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Study on the Evaluation of Green Technology Innovation Efficiency and Its Influencing Factors in the Central Plains City Cluster of China

Xu Dong ¹, Wensi Fu ¹, Yali Yang ^{2,*}, Chenguang Liu ¹ and Guizhi Xue ³

¹ School of Economics, Zhengzhou University of Aeronautics, Zhengzhou 450046, China

² School of Information Management, Zhengzhou University of Aeronautics, Zhengzhou 450046, China

³ School of Finance and Taxation, Henan University of Economics and Law, Zhengzhou 450016, China

* Correspondence: yangyali@zua.edu.cn

Abstract: Green technology innovation, containing economic, social and ecological triple value effects, plays an important role in promoting regional high-quality development. In this paper, we take the Central Plains city cluster, one of China's top ten national city clusters, as the research object and use the super-efficiency SBM-DEA model to measure and analyze its green technology innovation efficiency. The panel spatial Durbin model (SDM) is used to empirically investigate the market-based, policy and social factors that affect green technology innovation efficiency in the Central Plains city cluster. The main findings are as follows: (1) The green technology innovation efficiency in the Central Plains city cluster shows a fluctuating upward trend from 2009 to 2019, and the spatial differences are obvious, but this spatial difference has converged somewhat over time; (2) Economic development and industrial structure upgrading are the dominant market forces driving green technology innovation efficiency in the Central Plains city cluster, while opening up and enterprise performance hurt the efficiency of green technology innovation; (3) By strengthening environmental regulation and fiscal expenditures on science and technology, the government plays a guiding role in promoting green technology efficiency; (4) Human capital can provide talent support for green technology innovation to effectively promote the efficiency of green technology innovation in the Central Plains city cluster, while the impact of urbanization on green technology innovation efficiency is not significant; (5) In addition to urbanization, the market-based, policy, and social factors that affect green technology innovation efficiency in the Central Plains city cluster also present significant spatial spillover effects. To further promote green technology innovation efficiency in the Central Plains city cluster in the future, we should significantly promote the green transformation and upgrading of industrial structure, improve the quality of opening up to the outside world, strengthen environmental supervision and optimize its governance model, increase government support for green innovation, improve the talent cultivation and introduction system, and mobilize enterprises' enthusiasm for green technology innovation.

Keywords: Central Plains city cluster; green technology innovation efficiency; SBM-DEA model; panel SDM



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1. Introduction

Since the reform and opening-up, China's economy has undergone tremendous changes, creating a "China miracle" that has attracted the world's attention. In this process, the crude economic development mode has played a great role, but it has also led to a series of problems such as the deterioration of the ecological environment, the inefficient use of resources, and the lack of innovation and development momentum. How to deal with the contradiction between economic development and resources and the environment has become a major challenge for China. The Fifth Plenary Session of the 18th Communist Party of China's Central Committee put forward the new development philosophy of

innovation, coordination, greenness, openness and sharing, putting innovation and green in the forefront of development. Green technology innovation, as the combination of the two development concepts of innovation and green, is the fundamental plan to cope with resource and environmental constraints and thus achieve the deep integration of innovation driven and green development. The 19th National Congress of the Communist Party of China (CPC) requires “building a market-oriented green technology innovation system and implementing green technology innovation initiatives”, which further highlights the important role of green technology innovation in the process of promoting high-quality development of the economy and society in the new era.

As we enter the 21st century, city clusters with central cities as the core engine are increasingly becoming the basic carriers of international competition and division of labor. The advancement and retreat of the comprehensive strength of city clusters as well as the competitive and collaborative relationship between city clusters have an increasingly profound impact on the global political and economic landscape. In 2006, China proposed the urban agglomeration strategy in her 11th Five-Year Plan, making urban agglomeration the main form of promoting urbanization. In 2014, the Central Committee of the CPC and the State Council released the National New-type Urbanization Plan (2014–2020), in which 19 city clusters were planned for the whole country, hoping to build an urbanization strategic pattern of “two horizontal and three verticals”. Up to now, 10 city clusters have been upgraded to national-level. The Central Plains city cluster, as one of the 10 national-level city clusters, is located at the intersection of the land-bridge corridor and the Beijing-Guangzhou corridor in China’s “two horizontal and three vertical” urbanization strategy pattern, covering 30 cities in the five provinces of Henan, Hebei, Shanxi, Shandong and Anhui (as shown in Figure 1). It occupies an important position in China in terms of geographical location, population size and total economic volume. It has great development potential, but the economic structure supported by traditional industries with high energy consumption, high pollution and high emissions leads its development to still face a dilemma of increasing resource and environmental constraints and to a weak independent innovation capacity. The Central Plains City Cluster Development Plan, issued by the National Development and Reform Commission of China in December 2016, pointed out that the green and low-carbon development of the Central Plains city cluster should be driven by innovation. In this context, the green technology innovation that breaks through the traditional technology innovation model introduces ecological concepts and guides technology innovation to achieve resource conservation and environmental protection and has become an inevitable choice for the Central Plains city cluster to solve the contradiction between the ecological environment and economic development.

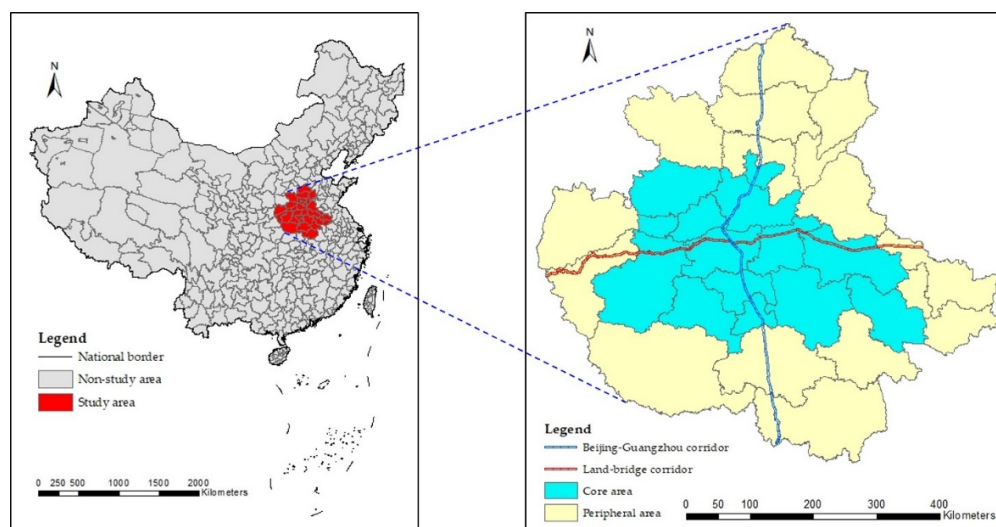


Figure 1. Study area of this paper.

Efficiency analysis is the core of economic and social science research [1]. With the shift of China's economy from a high growth stage to a high-quality development state, the importance of efficiency and productivity has become increasingly clear [2]. The 19th Party Congress further proposed the necessity of "promoting quality change, efficiency change and driver change in economic development". As one of the three major changes, efficiency change has become the masterstroke for China to promote modernization in the future. Green technology innovation efficiency is an important indicator to measure the development status of green technology innovation [3]. Improving green technology innovation efficiency is the necessary way to promote the organic combination of green development and innovation drive [4,5]. In this sense, the key for the Central Plains city cluster to achieve leapfrog development by relying on green technology innovation lies in breaking down the various barriers that restrict efficiency change and accelerating the efficiency of green technology innovation. So, what is the current level of green technology innovation efficiency in the Central Plains urban agglomeration? What are the intrinsic mechanisms that promote green technology innovation? What factors affect the efficiency of green technology innovation in the Central Plains urban agglomeration? What policies should be implemented to promote green technology innovation efficiency in the Central Plains urban agglomeration? An in-depth discussion of the above questions is of great significance with regard to speeding up the construction of ecological civilization and promoting the integration of green innovation and high-quality development in the Central Plains city cluster.

2. Literature Review

Since the Austrian-American political economist Schumpeter first proposed innovation theory in 1912, Western scholars have begun to elaborate on innovation from various aspects. In the 1970s, the interplay of innovation and industrial research created a new field of industrial technology innovation research. At the same time, due to the increasing pressure on resources and the environment brought by economic development, an increasing number of scholars have started to pay attention to the issue of industrial green development from the perspective of technology innovation. In the 1990s, the concept of "green technology innovation" was formally introduced and attracted attention [6]. Subsequently, academia has researched its definition, quantitative evaluation, value embodiment, and driving factors.

2.1. The Connotation of Green Technology Innovation

Academia has not reached an agreement on this issue. Most studies define the meaning of green technology innovation in terms of both the production process and innovation characteristics. From the perspective of the production process, green technology innovation mainly refers to technology innovation activities that reduce negative externalities on resources and the environment in the process of product design, production, distribution, and use [7]. From the perspective of innovation characteristics, green technology innovation is usually intrinsically related to sustainable development and the circular economy, focusing on driving the enhancement of the function of the economic-social-environmental composite system from the technology innovation dimension. The core characteristics of green technology innovation are the synergy of development goals, the diversification of innovation subjects, and the public welfare of achievement sharing [8,9].

2.2. The Quantitative Evaluation of Green Technology Innovation

In terms of evaluation dimensions, there are three main types of indicators for measuring green technology innovation: the first are input-based indicators, the most commonly used being research and development (R&D) expenditure [10,11]; the second type are output-based indicators, typically represented by the number of green patent applications or grants [12–14]; and the third type are performance-based indicators, the "green technology innovation efficiency", which draws on economic efficiency and total factor

productivity and is widely used [15,16]. In the field of evaluation scales, the existing studies have mostly been conducted at three spatial levels: enterprise, industry, and region [17]. At the enterprise level, most of the literature focuses on the green business philosophy and green technology culture of enterprises. At the industry level, green technology innovation in both pollution and technology-intensive industries, especially in the manufacturing sector, has received extensive attention. At the regional level, the evaluation of green technology innovation is mostly based on the provincial scale samples [18]. Regarding evaluation methods, most literature adopts one of the following two types of methods to measure the green technology innovation index or efficiency: one is data envelopment analysis (DEA) and stochastic frontier analysis (SFA) based on input-output models [19–21], and the other is the weighted index method based on specific index system [22].

2.3. The Value Embodiment of Green Technology Innovation

According to the existing literature, the value of green technology innovation is mainly embodied in three aspects. The first is economic value. Most studies have shown that green technology innovation has a positive impact on output scale, industrial structure, production efficiency, and value chain upgrading [23], but some studies have also pointed out that green technology innovation in craft didn't serve to boost the financial performance of enterprises [24]. The second is social value. The ultimate goal of green technology innovation is to improve peoples' well-being, and its social value is mainly expressed as the impact on corporate social responsibility [25]. The third is ecological value. It has been shown in the literature that resource utilization efficiency and environmental pollution in China has been improving as it is driven by green technology innovation [26,27]. In other words, green innovation has the potential to address the dilemma between consuming available resources and preserving them for the future [28].

2.4. The Driving Factors of Green Technology Innovation

Based on the connotational characteristics and development environment of innovation, studies have been conducted to explore the possible drivers of green technology innovation primarily from both internal and external perspectives. Internal drivers mainly come from firms, including their R&D investment, financial performance, executive characteristics, and governance patterns [29,30]. Some other scholars have also examined the driving mechanisms of green technology innovation from the perspective of corporate managerial traits and argued that there is a strong correlation between executive leadership and corporate green technology innovation [31]. On the one hand, external drivers come from government incentives and regulations. Rubashkina et al. (2015) and Chan et al. (2016) focused on the impact of tax relief and green credit on green technology innovation in enterprises and even industries, respectively [32,33]. Li et al. (2022) took Chinese construction enterprises as an example and pointed out that direct government investment and environmental regulation have a significant impact on green technology innovation, and the latter showed non-linear characteristics [34]. On the other hand, external drivers come from the macroeconomic environment and market demand. For example, Kammerer (2009) investigated the effects of competitive market environment and economic development level on green innovation [35]. Yasmeen et al. (2020) and Qu et al. (2021) pointed out that human capital and foreign investment have positive promotion effects on green technology innovation [36,37]. Fang et al. (2022) found that regional Internet development and innovation and entrepreneurship capacity helps to enhance the efficiency of green technology innovation, and there is a significant positive spatial spillover effect [38].

2.5. The Comments

As mentioned above, research on green technology innovation is in an overall flourishing development stage, and it is gradually shifting from the definition of theoretical connotations to the quantitative evaluation and identification of impact factors. The content is gradually deepened, but there are still the following points that are worth expanding

and improving. First, the spatial scale of measuring green technology innovation efficiency needs to be refined. Most of the existing studies took provincial units as samples, while there are fewer studies with urban areas (agglomeration) as the main objects. Second, the interpretation of the inner mechanism of green technology innovation is still unclear; many studies directly use econometric methods to identify the factors that may affect green technology innovation but lack theoretical analysis of the influence mechanism of these factors. Third, there is insufficient attention given to green technology innovation in the major strategic regions of China. Most studies are based on the overall perspective. The applicability of research findings to specific regions is questionable, and no academic outcomes on green technology innovation in the Central Plains city cluster have been found.

In view of this, we will take the Central Plains city cluster, one of China's top ten national city clusters, as the research sample and use the SBM-DEA model containing undesirable outputs to quantitatively measure its green technology innovation efficiency. Furthermore, we empirically identify the market-based, policy and social factors affecting green technology innovation efficiency in the Central Plains city cluster based on the elucidation of the intrinsic improvement mechanisms of green technology innovation. Compared with the existing literature, the main innovation points and contributions of this paper are reflected in the following three aspects. First, a three-dimensional theoretical analysis framework of the intrinsic driving mechanism of green technology innovation is constructed, which attempts to analyze the theoretical mechanism of promoting green technology innovation from market, policy and society. Second, we add to the lack of literature on green technology innovation in the Central Plains city cluster. This will be useful for scholars to study innovation-driven and green development issues in the Central Plains city cluster in the future. Third, our city-based study is more specific at the spatial scale and helps to better accommodate local heterogeneity in the policy analysis.

3. Evaluation of Green Technology Innovation Efficiency in the Central Plains City Cluster

3.1. Evaluation Indicator System

The theory of sustainable development is the core theoretical support for green technology innovation. The emergence of ecological crisis has made people realize that the pursuit of economic development while ignoring environmental protection will bring unimaginable disasters to humanity. The theory of sustainable development was born in this context, and advocates that while pursuing economic development, the affordability of the environment, resources and ecology should be fully considered, and the unity of current and long-term interests should be valued [39]. Green technology innovation integrates environmental factors, ecological benefits and social benefits into all steps of technology innovation, showing the beauty of sustainable and healthy economic, social and ecological development, which is the faithful practice of sustainable development theory. Therefore, theoretically speaking, the measurement of green technology innovation efficiency should not only reflect the innovation efficiency scientifically but also reflect the "green" attributes in the process of innovation. Referring to the study of Zhang et al. (2022) [40], we attempt to construct an evaluation index system for the Central Plains city cluster, taking into account the current situation of green technology innovation and the availability of data, as shown in Table 1.

The input indicators include human resources, financial resources and the innovation environment. Labor input is measured by the full-time equivalent of R&D personnel, and capital input is measured by the internal expenditure on R&D. As for the innovation environment, considering that green technology innovation relies on a certain knowledge accumulation, the collections of public libraries per 100 people is taken as the proxy variable.

Table 1. Evaluation index system of green technology innovation.

Input-Output	Indicator Type	Indicator	Indicator Unit
Inputs	Labor Forces	Full-time Equivalent of R&D Personnel	man-years
	Capital	Internal Expenditure on R&D	10,000 yuan
Desired Outputs	Innovation Environment	Collections of Public Libraries Per 100 People	copy
	Technological Output	Number of Green Patents Granted	piece
Undesired Outputs	Economic Output	Real GDP	100 million yuan
	Energy Consumption	Carbon Dioxide Emissions	ton
	Environmental Pollution	Average PM2.5 Concentration	µg/m ³

For the desired output, on the one hand, the economic benefits of green technology innovation are measured by the real GDP; on the other hand, the number of green patents granted is selected as a proxy variable for technology output.

The major difference between green technology innovation and traditional technology innovation is the consideration of undesired output caused by energy consumption and environmental pollution. In this paper, we select carbon dioxide emissions and the average concentration of PM2.5 to measure undesired output.

3.2. Evaluation Method

Stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are the most common methods used to evaluate the efficiency of green technology innovation. SFA is built on the basis of production function, considering the influence of random errors on estimated results, which has a better economic significance and can improve the accuracy of the calculated efficiency level. However, the disadvantage of this method is also obvious, as it needs to satisfy many strict assumptions about the production function and can only deal with the single-output problem. The principle of DEA is linear programming in mathematics, which is able to deal with the efficiency accounting problem of multiple inputs and multiple outputs without assuming a specific functional form, thus avoiding structural deviations due to misspecified production functions. However, the DEA method also has shortcomings. It ignores the influence of random errors on the final efficiency, which may lead to a decrease in the accuracy of efficiency calculation results. Since the green technology innovation efficiency evaluation indicator system constructed above involves a variety of outputs, we choose DEA as the base method of evaluation. Traditional DEA models did not consider the slack variation of inputs and outputs, and cannot identify undesired outputs well. The Slack-Based Measure (SBM) model proposed by Tone (2001) based on the basic principles of DEA solves these problems better and is widely used in academia [41]. To solve the problem of incomparable efficiency of different decision units on the same production frontier, we integrate the concept of super-efficiency into the SBM model, and use the super-efficiency SBM-DEA model based on the directional distance function to measure green technology innovation efficiency in the Central Plains city cluster. The basic form of the super-efficient SBM-DEA model is as follows.

$$\begin{aligned}
 \min \rho = & \frac{1 - \frac{1}{m} \sum_{i=1}^M \frac{s_{jm}^x}{x_{jm}^t}}{1 + \frac{1}{l+h} (\sum_{l=1}^L \frac{s_{jl}^y}{y_{jl}^t} + \sum_{h=1}^H \frac{s_{jh}^b}{b_{jh}^t})} \\
 \text{s.t.} \quad & \begin{cases} x_{jm}^t \geq \sum_{j=1, j \neq m}^n \lambda_j^t x_{jm}^t + s_{jm}^x \\ y_{jl}^t \geq \sum_{j=1, j \neq l}^n \lambda_j^t y_{jl}^t + s_{jl}^y \\ b_{jh}^t \geq \sum_{j=1, j \neq h}^n \lambda_j^t b_{jh}^t + s_{jh}^b \\ \lambda_j^t, s_{jm}^x, s_{jl}^y, s_{jh}^b \geq 0 \end{cases} \quad (1)
 \end{aligned}$$

where ρ is green technology innovation efficiency; x and y represent the inputs and outputs, respectively; m , l , and h denote the number of inputs, desired outputs, and undesired outputs, respectively; x_{jm}^t , y_{jl}^t , and b_{jh}^t refer to the input value, desired output value and undesired output value, respectively; s_m^x , s_l^y , and s_h^b are the slack variables of inputs, desired outputs, and undesired outputs, respectively; and λ is the weight vector of decision units.

3.3. Analysis of Evaluation Results

Based on the above method, we calculated green innovation efficiency in the Central Plains city cluster from 2009–2019, and Table 2 reports the results. Next, we will analyze the characteristic facts of green technology innovation efficiency in the Central Plains city cluster from three aspects: temporal evolution, spatial evolution, and temporal convergence.

Table 2. Evaluation results of green technology efficiency in the Central Plains city cluster from 2009 to 2019.

City Name	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Handan City	1.094	1.080	1.097	1.091	1.105	1.124	1.092	1.078	1.054	1.063	1.060
Xingtai City	0.531	0.403	0.259	0.505	0.533	0.486	0.584	0.459	0.511	0.717	0.681
Changzhi City	0.569	0.446	0.394	0.556	0.369	0.563	0.614	0.617	0.454	0.515	0.526
Jincheng City	0.682	0.707	1.025	1.003	0.521	1.041	1.158	0.389	0.502	0.415	0.077
Yuncheng City	0.485	1.048	1.034	1.200	0.642	0.644	0.650	0.624	0.540	0.438	0.449
Bengbu City	0.774	1.183	1.168	1.171	1.102	1.095	1.111	1.204	1.089	1.097	1.165
Huaibei City	1.252	1.435	0.813	0.653	0.672	1.004	0.696	0.653	0.703	0.614	0.627
Fuyang City	0.842	1.132	1.070	1.057	1.003	0.846	1.250	1.174	1.113	1.049	1.066
Suzhou City	1.056	1.085	1.066	1.107	1.061	1.045	1.020	1.073	0.865	1.456	1.443
Bozhou City	2.775	2.708	2.642	4.158	3.522	2.803	1.609	1.257	1.086	1.399	1.463
Liaocheng City	0.520	1.187	1.040	1.012	1.014	1.016	1.019	1.030	0.657	0.684	1.021
Heze City	0.653	0.771	0.643	0.751	0.627	0.565	0.599	0.617	0.595	0.661	1.019
Zhengzhou City	1.337	1.341	1.255	1.270	1.296	1.210	1.225	1.227	1.276	1.310	1.318
Kaifeng City	0.738	0.739	0.638	0.628	0.592	0.608	0.721	0.774	1.145	1.189	1.182
Luoyang City	1.013	1.035	1.013	1.008	1.013	1.077	1.146	1.025	1.015	0.772	0.706
Pingdingshan City	0.686	0.396	0.696	0.269	0.407	0.498	0.483	0.610	0.658	0.655	0.635
Anyang City	0.654	0.630	0.572	0.633	0.621	0.620	0.692	0.659	0.686	0.678	0.724
Hebi City	0.596	0.642	0.765	1.113	1.460	1.290	1.276	2.615	3.576	4.537	7.723
Xinxiang City	0.672	0.712	0.777	0.672	0.598	0.657	0.761	0.712	0.763	0.745	0.739
Jiaozuo City	0.484	0.599	0.500	0.655	0.693	0.694	0.786	0.695	0.749	0.733	0.682
Puyang City	1.057	0.745	0.818	0.706	1.043	0.614	0.778	0.773	1.202	1.250	1.064
Xuchang City	1.056	1.160	1.002	1.006	0.776	1.014	1.050	0.877	1.042	1.126	1.122
Luohe City	0.473	0.727	1.129	1.085	1.216	1.596	1.976	2.357	2.737	3.118	3.498
Sanmenxia City	0.402	0.557	0.513	0.617	0.692	0.443	0.497	0.550	0.983	0.636	1.132
Nanyang City	1.001	1.018	1.039	1.011	1.013	1.024	1.038	1.062	1.037	1.022	1.008
Shangqiu City	1.084	1.024	1.039	0.684	0.682	1.008	1.010	0.515	0.497	0.603	0.450
Xinyang City	1.033	1.080	1.082	1.123	1.111	1.150	1.153	2.347	1.363	1.342	1.328
Zhoukou City	1.081	1.079	1.082	1.078	1.077	1.088	1.085	1.093	1.060	1.133	1.192
Zhumadian City	0.514	1.010	1.004	1.009	1.186	1.005	1.009	0.818	1.078	1.147	1.005
Jiyuan City	0.763	1.013	1.207	1.071	1.067	1.107	1.117	1.165	1.330	1.369	1.064

Note: Collated from MaxDEA 8.22 software.

3.3.1. Temporal Evolution Trend

As shown in Figure 2, the green technology innovation efficiency in the Central Plains city cluster showed a fluctuating upward trend from 2009 to 2019, with an increase of 43.63% at the end of the study period compared with the beginning of the study period and an average annual increase of 3.69 percentage points. The trend of green technology innovation efficiency in the core area of the Central Plains city cluster is basically consistent with the overall city cluster, while the fluctuation in the peripheral area is more stable. From a phased perspective, the efficiency of green technology innovation in the Central Plains city cluster rose and fell between 2009 and 2013, but the fluctuation was small. Starting from 2013, the green technology innovation efficiency in the Central Plains city cluster has been showing a continuous increase. This stage corresponds to the period since the 18th Party Congress, when the construction of ecological civilization became a major national strategy and people's aspiration for green life became increasingly strong. Coupled with the

continuous promotion of the innovation-driven strategy, the efficiency of green technology innovation in the Central Plains city cluster has been improving more substantially.

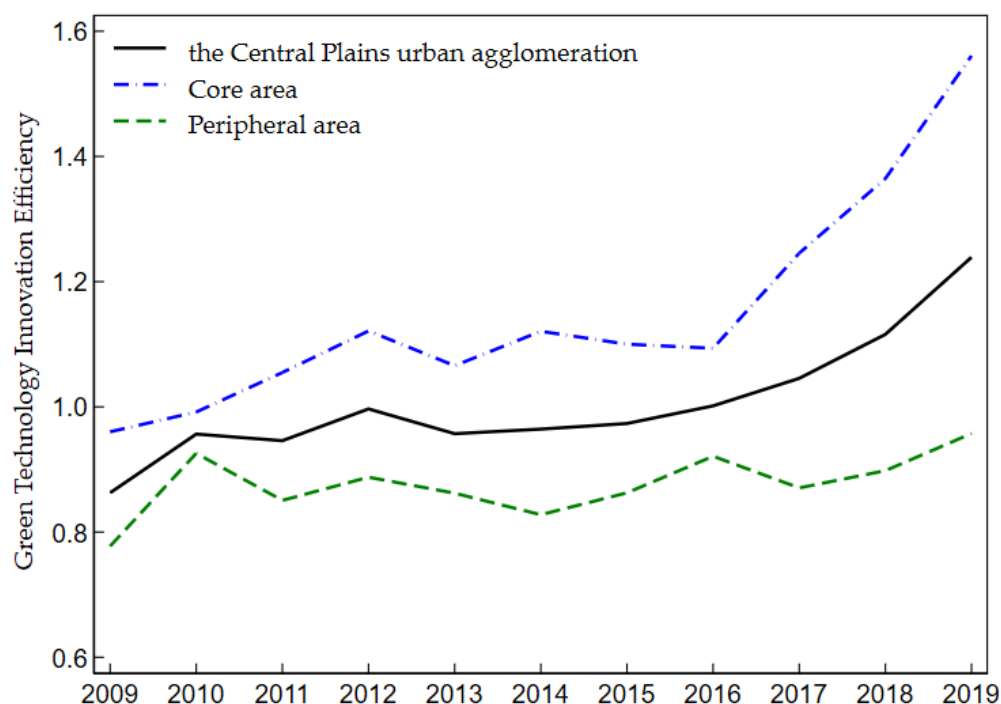


Figure 2. Trends of green technology innovation efficiency in the Central Plains city cluster from 2009 to 2019.

3.3.2. Spatial Evolutionary Pattern

Based on the measurement results and the natural breaks (Jenks) method, a spatial visualization map of green technology innovation efficiency in the Central Plains city cluster was drawn (as shown in Figure 3). It can be seen that there are obvious spatial differences in green technology innovation efficiency among cities in the Central Plains city cluster. In general, the green technology innovation efficiency of cities located in the core area and the eastern part of the Central Plains city cluster is higher, and the green technology innovation efficiency of the southeastern region remains stable during the study period, while the green technology innovation efficiency of the northwestern cities in the peripheral area is low. At the beginning of the study period (2009), there were 12 cities with green technology innovation efficiency at a high level (efficiency value greater than 0.8418), mainly distributed in the central and southern parts of the Central Plains city cluster. By the end of the study period (2019), the number of cities with high green technology innovation efficiency (efficiency value greater than 0.7394) increased to 19, and are mainly distributed in the eastern and southern parts of the Central Plains city cluster. Nine cities—Handan, Suzhou, Bozhou, Zhengzhou, Puyang, Xuchang, Nanyang, Xinyang, and Zhoukou—consistently ranked high in terms of green technology innovation efficiency throughout the study period.

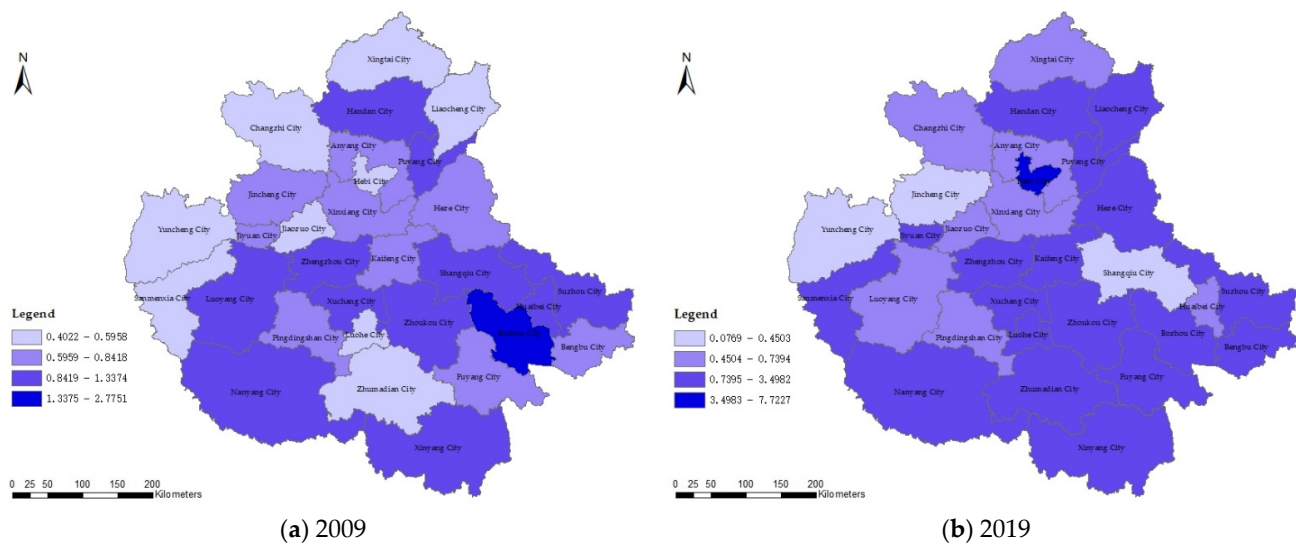


Figure 3. Spatial pattern evolution of green technology innovation efficiency in the Central Plains city cluster.

3.3.3. Spatio-Temporal Convergence Characteristics

The existing literature usually considers three types of convergence according to different convergence trends and meanings: σ convergence, absolute β convergence and conditional β convergence [42,43]. σ convergence mainly observes the changes of standard deviations of attribute variables, which can visually present the dynamic trend of regional differences of attribute variables, but lacks a rigorous statistical test of convergence characteristics. Absolute β convergence and conditional β convergence, on the other hand, circumvent this problem better and are favored by the majority of scholars. Therefore, according to the common practice in academia, the absolute β convergence test and the conditional β convergence test are used to determine whether the green technology innovation efficiency of the Central Plains city cluster has spatio-temporal convergence. Absolute β convergence means that a certain attribute value in different regions can achieve the same steady-state growth rate. Generally, the convergence coefficient is quantified by regressing the average growth rate of the attribute variable at the end of the period and the beginning of the period on the beginning level. The model of absolute β convergence test is as follows.

$$\frac{Y_{i,T} - Y_{i,0}}{T - 1} = \alpha + \beta_a Y_{i,0} + \mu_i \quad (2)$$

where $Y_{i,T}$ and $Y_{i,0}$ denote the ending and beginning values of attribute variables of the i th region, respectively. β_a is the absolute β convergence coefficient. If β_a is significantly negative, it indicates that there is an absolute convergence trend of this attribute variable among different regions, otherwise there is a divergence trend.

Conditional β convergence refers to the convergence of different region-specific attributes toward their respective steady-state growth rates after accounting for spatial heterogeneity, with the following basic regression model.

$$Y_{i,t} - Y_{i,t-1} = \alpha + \beta_c Y_{i,t-1} + \mu_{i,t} \quad (3)$$

where $Y_{i,t}$ and $Y_{i,t-1}$ denote the current period value and lagged period value of attribute variable of the i th region, respectively. β_c is the conditional β convergence coefficient. If β_c is significantly negative, it means that there is a trend of conditional convergence of attribute variable across regions, otherwise there is a trend of divergence.

Table 3 reports the results of the absolute β convergence and conditional β convergence tests for green technology innovation efficiency in the Central Plains city cluster from 2009–2019. First, the absolute β convergence coefficient is significantly negative and passes

the significance test at the 1% level, indicating that there is an absolute spatio-temporal convergence trend of green development efficiency in the Central Plains city cluster, with a convergence rate of $\lambda = 15.34\%$. Second, the conditional β convergence coefficient is significantly positive at the 10% level, indicating that there is no conditional convergence trend of green technology innovation efficiency in the Central Plains city cluster in space and time.

Table 3. Results of spatio-temporal convergence tests on green technology innovation efficiency in the Central Plains city cluster.

	Absolute β Convergence Test	Conditional β Convergence Test
β_a	−0.0784 *** (0.0112)	
β_c		0.0781 * (0.0473)
α	0.0928 *** (0.0108)	−0.0391 (0.0496)
λ	0.1534	
R^2	0.1311	0.0100
N	330	300

Note: Standard errors in parentheses; * $p < 0.1$, *** $p < 0.01$.

4. The Intrinsic Driving Mechanism of Green Technology Innovation

Green technology innovation refers to technology innovation activities and their accompanying results that are conducive to reducing the negative impact of social production and the living environment. Strengthening green technology innovation capability is an important way to improve resource utilization efficiency, enhance the resilience of regional economic development, and promote high-quality development of the “economy-society-environment” system [44]. By reviewing the literature, the possible factors for promoting green technology innovation cover three aspects: market, policy, and society, which are summarized as the following three effects (as shown in Figure 4).

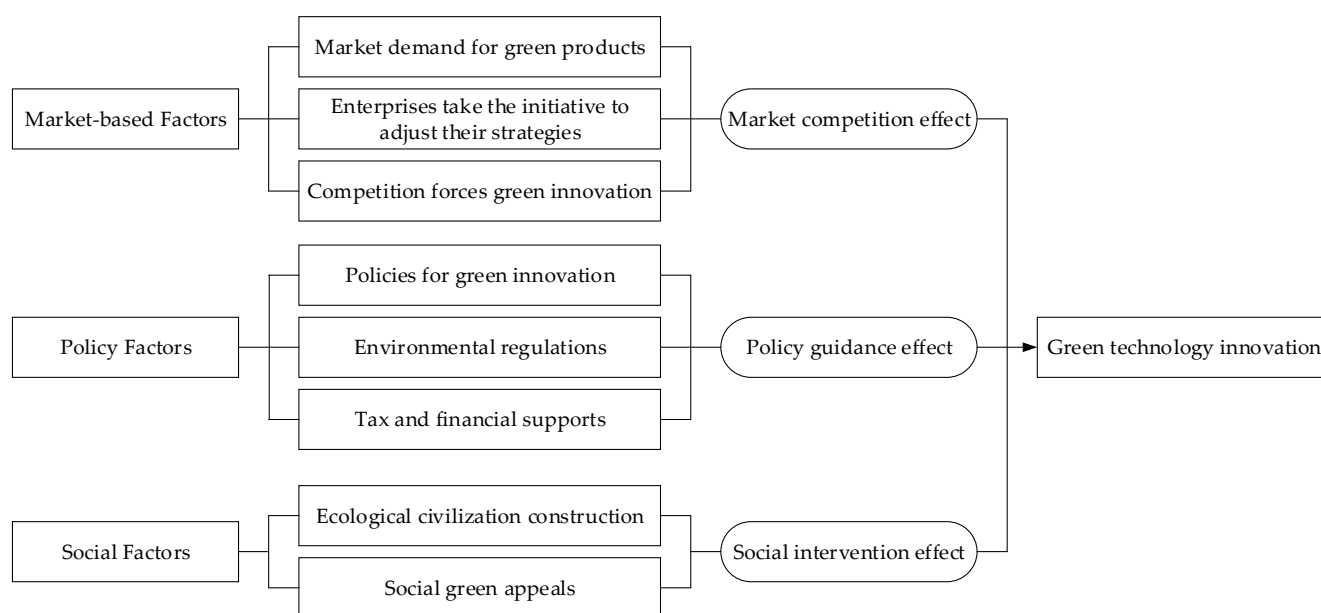


Figure 4. Schematic diagram of the intrinsic mechanism of promoting green technology innovation.

4.1. Market Competition Effect

With the improvement of residents’ living standards, their awareness of green environmental protection has gradually increased, the demand for consumer goods will

gradually diversify, and they will be more inclined to choose environmentally friendly goods [45]. As the most important market subject, enterprises must adjust their production and management decisions in the face of the market demand changing toward green products and they must shape their good green brand image to enable themselves to gain competitive advantages [46]. Meanwhile, there are many other competitors in the market who develop green products to gain more consumers and government support. To gain more resources and advantages, enterprises will actively and continuously promote green technology innovation. If enterprises are in a good competitive environment, they are better able to gain new knowledge, transfer new technologies, increase new revenues, and reduce the external cost of green innovation [47]. In summary, the market competition effect can ensure that enterprises obtain competitive advantages and economic benefits and enhance their enthusiasm for green technology research through the implementation of green technology innovation strategies.

4.2. Policy Guidance Effect

The government plays an extremely important guiding role in the process of promoting green technology innovation. On the one hand, the government can protect green technology innovation activities and promote green technology innovation by making laws and regulations; it can also make strict environmental policies to force enterprises to strengthen the research and application of green technologies, thus promoting green technology innovation [48]. On the other hand, the government can provide public services conducive to enterprises' green technology innovation activities, including green technology trading platforms and green environmental protection science and technology innovation platforms, and hence, it improve the green service system, increase investment in R&D, minimize the cost of green technology innovation of enterprises, create a good policy environment, and enhance the enthusiasm and initiative of enterprises in green technology innovation [49].

4.3. Social Intervention Effect

Technology construction theory points out that technology innovation is rooted in social factors and is produced under the interaction of specific politics, economy, culture and concepts [50]. In this sense, the development of green technology innovation activities is also closely related to the process of social development in China. First, since the 18th National Congress of the Communist Party of China, the construction of ecological civilization has been incorporated into the "Five-pronged overall plan" of socialism with Chinese characteristics. The harmonious development of human beings and nature has become an important component of the socialist core value system. Green has become a new concept leading China's high-quality development. The voice of the whole society seeking social sustainable development through green technology innovation is increasingly strong. Second, with the rapid development of the economy and urbanization, the living standards and education levels of people have significantly improved, and the demand for life has gradually changed from "expecting food, clothing and survival" to "expecting environmental protection and ecology", with green technology innovation being the fundamental means to meet this demand. Therefore, the intervention of all kinds of development factors in the process of social progress may provide a continuous impetus for green technology innovation.

5. Empirical Tests on Influencing Factors of Green Technology Innovation Efficiency in the Central Plains City Cluster

5.1. Research Hypotheses

We have analyzed the market competition effect, policy guidance effect and social intervention effect in promoting green technology innovation in Section 4, and the three effects constitute the theoretical framework of the drivers of green technology innovation. Based on the aforementioned mechanism analysis and drawing on the representative

research outcomes on green technology innovation available in academia, we attempt to empirically test the possible factors affecting green technology innovation efficiency in the Central Plains city cluster from the following eight aspects.

5.1.1. Economic Development

It is generally believed that the higher the economic development level is, the more it can attract funds for activities that support local green technology innovation and high-end innovation talent, thus generating a green incentive effect and cumulative innovation effect [51,52]. In addition, with the improvement of the regional economic development level, people's demand for a high-quality living environment will be more intense, inducing the transformation of enterprise innovation activities to environmentally friendly ones, thus promoting the improvement of green technology innovation efficiency. Based on this, we put forward the following hypothesis:

H₁: Economic development can create good market demand and provide material for green technology innovation, thus promoting the efficiency of green technology innovation in the Central Plains city cluster.

5.1.2. Industrial Structure

As an important basis for economic growth, industrial structure upgrading largely determines the pressure on regional resources and the environment and thus becomes an important factor affecting green technology innovation. From the general pattern of green development in major economies, industrial structure upgrading is usually accompanied by an "industrial structure dividend" [53], and the replacement of old and new industries leads to the gradual emergence of green production technologies, which enhances the momentum of industrial green technology innovation and thus promotes the efficiency of regional green technology innovation. Based on this, we propose the following hypothesis:

H₂: Industrial structure upgrading is beneficial for promoting green technology innovation efficiency in the Central Plains city cluster.

5.1.3. Opening Up

On the one hand, the introduction of foreign enterprises will bring competitive pressure to local enterprises and stimulate them to improve their technological level and product competitiveness, thus enhancing the economic benefits of green technology innovation while considering the resources and environment. On the other hand, the introduction of foreign investment may have a "pollution halo" and "pollution paradise" effect on the development of regional green innovation, as foreign investment will spread and diffuse advanced environmental protection production technology while also bringing backward production capacity into the local area [44]. Based on this, the following two opposing hypotheses are proposed.

H_{3a}: Expanding the opening to the outside world has a positive effect on green technology innovation efficiency in the Central Plains city cluster.

H_{3b}: Opening up may lead to the decline of the green technology innovation efficiency of the Central Plains city cluster.

5.1.4. Enterprise Performance

Theoretically, the improvement of enterprise performance will enable enterprises to obtain more abundant funds, which will be helpful in increasing the investment in green technology research and improve the level of green technology innovation. However, for real economic activities, there is often uncertainty about whether the improvement of enterprise performance has a significant green technology innovation effect, which is related to the size of the enterprise and the market environment in which it is located [54]. As a general rule, the increase in green R&D investment is more obvious for large enterprises with improved operational benefits, while smaller enterprises tend to spend their surplus funds on the expansion of reproduction and neglect the attention to green technology R&D.

A favorable market environment (often expressed as a higher degree of marketization) is useful for strengthening corporate social responsibility and green technology R&D [55]. However, it may also slow the pace of corporate green technology innovation due to the presence of certain market forces (e.g., monopolies and political affiliation) which are not conducive to enhancing the level of green technology innovation. Based on this, we introduce the following opposing hypotheses.

H_{4a}: The improvement of enterprise performance has a promoting effect on green technology innovation efficiency in the Central Plains city cluster.

H_{4b}: The improvement of enterprise performance hinders the efficiency of green technology innovation in the Central Plains city cluster.

5.1.5. Environmental Regulation

In the available studies, there are two contrasting views on the impact of environmental regulation on green technology innovation: the constraint hypothesis and the Porter hypothesis. The former argues that strengthening environmental regulation will increase the production burden of enterprises, resulting in their inability to sustainably promote the greening of production technologies [56,57]. The latter believes that strengthening environmental regulation can encourage enterprises to increase green R&D investment so that the benefits brought about by green technology innovation can offset the upfront cost and produce an innovation compensation effect [32,48]. The Central Plains city cluster is positioned as an innovation and entrepreneurship pioneer area and a green ecological development demonstration area in the central and western regions of China. Stricter environmental standards may have a greater innovation incentive effect. Based on this, the following hypothesis is proposed.

H₅: Strengthening environmental regulation has a positive incentive effect on green technology innovation efficiency in the Central Plains city cluster.

5.1.6. Government Support

Green technology innovation has a strong positive externality; enterprises usually have difficulty obtaining all innovation benefits but bear the high cost of innovation. In this way, the enthusiasm of enterprises to carry out green technology innovation will be highly discouraged. The government's financial and policy support for science and technology plays an important role in sustaining green technology innovation activities. By establishing public platforms and providing certain funds and preferential policies to create a good soft and hard environment, government support for enterprises to carry out green technology innovation activities plays an important supporting role in enhancing regional green technology innovation capacity [58,59]. Based on this, we put forward the following hypothesis.

H₆: Science and technology support from the government helps to improve the efficiency of green technology innovation in the Central Plains city cluster.

5.1.7. Human Capital

Human capital, mainly in the form of high-end technical talent, is the power source of green technology innovation activities. Human capital is composed of knowledge, technology, and ability that have economic value coalesced in workers, among which the education level is the most important factor affecting the formation of human capital [60]. With the improvement of people's education level, their requirements for life quality and living environment will also rise, and the demand for green products will increase, forcing enterprises to strengthen green technology research and the supply of green products, thus promoting regional green technology innovation efficiency [61]. Based on this, the following hypothesis is proposed in this paper.

H₇: Human capital has a facilitating effect on green technology innovation efficiency in the Central Plains city cluster.

5.1.8. Urbanization

As the level of urbanization rises, people's demand for quality of life increases, which requires both innovation-driven economic development and strengthened environmental management. Green technology innovation is the inevitable choice to meet both demands. Therefore, in the process of urbanization, people's yearning for green and high-quality life has become an important catalyst to stimulate green technology innovation. However, urbanization is also a double-edged sword. With the massive influx of population, urbanization may lead to various urban dilemmas, such as traffic congestion, environmental pollution and energy shortages, which may have negative effects on the efficiency of green technology innovation. At present, the Central Plains city cluster is in the stage of accelerated new urbanization, and under the intervention of various complex factors, the impact of urbanization on green technology innovation is uncertain, which may be both positive and negative [62]. Based on this, we propose the following two opposing hypotheses.

H_{8a}: Urbanization is conducive to the improvement of green technology innovation efficiency in the Central Plains city cluster.

H_{8b}: Urbanization is not favorable to the improvement of green technology innovation efficiency in the Central Plains city cluster.

5.2. Econometric Model

The first law of geography states that “everything is spatially dependent; the closer the distance, the stronger the dependence; the farther the distance, the weaker the dependence” [63], which determines the spatial dependence of economic and social activities in any space [64]. Besides, some studies have shown that green technology innovation has the characteristics of agglomeration and diffusion, and green innovation activities between regions have interactive influence based on factor flow [9]. Therefore, the traditional econometric model is not suitable to analyze the influencing factors of green technology innovation efficiency in the Central Plains city cluster, and the spatial econometric model should be used as an analysis tool. Most frequently used spatial econometric models include the spatial autoregressive model (SAR), spatial error model (SEM), and spatial Durbin model (SDM). However, the SAR model has the problem of fixed proportions in decomposing spatial effects, while the SEM model cannot decompose the spatial spillover effects of influencing factors [65]. Therefore, we adopt the SDM model containing both dependent and independent variables with spatial lags as the benchmark model for the analysis of spatial interaction effects of influencing factors of green technology innovation efficiency in the Central Plains city cluster. The general form of the SDM model is as follows.

$$\ln g_{tie_{it}} = \alpha + \rho W \ln g_{tie_{jt}} + X_{it} \beta + W X_{jt} \theta + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

where $\ln g_{tie}$ is the vector of explained variable and X is the matrix of explanatory variables composed of a series of influences. W is the matrix of spatial weights to measure the dependence between different spatial units. α denotes the intercept term, ρ is the spatial autoregressive coefficient, and β and θ denote the vector of regression coefficients of the explanatory variables and their spatial lagged terms, respectively. μ_i , λ_t , and ε_{it} represent spatial fixed effects, time fixed effects, and random perturbation terms of the model, respectively.

5.3. Description of Indicators and Data

The explained variable (green technology innovation efficiency of each city in the Central Plains city cluster), $\ln g_{tie}$, was calculated according to the method provided in Section 3 and was logged to attenuate the possible impacts of heteroskedasticity.

The explanatory variables include:

1. Economic development level ($\ln rpgdp$). Measured by real gross domestic product per capita, using a logarithmic form.

2. Industrial structure upgrading (*indupgrd*). The proxy indicator is industrial structure upgrading index, which is calculated according to the method provided by Gan et al. (2011) [66].
3. Degree of opening-up (*open*). Measured by the share of foreign direct investment in regional GDP.
4. Enterprise performance (*epi*). Measured by the proportion of total profits to total assets of industrial enterprises above designated size.
5. Environmental regulation intensity (*er*). With reference to the method of Wang and Li (2015) [67], we construct a comprehensive index of environmental regulation intensity based on industrial waste water emissions, industrial sulfur dioxide emissions and industrial dust emissions.
6. Government support for science and technology (*govsts*). Measured by the share of science and technology expenditures in total fiscal expenditures.
7. Human capital (*lnhstu*). Measured by the number of college students per 10,000 population, using a logarithmic form.
8. Urbanization level (*urbzn*). Measured by the urbanization rate of resident population (the proportion of urban population in the resident population).

The data of basic indicators for calculating the above variables are mainly taken from the China City Statistical Yearbook, the Hebei Statistical Yearbook, the Shanxi Statistical Yearbook, the Anhui Statistical Yearbook, the Shandong Statistical Yearbook, the Henan Statistical Yearbook, and the statistical yearbooks of related cities. It should be noted that the raw data of GDP per capita is calculated at current prices, which is not comparable from year to year. In this paper, we deflate it based on 2009 constant prices. The original data unit of foreign direct investment that is used for calculating the level of opening-up is “USD 10000”. We convert this into “100 million yuan” based on the period average exchange rate of RMB to USD. As for the spatial weight matrix $\mathbf{W}$, it is constructed based on the queen adjacency relation: if city i and city j share a common boundary or vertex, the element $w_{ij} = 1$ in matrix $\mathbf{W}$, otherwise $w_{ij} = 0$. Table 4 reports the descriptive statistics of variables used in the empirical analysis.

Table 4. Descriptive statistics of variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
<i>lngtie</i>	330	−0.1149	0.4643	−2.5649	2.0442
<i>lnrpgdp</i>	330	10.3095	0.4958	8.8940	11.5048
<i>indupgrd</i>	330	0.7414	0.2605	0.2664	1.5600
<i>open</i>	330	2.2581	1.5828	0.0088	7.2079
<i>epi</i>	330	9.7983	5.2565	0.2848	33.8216
<i>er</i>	330	0.4825	0.6676	0.0000	4.8535
<i>govsts</i>	330	1.2490	0.7429	0.2247	4.9916
<i>lnhstu</i>	330	4.4837	0.7769	2.8532	6.9489
<i>urbzn</i>	330	46.2048	9.4512	19.5925	74.5798

5.4. Empirical Results and Discussion

5.4.1. Testing and Selection of the Spatial Panel Model

First, the statistical applicability of the spatial panel regression model was tested with the help of the global Moran’s I. The result (row 1 in Table 5) shows that the mean value of Moran’s I of green technology innovation efficiency in the Central Plains city cluster during the study period is 0.1604, and the corresponding accompanying probability is less than 10%, indicating that there is indeed a spatial correlation of green technology innovation efficiency in the Central Plains city cluster. Therefore, we should use a spatial panel model to examine the possible factors affecting green technology innovation efficiency in the Central Plains city cluster. Second, although Elhorst (2014) theoretically stated that the SDM model is superior to the SAR model and the SEM model in most cases, it is still necessary to verify through data [65]. We estimated the three models and then determined

whether the SDM model could be degraded to the SAR model or the SEM model with the help of the LR test and Wald test. The results (rows (2)–(5) in Table 5) show that both the LR test and Wald test reject the null hypothesis that the SDM model degenerates into the SAR model or SEM model at the significance level of 1%, so it is more suitable to use the SDM model to empirically test the influencing factors of green technology innovation efficiency in the Central Plains city cluster. Finally, the Hausman test is used to determine whether the SDM model should use fixed effects or random effects. The result (row 6 in Table 5) shows that the Hausman test statistic is 31.2028, with a concomitant probability much lower than 1%; thus, the null hypothesis of random effect should be rejected. According to the above tests, we should adopt the fixed-effect SDM model to conduct a benchmark regression on the influencing factors of green technology innovation efficiency in the Central Plains city cluster.

Table 5. Tests for the selection of spatial panel model form.

No.	Test	Statistic	<i>p</i> -Value
(1)	Moran's I	0.1604 *	0.0756
(2)	LR Test for SDM→SAR	53.4052 ***	0.0000
(3)	LR Test for SDM→SEM	51.563 1 ***	0.0000
(4)	Wald Test for SDM→SAR	58.5339 ***	0.0000
(5)	Wald Test for SDM→SEM	60.6025 ***	0.0000
(6)	Hausman Test	31.2028 ***	0.0001

Note: Standard errors in parentheses; * $p < 0.1$, *** $p < 0.01$.

5.4.2. Analysis on the Estimated Results

Based on the adjacency spatial weight matrix, Table 6 reports the estimated results of fixed-effect SDM. It can be seen that the spatial autoregressive coefficient (ρ) passes the test at the 1% significance level, which is consistent with Moran's I test. Meanwhile, the regression coefficients of most explanatory variables and their spatial lagged terms pass the significance test, indicating that the overall performance of the model is good. However, according to LeSage and Pace (2009), the parameter estimates of the SDM model do not truly reflect the marginal effects of the explanatory variables on the explained variable due to the presence of feedback effects arising from endogenous spatial interaction terms. We need to decompose them into direct and indirect effects (spatial spillover effects) with the help of partial differential equations [68]. Table 7 reports the results of the decomposition of direct and indirect effects for the fixed-effect SDM model. Next, we will explain the market-based, policy and social factors that affect green technology innovation efficiency in the Central Plains city cluster based on Table 7.

Table 6. Estimation results of SDM model based on adjacency spatial weight matrix.

Variable	Coef.	Std. Err.	Variable	Coef.	Std. Err.
<i>_cons</i>	0.2646 ***	0.0108	$W \times lngtie(\rho)$	0.1561 ***	0.0607
<i>lnrpgdp</i>	0.8787 ***	0.3132	$W \times lnrpgdp$	1.0618 **	0.4678
<i>indupgrd</i>	0.0229 **	0.0108	$W \times indupgrd$	0.0405 ***	0.0152
<i>open</i>	0.0696 *	0.0363	$W \times open$	−0.2262 ***	0.0780
<i>epi</i>	−0.0132 **	0.0065	$W \times epi$	−0.0366 **	0.0143
<i>er</i>	0.1403 ***	0.0396	$W \times er$	0.2662 **	0.1172
<i>govsts</i>	0.0780 *	0.0428	$W \times govsts$	0.0770 *	0.0410
<i>lnhstu</i>	−0.4976 ***	0.1150	$W \times lnhstu$	−0.6541 *	0.3423
<i>urbzn</i>	0.0071	0.0088	$W \times urbzn$	−0.0037	0.0188
R^2	0.0099		AIC	90.9710	
N	330		BIC	159.3547	

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7. Spatial effect decomposition of SDM model based on adjacency spatial weight matrix.

Variable	Direct Effect		Indirect Effect		Total Effect	
	dy/dx	Std. Err.	dy/dx	Std. Err.	dy/dx	Std. Err.
<i>lnrpgdp</i>	0.8531 ***	0.3066	0.9441 **	0.4503	1.7972 **	0.8040
<i>indupgrd</i>	0.0519 **	0.0226	0.0660 ***	0.0250	0.1179 ***	0.0431
<i>open</i>	0.0637 *	0.0356	−0.2198 ***	0.0792	−0.1561 *	0.0804
<i>epi</i>	−0.0143 **	0.0065	−0.0395 ***	0.0149	−0.0538 ***	0.0153
<i>er</i>	0.1483 ***	0.0406	0.2942 **	0.1206	0.4425 ***	0.1392
<i>govsts</i>	0.0762 *	0.0428	0.0661 *	0.0380	0.1423 *	0.0776
<i>lnhstu</i>	0.5179 ***	0.1172	0.7472 **	0.3559	1.2651 ***	0.4051
<i>urbzn</i>	0.0070	0.0088	−0.0026	0.0192	0.0044	0.0216

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

(1) Economic development has a significant supporting effect on the improvement of green technology innovation efficiency in the Central Plains city cluster, which verifies Hypothesis H₁. The direct effect and indirect effect are positive at the 1% and 5% significance levels, respectively, indicating that economic development not only helps improve local green technology innovation efficiency but also promotes green technology innovation efficiency in neighboring cities. The positive spatial spillover effect implies that the economic development competition among cities in the Central Plains city cluster is healthy, which results in a synergistic promotion effect on the efficiency of green technology innovation.

(2) Industrial structure upgrading not only directly pulls the efficiency of green technology innovation in the Central Plains city cluster, but also has a significant positive spillover effect. The direct, indirect and total effects of the variable *indupgrd* are significantly positive in Table 7, which is consistent with Hypothesis H₂. Some studies have shown that industrial structure upgrading contains strong green development competitiveness [17,69]. Along with the industrial transformation and upgrading of the Central Plains city cluster, the rapid development of strategic emerging industries such as energy conservation and environmental protection, new energy, and new energy vehicles have gathered abundant high-end green development factors for the development of the Central Plains city cluster, thus strongly driving its green technology innovation efficiency.

(3) The opening-up provides an external dividend for the improvement of green technology innovation efficiency in the Central Plains city cluster, but the spatial spillover effect has a tendency of vicious bottom-up competition. The direct effect of the *open* variable is significantly positive at the 10% level, indicating that expanding openness through the introduction of foreign investment can bring advanced green production technology and management modes to the Central Plains city cluster and promote the local green technology innovation efficiency, which is consistent with Hypothesis H_{3a}. However, the indirect effect of openness is significantly negative at the 1% level and leads to a significant negative total effect, which means that the entry of foreign capital causes competition among cities in the Central Plains urban agglomeration and generates inefficient market competition, causing some backward production capacity and pollutants to be taken over by neighboring cities and becoming a “pollution haven” for low-end foreign capital [70]. As a result, the overall green technology innovation efficiency of the Central Plains city cluster is impaired, which confirms Hypothesis H_{3b} to some extent.

(4) The improvement of enterprise operating performance fails to effectively translate into the accumulation of green technology innovation in the Central Plains city cluster, but becomes an obstacle to the improvement of green technology innovation efficiency. The direct and indirect effects of variable *epi* in Table 7 are significantly negative at the 5% and 1% levels, respectively, verifying Hypothesis H_{4b} but contradicting Hypothesis H_{4a}. There are two possible reasons for this result. First, traditional industries still occupy a major share of the industrial structure of cities in the Central Plains city cluster, making it possible for enterprises to enhance their operational performance to reinforce traditional production technology preferences and, hence, they lack the motivation to conduct green technology

research, which directly inhibits the efficiency of green technology innovation. Second, over a certain period, market share is relatively stable. The increased profitability of local enterprises means that enterprises in neighboring cities have poor operating performance and are less able to bear the R&D investment required for green technology innovation in an increasingly competitive market environment. As a result, the efficiency of green technology innovation in neighboring cities declines [71].

(5) Strengthening environmental regulation can effectively motivate green technology innovation activities and enhance green technology innovation efficiency in the Central Plains city cluster. The direct and total effects of variable *er* in Table 7 are significantly positive at the 1% level, which is consistent with the expectation of Hypothesis H₅, indicating that the current environmental regulation policies implemented in the Central Plains city cluster have a direct promotion effect on the efficiency of green technology innovation in the cities. In addition, the indirect effect of variable *er* is significantly positive at the 5% level, indicating that strengthening environmental regulation has a favorable spillover effect on the efficiency of green technology innovation in the Central Plains city cluster. This may be mainly due to the good design of the development plan of the Central Plains city cluster, where environmental regulation presents a positive competition, leading it to promote local green technology innovation efficiency while providing incentives for neighboring cities to carry out green technology innovation activities.

(6) Government support for science and technology strongly pulls the development of green innovation in the Central Plains city cluster and becomes an important driver for the improvement of green technology innovation efficiency. The direct, indirect and total effects of variable *govsts* in Table 7 is statistically significant at the 10% level, confirming Hypothesis H₆. According to the theoretical analysis, by increasing R&D expenditures, the government can remove the worries for enterprises to carry out green technology innovation [72], thus enhancing the enthusiasm and initiative of enterprises in terms of green technology innovation and improving green technology innovation efficiency in the region. Along with the innovation-driven transformation and upgrading of industries in the Central Plains city cluster, the government has provided substantial support in establishing basic innovation platforms and increasing investment in innovation R&D. The policy guiding effect of green innovation is remarkable, which has laid a solid foundation for improving the efficiency of green technology innovation in the Central Plains city cluster. In addition, when local cities increase science and technology support, surrounding cities will also strengthen science and technology support due to the dual pressure of innovation competition and environmental governance, thus producing a positive spatial spillover effect of green innovation.

(7) Human capital provides talent support for green technology innovation in the Central Plains city cluster and has become one of the important sources to promote the efficiency of green technology innovation. The direct effect of variable *lnhstu* in Table 7 is statistically significant at the 1% level, which is consistent with the expectation of Hypothesis H₇, indicating that with the increase in high-end talent, the green technology innovation efficiency in the Central Plains city cluster is directly enhanced. Moreover, the indirect effect of the variable *lnhstu* passes the significance test at the 5% level, indicating that human capital can form a positive spillover to neighboring cities while promoting local green technology innovation efficiency. The main reason is perhaps that the convenient transportation network of the Central Plains city cluster is favorable to the free flow of high-quality talent between cities, and the knowledge spillover formed through the flow of talent promotes the simultaneous improvement of green technology innovation efficiency in neighboring cities.

(8) Urbanization has no significant impact on green technology innovation efficiency in the Central Plains city cluster. Even at the significance level of 10%, both the direct and indirect effects of the *urban* variable in Table 7 fail to pass the test, and Hypotheses H_{8a} and H_{8b} cannot be confirmed, indicating that urbanization fails to create a good social environment for the enhancement of green technology innovation efficiency in the Central

Plains city cluster. The reason for this result is perhaps that the development mode of the Central Plains city cluster is still relatively extensive in the process of urbanization, and the quality of urbanization development is not taken into account. Therefore, the potential of green development factors has not been fully released, which restricts the improvement of green technology innovation efficiency in the Central Plains city cluster.

5.4.3. Robustness Tests

To guarantee the reliability of the above estimation results, this paper adopts two methods to conduct robustness tests. Meanwhile, according to the previous analysis, the model regression coefficients are not true marginal effects and should focus on the interpretation of direct and indirect effects, so the robustness tests only show the results of spatial effect decomposition. First, considering that the spatial weight matrix setting has a significant impact on the estimation results of the spatial regression model, the previous results still hold if the spatial weight matrix is replaced, indicating that our study is robust. Specifically, the inverse distance spatial weight matrix is used to replace the adjacency weight matrix to re-estimate the SDM model, and the results are shown in Table 8. As seen, the direct, indirect and total effects of all explanatory variables remain largely consistent with Table 7 in terms of sign direction and significance level, although there is some variation. Second, changes in the form of the spatial regression model may also affect the robustness of the regression results. Following the suggestion of Vega and Elhorst (2015), we re-estimate the impact of all influencing factors on the efficiency of green technology innovation in the Central Plains city cluster using the SLX model that only contains spatial lags of explanatory variables [73], and the results are shown in Table 9. The results show that the direct, indirect and total effects of each explanatory variable on green technology innovation efficiency in the Central Plains city cluster remain highly consistent with Table 7. Based on the above tests, the conclusions of our empirical analysis are highly plausible.

Table 8. Spatial effect decomposition of the SDM model based on an inverse distance spatial weight matrix.

Variable	Direct Effect		Indirect Effect		Total Effect	
	dy/dx	Std. Err.	dy/dx	Std. Err.	dy/dx	Std. Err.
<i>lnrpgdp</i>	0.8490 **	0.3501	1.1337 *	0.5829	1.9827 *	1.1794
<i>indupgrd</i>	0.0618 **	0.0265	0.0876 *	0.0454	0.1494 **	0.0646
<i>open</i>	0.1010 ***	0.0353	−0.2685 ***	0.0937	−0.1674 *	0.0872
<i>epi</i>	−0.0157 **	0.0070	−0.0148 *	0.0078	−0.0305 *	0.0150
<i>er</i>	0.1310 ***	0.0409	0.7424 **	0.3122	0.8734 ***	0.3200
<i>govsts</i>	0.0776 *	0.0453	0.0481 ***	0.0118	0.1257 ***	0.0357
<i>lnhstu</i>	0.4343 ***	0.1176	1.3535 ***	0.5106	1.7878 ***	0.5028
<i>urbzn</i>	0.0098	0.0090	−0.0270	0.0218	−0.0172	0.0205

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 9. Spatial effect decomposition of the SLX model based on an adjacency spatial weight matrix.

Variable	Direct Effect		Indirect Effect		Total Effect	
	dy/dx	Std. Err.	dy/dx	Std. Err.	dy/dx	Std. Err.
<i>lnrpgdp</i>	0.8518 ***	0.3146	0.8989 **	0.4173	1.7507 **	0.7202
<i>indupgrd</i>	0.0335 **	0.0153	0.0254 ***	0.0096	0.0589 ***	0.0205
<i>open</i>	0.0641 *	0.0363	−0.2016 ***	0.0697	−0.1375 **	0.0676
<i>epi</i>	−0.0138 **	0.0066	−0.0342 ***	0.0128	−0.0480 ***	0.0126
<i>er</i>	0.1447 ***	0.0397	0.2676 ***	0.1029	0.4123 ***	0.1173
<i>govsts</i>	0.0780 *	0.0430	0.0872 **	0.0409	0.1652 **	0.0783
<i>lnhstu</i>	0.5101 ***	0.1155	0.6533 **	0.3025	1.1634 ***	0.3399
<i>urbzn</i>	0.0074	0.0088	−0.0060	0.0167	0.0014	0.0184

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6. Conclusions and Implications

6.1. Research Conclusions

In this paper, we use the SBM-DEA model to evaluate green technology innovation efficiency and its spatial and temporal characteristics in the Central Plains city cluster from 2009 to 2019. Furthermore, on the basis of clarifying the intrinsic driving mechanism of green technology innovation, a panel SDM model is used to empirically investigate the influencing factors of green technology innovation efficiency. The conclusions of this paper are as follows. First, the green technology innovation efficiency in the Central Plains city cluster shows a fluctuating upward trend with obvious spatial differences, but these spatial differences have converged somewhat over time. Second, market-based factors have different impacts on the efficiency of green technology innovation in the Central Plains city cluster. Economic development and industrial structure upgrading are the dominant market forces driving the efficiency of green technology innovation in the Central Plains city cluster, while the degree of opening-up and enterprise performance improvement do not contribute to green technology innovation efficiency in the Central Plains city cluster. Third, policy factors have a positive guiding impact on the efficiency improvement of green technology innovation in the Central Plains city cluster. By strengthening environmental regulation and scientific and technological support, the government has strongly promoted green technology innovation efficiency in the Central Plains city cluster. Fourth, there is variability in the influences of social factors on green technology innovation efficiency in the Central Plains city cluster. Human capital becomes an important source of promoting green technology innovation efficiency by providing abundant talent support for green technology innovation. In contrast, urbanization fails to have a substantial impact on green technology innovation efficiency. Fifth, geographic space cannot be ignored in influencing the efficiency of green technology innovation. All market-based, policy and social factors except urbanization have significant spatial spillover effects on green technology innovation efficiency in the Central Plains city cluster.

6.2. Policy Implications

According to the above findings, several policy implications aimed at further promoting green technology innovation efficiency in the Central Plains city cluster can be mentioned:

(1) Significantly promote the green transformation and upgrading of the industrial structure. Focusing on coal, building materials, nonferrous metals and other pillar traditional industries in the Central Plains city cluster, we must strengthen the research on key technologies for green transformation and enhance the green innovation capacity of traditional production capacity. We need to enhance the core technology reserve of green emerging capacity and boost green emerging industries such as energy conservation and environmental protection, new energy vehicles, and new energy equipment. The integrated development of the manufacturing and service industries should be actively promoted, the connection between energy conservation and environmental protection technology service companies and manufacturing enterprises should be strengthened, and the professional application of green energy-saving technologies should be promoted.

(2) It's necessary and urgent to improve the quality of opening-up. On the one hand, the Central Plains city cluster should actively introduce high-quality foreign-invested enterprises, learn their advanced production technology and management philosophy, upgrade backward production equipment and improve comprehensive service functions. On the other hand, the government should strictly control the access mechanism of investment attraction, avoid the problem of "pollution haven" due to undertaking pollution-intensive industries from developed countries (regions), and give preferential subsidies to foreign enterprises to encourage them to carry out green technology innovation activities.

(3) Continue to strengthen environmental regulation and play the role of forcing and encouraging enterprises' green technology innovation on the premise of strict environmental regulation to promote environmental governance "management and service" reform.

We need to develop scientific control policies to address outstanding environmental issues and enhance the effectiveness of environmental policies and require high pollution and high emission enterprises to design green technology improvement programs that meet their own conditions and broaden technological transformation and upgrading in an orderly manner within a certain period.

(4) Government financial support for green technology innovation needs to be increased. We must ensure that government spending on science and technology is guided by green innovation and create a market environment with green innovation as a competitive advantage. Meanwhile, special funds for green technology innovation should be set up to expand green financing channels for enterprises. In addition, it is necessary to improve the local financial expenditure system for science and technology according to the heterogeneity of green development in each city and to determine key development projects around areas with energy conservation and emission reduction, clean energy, and green environmental protection.

(5) We need to improve the rules and institutions for cultivating and introducing talent. We should firmly establish the concept that talent is the source of power to support green technology innovation, develop strategic development plans that are helpful to cultivate, attract and retain talent, and improve the social security system so that high-end talent engages in green technology innovation without worries. Moreover, we should strengthen basic and higher education, increase curriculum and research projects in fields related to environmental protection and innovation-driven development, and promote the integration of human capital accumulation and green innovation activities.

(6) The enthusiasm of enterprises for green technology innovation needs to be encouraged. We should step up the protection of the intellectual property rights of green technology to safeguard the benefits of enterprises' innovation. It is necessary to set up special research and development projects for green technology innovation in areas with significant market demand, such as energy conservation and environmental protection, clean energy, and cleaner production, and promote the market-based application of green technology research and development results. Optimizing the enterprise service process reduces all kinds of shackles that restrict the development of enterprises and reduce their cost of production and operation so that enterprises have sufficient confidence to transform the operational benefits into green technology innovation.

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