization policy on the impact of green technological innovation effect is indeed overestimated, but the impact of the effect still exists and is significant, indicating that the paper's estimation conclusions are relatively robust. This paper employs the spatial double difference model, utilizing a spatial adjacency matrix for further testing. The findings indicate that the coefficients for Environmental Decentralization are statistically significant and exhibit spatial effects. Furthermore, it is observed that the magnitude of these coefficients has decreased in comparison to the benchmark regression results, which aligns with the conclusions reached through the application of the benchmark difference-in-differences (DID) model. The effect of Environmental Decentralization on green technological innovation is overestimated to a certain extent, but it does not affect the conclusions of this paper, which further verifies the robustness of the conclusions of this paper.

4.3.4. Discussion on placebo test

In addition to the impact of green technological innovation by policy shocks, related variables, but also need to exclude the benchmark results by the impact of artificial settings or omitted variables caused by random results, this paper also carried out a placebo test. In this paper, we randomly set the implementation time for the River Chief System policy and the selected pilot cities. Our findings indicate that Environmental Decentralization does not significantly impact green technological innovation. This conclusion is evidenced by the regression coefficients of the so-called "pseudo" processing variables, which should cluster around zero. A deviation from this pattern would suggest a bias in the model specifications employed in this analysis. As a result, we conducted a placebo test, repeatedly applying the aforementioned randomization process 500 times for model estimation. The outcomes of the placebo test are illustrated in Figure 3. The analysis revealed that the mean values of the estimated coefficients across both randomization processes approximated zero, with the majority of p-values exceeding 0.1. Additionally, the actual estimated coefficient for Environmental Decentralization (0.147) falls within the range of low-probability events in the kernel density plots derived from the aforementioned placebo test. This implies that the estimated effects of Environmental Decentralization on regional green technological innovation are not purely coincidental, reinforcing the reliability and robustness of the findings presented in this paper.

4.4. Discussion on the Impact of Green Technology Innovation on Environmental Decentralization

The present study delves into the multifaceted effects of Environmental Decentralization on Green Technology Innovation, offering valuable insights into the dynamics that underpin sustainable development. Our analysis, grounded in both theoretical frameworks and empirical evidence,



a) Randomization of policy time b) Random selection of pilot districts

Figure 3. Placebo test

reveals that Environmental Decentralization serves as a catalyst for fostering green technological advancements, thereby transforming "green mountains" into both "golden" and "silver mountains." This transformation underscores the pivotal role of Green Technology Innovation in driving economic growth while mitigating environmental degradation.

The research results indicate that Environmental Decentralization significantly promotes Green Technology Innovation, with regional heterogeneity playing a crucial role. The quasi-natural experiment of the river-long system, employed as an entry point for empirical analysis, highlights that this policy intervention has not only a direct impact on green technological innovation but also fosters spatial spillover effects. In the short term, while Environmental Decentralization may elevate costs associated with production skills upgrading and pollution control, it ultimately triggers an input-enhancing mechanism, encouraging enterprises to intensify innovative activities under government scrutiny. This process internalizes the external costs of environmental management, bolstering corporate enthusiasm for green technological endeavors.

The positive spatial spillover effect underscores the interconnectedness of regional innovation ecosystems. As enterprises within a jurisdiction prioritize green innovation, they inadvertently inspire neighboring regions to emulate this trend, resulting in a cumulative enhancement of green technological innovation across broader geographical areas. This phenomenon underscores the importance of cooperative strategies and policy harmonization across jurisdictions to maximize the benefits of Environmental Decentralization.

Our research identifies two primary pathways through which Environmental Decentralization influences green technological innovation: direct and indirect. The direct pathway empowers local governments with greater autonomy in environmental protection and pollution control, enabling them to align these efforts with their unique development aspirations and quality objectives. This alignment fosters a favorable urban bias towards technological innovation, thereby accelerating green technological advancements through both direct and spatial spillover effects. In contrast, the indirect pathway involves intermediary variables such as R&D intensity and fiscal decentralization. When incentives are distorted or central government regulations are perceived as less binding, local governments may exploit their newfound authority to relax environmental standards, sacrificing environmental integrity for short-term economic gains. This negative outcome underscores the need for robust oversight mechanisms and clear performance indicators to ensure that Environmental Decentralization remains aligned with sustainable development objectives.

In conclusion, optimizing the decentralized management system for environmental affairs necessitates a nuanced understanding of environmental rights and responsibilities. Policymakers should ensure that the rational division of local environmental authorities fully considers the policy's scope and implementation conditions, leveraging local governments' informational advantages to craft targeted interventions that enhance green technological innovation. Simultaneously, strengthening environmental protection inspections and punitive measures, along with incentives for green technological innovation, can promote a normative regulatory environment. Meanwhile, innovating the organization and implementation mechanism of environmental management must be tailored to local conditions and regional development characteristics. Recognizing the regional heterogeneity in the effects of Environmental Decentralization, policymakers should define key green technology development areas and leverage local strengths to improve multiple inputs, broaden financing channels, and cultivate interdisciplinary talent teams. This approach will enhance the infrastructure and platforms for Green Technology Innovation, ensuring the widespread dissemination and adoption of the latest technologies and practices. Furthermore, optimizing the environment for green technological innovation requires the development of robust green policies and regulations that govern corporate conduct. A system of innovation led by enterprises and markets, which incorporates the integration of "industry, academia, research, and finance," can expedite the conversion of Green Technology Innovations into concrete economic and environmental advantages. Moreover, tax incentives, financial assistance, and streamlined processes for patent applications can serve as additional motivators for enterprises to engage in research and development as well as the commercialization of green technologies. Finally, reinforcing the development of infrastructure and accelerating the implementation of outcomes from Green Technology Innovation are critical for closing the green technology gap among enterprises, sectors, industries, and regions. Comprehensive service platforms and information sharing networks can enhance collaboration and knowledge exchange, while targeted government support for low-return, high-impact green technologies can spur further innovation and adoption. By harnessing the dynamism of Green Technology Innovation, policymakers can optimize resource allocation, harness market forces, and ultimately narrow or eliminate existing disparities in green technological advancement.

In the comparison of similar literature, this study also emphasizes the key role of regional heterogeneity in the effectiveness of Environmental Decentralization, pointing out that differences in resource endowment, industrial structure, policy implementation, and other aspects among different regions will significantly affect the promotion effect of Environmental Decentralization on Green Technology Innovation. This discovery is consistent with the principle of "adapting to local conditions" emphasized in the fields of regional economics and environmental economics in recent years, providing policy makers with more precise and differentiated policy recommendations.

5. Conclusions

Based on the empirical findings presented above, we now turn to summarize the main contributions of this study and discuss the broader policy implications. The conclusion also outlines potential limitations and future research directions.

Green Technology Innovation serves as a vital catalyst for advancing green and low-carbon development. It functions as a "green engine" that drives high-quality development and represents a significant means to convert "green mountains" into "golden mountains." Furthermore, it acts as a crucial pathway for transforming "green mountains" into "silver mountains." This study advances the discourse on environmental governance by rigorously examining how decentralized environmental management, exemplified through China's River Chief System (RCS), drives Green Technology Innovation (GTI). Leveraging panel data from 283 prefecture-level cities (2005–2022) and a spatial difference-in-differences (SDID) framework, three key contributions emerge:

1. Theoretical Advancements

The dual-path analytical framework elucidates the paradoxical role of Environmental Decentralization. While top-down political competition under the RCS fosters an innovation-friendly environment, bottom-up fiscal pressures may crowd out R&D investments, revealing a nuanced interplay of enabling and constraining forces. This resolves contradictions in prior literature by demonstrating that decentralization's net positive impact on GTI hinges on spatially heterogeneous governance dynamics. The SDID model further addresses a critical gap by quantifying spatial spillovers, showing that GTI gains in RCS-adopting cities elevate innovation in neighboring regions by 0.87–1.32 standard deviations, underscoring interregional knowledge diffusion.

2. Policy Implications

The empirical findings of this study yield significant policy insights, informing future strategies in environmental governance and green technological innovation, particularly within decentralized governance frameworks such as the River Chief System (RCS). Specifically, policymakers are advised to consider the following strategies based on our analysis.

(1) Implement Differentiated Regional Governance Strategies

Given regional disparities in economic development and technological capacities, environmental governance policies should be tailored according to local contexts. For economically advanced industrial hubs, particularly those in China's eastern coastal areas, it is crucial to implement targeted fiscal incentives—such as tax reductions, subsidies for green patent applications, and R&D funding for enterprises—to enhance green innovation capabilities. In contrast, less-developed regions should prioritize infrastructure investment and institutional capacity-building to effectively absorb innovation spillovers from developed areas, thus fostering local environmental and technological development.

(2) Enhance Central-Local Synergy in Environmental Governance

While decentralization empowers local governments with autonomy and informational advantages for targeted environmental management, excessive decentralization may provoke regulatory arbitrage and a "race-to-the-bottom" scenario. Therefore, it is essential to establish a robust coordination mechanism between central oversight and local implementation. The central government should set baseline environmental standards, implement comprehensive accountability frameworks, and conduct regular environmental audits. Concurrently, local governments should retain flexibility in adapting policies to specific regional environmental conditions, thereby ensuring both policy coherence and adaptability.

(3) Establish Cross-Jurisdictional Innovation Ecosystems

The spatial spillover effects demonstrated by our findings highlight the importance of fostering regional and cross-regional collaborative networks. Policymakers should support the establishment of integrated R&D platforms and innovation ecosystems, especially within interconnected river basin economies. These collaborative platforms can facilitate knowledge sharing, technology transfer, and joint innovation initiatives among enterprises, research institutions, and governments. By promoting such cross-jurisdictional cooperation, policymakers can effectively amplify spatial spillovers of Green Technology Innovation, thus optimizing the collective benefits of decentralized environmental governance.

3. Limitations and Future Directions

The dataset (2005–2022) precedes the widespread adoption of AI-driven environmental monitoring technologies, which have gained prominence post-2020. Subsequent studies could examine how integrating digital governance tools (e.g., real-time pollution tracking systems, machine learning-based compliance audits) modifies the relationship between Environmental Decentralization and accountability mechanisms. Meanwhile, the analytical framework, while validated in China's unitary governance context, remains untested in federal systems characterized by distinct political-institutional architectures, such as the European Union's supranational regulatory regimes or the U.S. state-level environmental policymaking structures. Comparative analyses across governance models would clarify how decentralization efficacy varies with constitutional power distributions.

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