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Green Technology Innovation and High-Quality Economic Development: Spatial Spillover Effect*

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Abstract:

Against the background of green development, green technology innovation is an important driving force for high-quality economic development. Countries are facing energy shortages, environmental deterioration and other issues that limit high-quality economic development by extending green technology innovation. The study aims to investigate the impact of green technology innovation and its spillover effect on high-quality economic development. For this purpose, the study applies panel data on 30 provinces in China from 2010 to 2019 to construct a spatial Durbin model. The study finds that green technology innovation in the region plays a positive role in promoting high-quality economic development. The findings show that green technology innovation in the Eastern Region could promote high-quality economic development. Nevertheless, the role of the Central and Western Regions is not significant and negative. Green technology innovation in the Central and Eastern Regions shows a significant positive role in promoting the high-quality economic development level of the surrounding areas. However, spillover effects in the Western Region are not obvious.

Keywords: Green technology, green growth, sustainable development, economic growth, innovation

JEL: O13, O44, P18, P28, Q2, Q5

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1. Introduction

All countries face a series of issues related to rapid resource consumption and energy resource shortages. In this case, it is necessary to develop relevant incentives and mechanisms to boost green technology innovation (GTI) to solve the abovementioned issues. Promoting green development, establishing and improving the economic system of green and low-carbon circular development, and building a market-oriented GTI system are the key parts of promoting economic growth (Shpak et al., 2021; Artyukhov et al., 2021). The report of the 19th People's Congress of the Communist Party of China (2017) clearly stated that it is necessary to build a market-oriented GTI system to drive economic growth with innovation. As an important way to achieve sustainable economic, social, and ecological development, GTI could improve regional GTI capabilities and optimise the spatial pattern of development. In addition, it enhances the efficiency of resource allocation, the structure of the industry, and the quality and efficiency of economic growth.

Endogenous economic growth theory holds that technological progress is the determining factor of economic development. Technological innovation has gradually become an important way for China to achieve economic transformation and improve its comprehensive strength with the rapid development of the digital economy and Internet information technology. Moreover, technological innovation is important in promoting economic growth and social development (Wang et al., 2021). As an important way to achieve sustainable economic, social, and ecological development, GTI could save resources and reduce environmental pollution by greening production, increasing energy efficiency, conserving energy, etc. (Chen et al., 2022). Furthermore, it could improve the competitiveness of enterprises, improve regional GTI capabilities, and optimise the spatial pattern of development. Chygryn et al. (2020) concluded that GTI boosts companies' green competitiveness.

In addition, it enhances the efficiency of resource allocation, promotes optimisation and upgrading of the industrial structure, improves the quality and efficiency of economic growth, and promotes high-quality development of the economy (Acemoglu et al., 2012; Gavkalova et al., 2022; Lahouirich et al., 2022). In promoting high-quality economic development (HQED), GTI has a double-threshold effect on financial development and some intermediary effects on industrial upgrading and rationalisation (Sun et al., 2021; He et al., 2021; Braun and Wield, 1994; Zhu and Xiao, 2021). Scholars have mostly studied the industrial structure, environmental regulation, green finance, and other aspects of GTI. The research into the relevant theoretical system tends to be perfect, but there is less research into the relationship between GTI and HQED. All countries in the world are facing energy shortages, environmental deterioration, and other issues, such as how to achieve HQED through GTI to drive the economy, which is a key academic concern.

As China has entered a new stage of development – "high quality", the inherent requirement of economic growth, accelerating the construction of ecological civilisation and building a market-oriented GTI system are the top priorities for China's future development. Thus, under the goal of the 19th People's Congress of the Communist Party of China (2017) "steady world, steady progress", the following research questions are underlined: Can GTI effectively promote high-quality economic development (HQED)? Is there a spatial spillover effect? Is there spatial heterogeneity? This paper aims to study the impact of GTI and its spillover effect on HQED for 30 provinces in China from 2010 to 2019. The paper contributes to the theoretical framework by developing (1) approaches for the assessment of GTI and HQED based on the entropy method; (2) approaches for identifying the spillover effect of GTI on HQED between regions based on global Moran's I index and local Moran's index; and (3) a methodology to check the impact of GTI and HQED based on the spatial autoregressive (SAR) model, spatial error model (SEM) and spatial Durbin model (SDM). It allows outlining the policy implications for countries to optimise industrial policies according to local conditions and alleviate the tense energy crisis.

The paper is structured as follows: Section 2 is a literature review, exploring the theoretical landscape of GTI and HQED assessment and core influencing indicators; Section 3 presents the methodology, describing the data, instruments and methodology to estimate GTI and HQED and check the GTI impact and a spillover effect on HQED; the results of the investigation are presented in Section 4; and Section 5 contains discussion and conclusions, describing core empirical results and policy implications considering the findings.

2. Literature Review

When economic development reaches a certain stage, more attention is given to innovative green development, environmental protection and energy conservation. The transformation of this development concept benefits from green growth, innovation, and other ecological policies that the Chinese government has been advocating in recent years. Furthermore, studies have concluded that GTI is expected to produce a double dividend of balancing environmental protection and promoting economic development (Tovar and Martín-Cejas, 2010; Yan and Qi, 2017; Wang et al., 2019).

2.1 Innovative effect of GTI

GTI itself is an innovation. GTI could alleviate the shortage of innovation resources, guide enterprises to a green development mode, and play an important role in promoting sustainable development of the economy. In addition, it also helps to optimise industrial development patterns, optimise the industrial structure, alleviate the energy crisis, promote HQED, and provide a reference value for promoting China's rapid and sustainable development. It should be noted that studies have proven the positive effect of smart technologies on extending green innovations among all sectors and levels (national, regional and local) (Kuzior et al., 2019;

Andros et al., 2021; Kwilinski et al., 2019; Zhang, 2015). Peng et al. (2021) applied the spatial Durbin model (SDM) to prove that the GTI positively affects the HQED of Chinese cities. In addition, Zhou et al. (2021) used decomposition analysis based on the logarithmic mean Divisia index to explain the heterogeneity of GTI. Zhou et al. (2021) concluded that research and development (R&D) plays a core role in spreading GTI. Zeng et al. (2022) applied slack-based measures and the global Malmquist-Luenberger index to analyse the role of GTI in achieving carbon neutrality under sustainable development. They concluded that GTI allows declining carbon emissions and achieves carbon neutrality development.

2.2 Coordination effect of GTI

GTI includes process innovation through improving enterprise hardware equipment to improve the enterprise's energy utilisation and green manufacturing capabilities. It leads to effectively reducing the enterprise's energy consumption and pollution emissions and then reducing the costs of enterprise energy purchase and pollution control. At the same time, energy conservation and emission reduction lead to a compression of production costs, prompting enterprises to change the traditional production model of high chain inputs and low outputs and high energy consumption and high pollution. It effectively spreads clean technology governance and environmental protection signals. At the same time, it also plays the role of "survival of the fittest". Li and Gao (2022) used the tripartite evolutionary game model to analyse the reasons for investing in GTI companies. They concluded that companies would invest more in GTI if the gap between prices on different levels of technologies increased. In addition, Li and Gao (2022) highlighted that implementing GTI with relevant environmental regulation in companies allows a reduction in negative environmental impacts. A similar approach was applied by Wang et al. (2021). Their findings showed that GTI allows declining resource use and increases companies' performance. However, it would be achieved if all stakeholders (government, businesses, consumers) had mutual goals for greening growth. It should be noted that transferring high-energy-consuming industries to low-emission, low-pollution and low-energy-consuming industries brings structural dividends. Consequently, it promotes technological innovation in upstream and downstream sectors through the forced effect of affiliated enterprises to achieve the harmonious development of humans and nature.

2.3 Sustainable effect of GTI

Green technology conserves resources, reduces pollution, achieves sustainable development, and promotes green growth, and GTI continues to promote green growth. It will become an important support for promoting the progress of ecological civilisation, adhering to pollution prevention and control, and promoting HQED. Promoting GTI, taking the road of sustainable development, enhancing environmental protection awareness, and promoting HQED are also inevitable choices to promote the transformation of the economic development mode. Asadi et al. (2020) applied partial least squares structural equation modelling (PLS-SEM) and confirmed that GTI positively affects hotels' financial performance. Asadi et al. (2020) analysed a case of 183 hotels in Malaysia. Weng et al. (2015) confirmed the hypothesis that GTI positively affects environmental and economic performance. For this purpose, the study applied partial least squares (PLS) analysis and used data from 202 Taiwanese companies. Furthermore, the findings of Ge et al. (2018) showed that the implementation of GTI allowed sustainable competitive advantages for 241 Chinese green firms. In this regard, the study breaks through traditional technological innovation, implements green innovation, and changes the conventional economic development mode, which is the main driving force for HQED.

2.4 Open effect of GTI

The open effect of GTI is mainly reflected in the costs and high-quality environmental attraction effects. GTI could effectively improve production efficiency of enterprises, enhance product quality while compressing production costs, expand market share and promote expansion of enterprises' foreign trade business. It should be noted that the high-quality environment attraction effect refers to the high-quality production of a high-quality ecological environment, and a good industrial environment has a strong attraction for foreign investment. GTI could effectively promote the optimisation and upgrading of the environmental and industrial structure and then promote open development. In addition, GTI requires relevant financial support, which cannot be attracted without a sufficient level of HQED. On the other hand, stakeholders do not invest in GTI without understanding the direct and indirect social, economic and ecological effects (Chygryn and Krasniak, 2015). In addition, Gajdzik and Sroka (2021), based on the steel industry, confirmed that green investment in new technologies decreases the anthropogenic environmental impacts. Based on US and Ukrainian experience, the findings of Sotnyk et al. (2018) showed that feed-in tariffs and green credits were the most effective incentives to spread GTI among households.

2.5 Sharing effect of GTI

GTI contributes to protecting the ecological environment and provides people with more high-quality green products. As far as environmental quality is concerned, the high-quality ecological environment is jointly owned by members of society. Environmental quality is related to the health and quality of life of the masses. In addition, GTI could not have sufficiently penetrated society without relevant education. Thus, increasing financing for green education is the core trigger in GTI implementation and HQED. Vekic et al. (2020) confirmed that investment in green education allows achieving the region's sustainable development. In addition, Titko et al. (2021) and Verina et al. (2021) have proven that achieving green growth and spreading GTI require relevant digital transformation in the high education system.

GTI could improve environmental quality and the masses' living environment and enhance residents' happiness and satisfaction. The economic benefits of green products are concerned. When people's lives are greatly satisfied, people pay increasing attention to their quality of life and physical health. In this case, green products could not only meet people's pursuit of health but also effectively improve people's quality of life and then play a role in expanding domestic demand and driving economic development.

3. Methodology

3.1 Metric selection

The dependent variable selected in this paper is high-quality economic development (HQED). Based on previous studies (Yang et al., 2021; Shen et al., 2022; Chen et al., 2020), HQED describes the complex coordination relationship of multidimensional and multilevel factors between the growth of economic "quantity" and the improvement of economic "quality". The assessment of high-quality economic development should be based on the "five major development concepts": innovative development, coordinated development, sustainable development, open development, and shared development. Innovative development is characterised by the efficiency of research and development (R&D) in the regions using the following indicators (Kuzior, 2022; Zeynalli et al., 2022; Ayub Khan et al., 2022): R&D funding intensity (% of GDP), R&D personnel input (persons), R&D internal activities (million yuan), R&D new product development funding (million yuan), R&D new product sales revenue (million yuan), total profits in high-tech industries (million yuan), number of R&D patents for inventions in force (items). It should be noted that indicators describing innovative development are stimulants. The second group (coordinated development) involves six indicators merged into three subgroups (Oe, et al., 2022; Ginevičius et al., 2021): growth coordination, industrial structure and urban–rural structure (Table 1). This group contains three stimulants and three inhibitors.

Table 1: Indicator system for assessment of coordinated dimensions of HQED

Variables	Direction of impact on HQED
Subgroup: Growth coordination	
Employment is stable, %	inhibitor
Fiscal self-sufficiency coefficient, %	stimulant
Government debt burden, %	inhibitor
Subgroup: Industrial structure	
Industrial structure premiumization index, %	stimulant
Subgroup: Urban–rural structure	
Urbanisation process, %	stimulant
Level of urban–rural income coordination, %	inhibitor

Source: authors' work

The third group (sustainable development) involves seven indicators merged into three subgroups (Oe et al., 2022; Chen et al., 2020): energy consumption, green growth and environmental pollution. Detailed information on the indicators of sustainable development for the assessment of HQED is shown in Table 2.

Table 2: Indicator system for assessment of sustainable development of HQED

Variables	Direction of impact on HQED
Subgroup: Energy consumption	
Watt of power consumption, billion kWh	inhibitor
Subgroup: Environmental pollution	
Solid waste per unit of output, tonne	inhibitor
Wastewater per unit of output, tonne	inhibitor
Exhaust gases per unit of output, %	inhibitor
Subgroup: Green growth	
Urban green coverage, %	stimulant
Per capita green park area, square metres	stimulant
Harmless treatment rate of domestic garbage, %	stimulant

Source: authors' work

The last dimension (shared development) includes two subgroups: infrastructure and social wellbeing (Lyeonov et al., 2021; Gentle, 2022). All indicators, excluding the gap between urban and rural consumption (inhibitor), are stimulants (Table 3).

Table 3: Indicator system for assessment of shared development of HQED

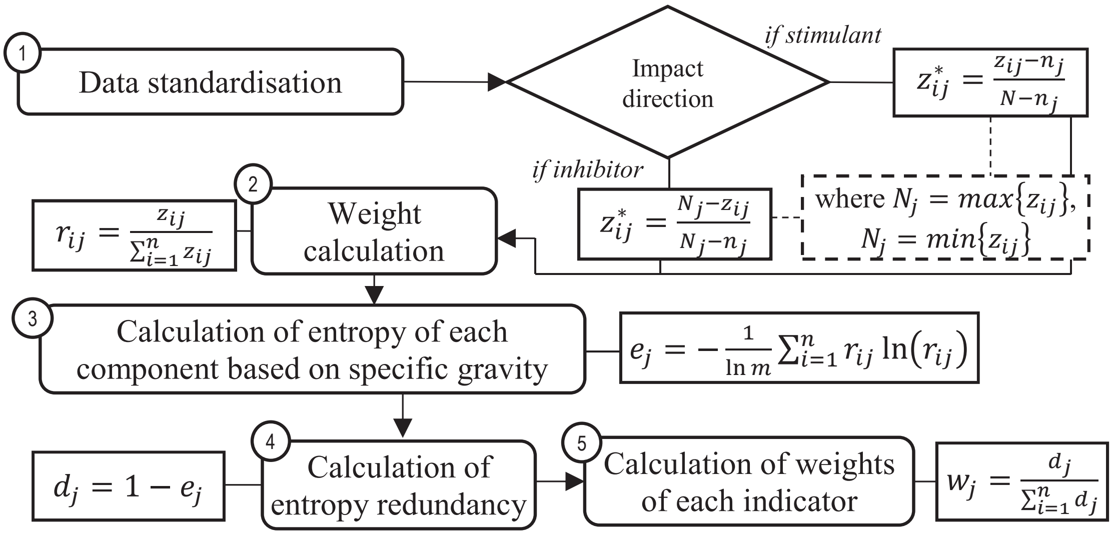
Variables	Direction of impact on HQED
Subgroup: Infrastructure	
Perfection of educational facilities, books/person	stimulant
Medical facility adequacy, zhang/person	stimulant
Perfection of transportation facilities, units/10,000 people	stimulant
Perfection of network facilities, individuals/people	stimulant
Subgroup: Society's wellbeing	
Expenditure on education per capita, meta/person	stimulant
Per capita disposable income, meta/ person	stimulant
Consumption index, %	stimulant
Gap between urban and rural consumption, meta/person	inhibitor

Source: authors' work

Explanatory variable. The analysis of approaches to estimate the GTI shows that the scientific community has not accepted unified assessment methods. All approaches can be divided into two groups. The first group is based on assessing green investments in R&D in the green innovation sphere (Zhang, 2015). The second group estimates the following indicators: green product innovation, green process innovation, the number of green invention patents granted, and the number of regional invention patents (Ariken et al., 2020; Dong and Wang, 2019; Jia and Zhang, 2014; Claudia and Klaus, 2014; Moran, 1950). In the study framework, the GTI is estimated as the sum of the number of green inventions in the current year and the number of green utility models applied in the current year as an alternative indicator for GTI.

The study applies the entropy method to calculate the HQED and GTI based on a previous study by Moskalenko et al. (2022). The entropy method enables the inclusion of interdependence between indicators and their relative significance in the overall index (Kwilinski et al., 2020). This is achieved by assessing the entropy of each indicator, which accounts for the level of unpredictability or ambiguity in the data and assigns more significance to indicators with lower entropy, indicating higher information or ability to differentiate. Additionally, the application of entropy methods can aid in the recognition of crucial influencers and elements that contribute to the comprehensive index, providing valuable insight for policy and decision-making. The general algorithm of entropy methods is shown in Figure 1.

Figure 1: Theoretical algorithm of entropy method to estimate HQED and GTI



Source: authors' work

Considering Figure 1, at the first stage, all data are standardised considering the impact direction (stimulant or inhibitor). The next stage aims to calculate the weight. Then, the study indicates the entropy of each component based on its specific gravity. Based on the results from the previous stages, the entropy redundancy and weights of each indicator are calculated.

Control variables: It should be noted that HQED is affected by numerous factors. For instance, considering Chen (2020), the well-developed transport infrastructure allows regional economic growth. At the same time, HQED requires sufficient government support and investments (Yang et al., 2021; Chen et al., 2020; Bekhti et al., 2022; Oláh et al., 2021). In addition, the findings confirm that opening of the economy allows mutual benefits and win–win results to be achieved due to the development of the destination community and boosting international circulation. Furthermore, the increasing education level in society provokes the development of innovations and knowledge sharing at all levels (government, business, society) and among all industries (Artyukhov et al., 2021; Dzwigol, 2022). In this case, the study uses the following indicators as control variables:

- transport infrastructure;
- financial support (share of government fiscal expenditure in GDP);
- industry structure (share of tertiary industry output in GDP);
- urbanisation (share of registered population in urban areas in total population);
- economic openness;
- education development (number of students in the total number of people in the region).

The study generalises panel data for 30 provinces (municipalities) and autonomous regions in China (excluding Hong Kong, Macao, and Taiwan) from 2010–2019. All provinces and autonomous regions are analysed within three regions: Eastern, Western and Central. The Eastern Region of China is the most developed and economically prosperous region in the country. In the period from 2010 to 2019, the Eastern Region of China experienced significant economic growth, driven by its advanced manufacturing, high-tech industries, and service sector (China Statistical Yearbook, 2021). The most innovative companies (Alibaba, Huawei and Tencent) are located in the Eastern Region. The Central Region has a rich history and cultural heritage, as well as agricultural production and mineral resources. The significant economic growth of the Central Region is driven by its manufacturing, agriculture, and tourism sectors. The region has a vast range of universities and research institutions, contributing to its reputation as a centre for scientific and technological innovation. The Western Region has abundant natural resources, including minerals, energy, and agricultural products. At the same time, the Western Region faces challenges related to its infrastructure, environment, and economic development. The Chinese government has implemented various policies to support the development of the Western Region, including the "Go West" policy and the Belt and Road Initiative. The information base of the investigation was the China Statistical Yearbook (2021), China Science and Technology Statistical Yearbook (National Bureau of Statistics of China, 2022), Chinese Employment Statistics Yearbook (2021) and China High-tech Industry Statistical Yearbook (National Bureau of Statistics of China (2022), the official websites of the National Bureau of Statistics and the statistical bureaus of various provinces (cities) (National Bureau of Statistics of China, 2022).

3.2 Model settings

Before determining whether to use spatial measurement methods, the spatial relevance of the study object was first tested. If there is a spatial correlation, the spatial econometric model can be used for analysis. In the opposite case, it can be considered inappropriate for research. Therefore, in the first stage, the study checks the spatial correlation between China's HQED and GTI.

(1) Spatial weight matrix setting

The study uses a spatial weight matrix that includes an adjacent spatial matrix, geospatial matrix, economic space matrix and nested matrix. The spatial weight matrix setting $W_{i,j}$ reflects the spatial interaction relationship and dependency characteristics. Nested matrices are used for regression analysis of econometric models. A robustness analysis is performed by applying adjacent spatial, geospatial, and economic space matrices. First, the adjacent spatial matrix, a simple binary spatial weight matrix, is set as follows.

$$W_{i,j} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases} \tag{1}$$

Then, the study applies the geospatial matrix. Considering Wang (2013), the closer the two regions are, the greater their weight:

$$W_{i,j} = \begin{cases} \dfrac{1}{d_{ij}}, & i \neq j \\ 0, & i = j \end{cases} \tag{2}$$

Among them, $W_{i,j}$ represents the transport distance between the two provincial capitals, and the transport distance can well reflect the social and economic development relationship between the cities.

Now, the economic space matrix is used. Geographical factors are not the only factors that lead to spatial effects, and spatial units with similar economic levels can better absorb and utilise financial resources. Thus, it moves closer to an increasing scale of returns. Drawing on a construct based on an inverse distance matrix, the economic matrix is defined as follows:

$$W_{i,j} = \begin{cases} \dfrac{1}{\left|Y_i - Y_j\right|}, & i \neq j \\ 0, & i = j \end{cases} \tag{3}$$

The fourth step is nested matrices. The nested matrix is an inverse distance space matrix, and the economic space weight matrix is organically combined. The purpose is to portray the comprehensiveness and complexity of spatial effects as accurately as possible. The way to show this is to set the nested weight matrix to one product of an inverse distance weight matrix with a diagonal matrix.

(2) Spatial correlation test method

In the first stage, the global autocorrelation is estimated. To investigate the spatial interaction and spillover effect of the GTI on HQED, the global Moran's I index is used for spatial correlation testing (Equation 4) based on the methodology (Moran, 1950; Samad and Manzoor, 2011; Anselin, 1995).

$$Moran's\,I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}(Y_{it}-\bar{Y})(Y_{jt}-\bar{Y})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}} \tag{4}$$

where $w_{i,j}$ is the weight matrix and $\bar{Y}$ is the average of Y_{it} Y_{jt}, which are the development levels of *i* provinces and cities and *j* provinces and cities in China in the year *t*, respectively.

In the next stage, the local Moran's index is calculated, which allows estimation of the local autocorrelation (Equation 5).

$$Local\,Moran's\,I_i = \frac{(Y_{jt}-\bar{Y})}{S^2}\sum_{j=1}^{n} w_{i,j}(Y_{jt}-\bar{Y}) \tag{5}$$

The values of Moran's I index range from [−1,1], and a positive index indicates a positive spatial correlation; conversely, there is a negative spatial correlation.

(3) Spatial econometric model setting

To investigate the spatial effects of GTI and HQED, the spatial econometric model is constructed as follows:

$$Y = \rho WY + \beta X + \theta WX + \mu \tag{6}$$

$$\mu = \lambda W\mu + \varepsilon, \varepsilon \sim N\left[0, \sigma^2 I\right] \tag{7}$$

where Y is the dependent variable, X is the explanatory variable, W is the spatial weight matrix of 30*30 dimensions, β is the correlation coefficient for X, β is the correlation coefficient, ρ and θ are the spatial correlation coefficients, λ is the spatial error coefficient, μ is a random error and follows the normal distribution ε.

When $\rho \neq 0, \theta = 0, \lambda = 0$ the spatial econometric model is a spatial autoregressive (SAR) model.

When $\rho = 0, \theta = 0, \lambda \neq 0$ the spatial econometric model is a spatial error (SEM) model.

When $\rho \neq 0, \theta \neq 0, \lambda = 0$ the spatial econometric model is a spatial Durbin (SDM) model.

A spatial econometric model incorporates spatial weight matrices in the regression analysis, representing the spatial relationships between observations. These matrices adjust the regression coefficients to consider spatial autocorrelation, providing more accurate estimates of variable relationships and accounting for the impact of spatial proximity on the outcome of interest. To eliminate the heteroscedasticity effect, the study applies a logarithm procedure to all variables.

To determine the specific form of the spatial econometric model, a series of tests is conducted. The process involves three stages. In the first stage, the Lagrange multiplier (LM) test is conducted, and the SEM and SAR models are tested using nested weight matrices. If the findings pass the significance test, spatial econometric models with nested matrices are applied. In the second stage, the SDM model is tested to determine whether it can be converted to a spatial lag model (SDM→SAR) or a spatial error model (SDM→SEM) using the LR test and the Wald test, respectively. In the third stage, a Wald test is performed on the SDM model to determine the statistical significance of the coefficients. This methodology allows the selection of the most suitable spatial panel model based on the test results.

To check the validity of the achieved results, the outputs are compared with those of the double fixed-effect SDM model using the adjacent spatial weight matrix (replacing the nested spatial weight matrix), the economic distance spatial weight matrix, and the geospatial weight matrix.

4. Results

4.1 Descriptive statistics

The descriptive statistical results (Table 4) show that the maximum value of China's HQED level is 10.461, the minimum value is 8.721, and the average value is 9.345. It allows us to conclude that HQED in China is balanced for the analysed time. The maximum value of GTI is 10.934, the minimum value is 3.401, and the average is 7.838. This result shows that the development of GTI in China is more obvious.

Table 4: Results of descriptive statistics

Variable	Symbol	Observ.	Mean	St. dev.	Min	Max
High-quality economic development	**HQED**	300	9.345	0.419	8.271	10.461
Green technology innovation	**GTI**	300	7.838	1.385	3.401	10.934
Transport infrastructure	**Gov**	300	11.655	0.847	9.390	12.728
Financial support	**Fci**	300	3.127	0.379	2.359	4.141
Structure of the industry	**St**	300	0.457	0.098	0.286	0.835
Urbanisation	**Urb**	300	0.571	0.125	0.338	0.896
Economic openness	**Open**	300	0.284	0.307	0.013	1.464
Education development	**Edu**	300	1.928	0.502	0.799	3.453

Note: Min = minimum value among the analysed data; Max = maximum value among the analysed data; Mean = average value of the analysed data; St. dev. = standard deviation; Observ. = number of observations

Source: authors' own estimations

The maximum value of transport infrastructure is 12.728, the minimum is 9.390, and the gap between the two is small, indicating that the development of transport infrastructure promotes HQED. The average financial support is 3.127, indicating that the Chinese government plays an important role in financial aid. The average value of the industrial structure is 0.457, indicating that the tertiary industry has developed rapidly and occupies a relatively high proportion. The primary, secondary, and tertiary industrial structures are reasonable. The maximum value of the urbanisation process is 0.896, the minimum value is 0.338, the average value is 0.571, the gap between the maximum and the minimum value is large, and the average value is low, indicating that China's urbanisation process has obvious regional differences. The overall urbanisation process needs to be further improved.

4.2 Spatial correlation test

In the next step, the study combines the settings of the four weight matrices (adjacent spatial matrix, geographical matrix, economic space matrix and nested matrix) to calculate the global Moran's I index of HQED and GTI from 2010 to 2019 (Table 5).

Table 5: Global Moran's I index of GTI and HQED

Time	**Type of matrix**							
	Adjacent spatial		***Geographic distance***		***Economic space***		***Nested***	
Year	**GTI**	**HQED**	**GTI**	**HQED**	**GTI**	**HQED**	**GTI**	**HQED**
2010	0.202*	0.120*	0.094***	0.081*	0.094***	0.344***	0.218***	0.422***
2011	0.241**	0.165**	0.099***	0.092*	0.099***	0.367***	0.223***	0.393***
2012	0.245**	0.185**	0.096***	0.097*	0.096***	0.369***	0.231***	0.350***
2013	0.221**	0.194**	0.089***	0.099*	0.089***	0.364***	0.231***	0.311***
2014	0.255**	0.168**	0.094***	0.104*	0.094***	0.369***	0.200***	0.314***
2015	0.283***	0.163**	0.103***	0.108*	0.103***	0.340***	0.225***	0.268***
2016	0.290***	0.143*	0.106***	0.097*	0.106***	0.328***	0.224***	0.332***
2017	0.275**	0.162**	0.102***	0.124**	0.102***	0.320***	0.208***	0.347***
2018	0.296***	0.136**	0.111***	0.087*	0.111***	0.278***	0.238***	0.263***
2019	0.280**	0.139**	0.108***	0.096*	0.108***	0.262***	0.239***	0.225***

Note: *** = significant at 1%; ** = significant at 5%; * = significant at 10%

Source: authors' own estimations

Judging from the Moran's I index under the four spatial weight matrices in Table 5, the Moran's I indices of GTI and HQED under the weight matrix pass the significance test. Moreover, the economic space and the nested matrix pass the 1% significance test, and there are certain differences between GTI and HQED under the four spatial weight matrices. However, in general, there is a significant positive global spatial autocorrelation between China's GTI and HQED. This confirms that China's GTI and HQED are not completely random and are affected by areas with similar spatial characteristics. The findings confirm the high degree of spatial agglomeration in China for GTI and HQED. This allows us to conclude that it is a spatial correlation suitable for empirical analysis with spatial metrology models.

4.3 Spatial econometric model selection

The results of the LM test are presented in Table 6. The findings pass the significance test, allowing the application of spatial econometric models with nested matrices.

Table 6: Spatial dependency test

LM inspection	LM value	p value
LM_test_Error	11.580	0.006
Robust LM_test_Error	12.831	0.000
LM_test_Lag	12.708	0.000
Robust LM_test_Lag	25.532	0.000

Note: LM value = Lagrange multiplier statistics; p value = significance level to reject the null hypothesis of the Lagrange multiplier test

Source: authors' own estimations

The results of the Wald test show that the chi2(7) value is 44.13, which indicates that the SDM should be analysed with fixed effects (Table 7).

Table 7: LR test and Wald test results

Test	Indicator	Value
LR inspection		
Likelihood-ratio test (Assumption: SAR nested in SDM)	LR chi2(7)	42
	Prob>chi2	0.000
Likelihood-ratio test (Assumption: SEM nested in SDM)	LR chi2(7)	40
	Prob>chi2	0.000
Wald test		
Wald test for SAR	chi2(7)	45.95
	Prob>chi2	0.000
Wald test for SEM	chi2(7)	44.13
	Prob>chi2	0.000

Source: authors' own estimations

To further analyse the impact of GTI on HQED, the SAR, SEM, and SDM models are retrieved and compared. The regression results are shown in Table 8. The findings show that the goodness of fit of the SDM model is 0.8756, the best fit among the models. In addition, the Log-L value is also higher than those of the other models, and the coefficient significance of each variable is high. Therefore, it is reasonable to choose a fixed-effect SDM model to analyse the impact of GTI on HQED. According to the regression results of the SDM model, the index of GTI is 0.0299, and it passes the 1% significance test, indicating that GTI plays a significant role in promoting HQED.

Table 8: Regression results

Variable	SAR		SEM		SDM	
	coef.	p value	coef.	p value	coef.	p value
GTI	0.0309***	0.0091	0.0323***	0.0092	0.0299***	0.0088
Fci	0.0671*	0.0349	0.0747**	0.0356	0.0808**	0.0357
Gov	0.0407*	0.0231	0.0362	0.0232	0.0309**	0.0219
Str	0.218***	0.0731	0.208***	0.0740	0.122*	0.0765
Urb	0.295*	0.1561	0.282*	0.1519	−0.143	0.1669
Open	0.0001***	0.0003	0.0001	0.0003	0.0002**	0.0004
Edu	0.0573***	0.0186		0.0185	0.0392**	0.0194
W*GTI	–	–	–	–	0.0783***	0.0265
W*Fci	–	–	–	–	0.289***	0.0901
W*Gov	–	–	–	–	−0.158**	0.0618
W*Str	–	–	–	–	0.00207	0.2107
W*Urb	–	–	–	–	0.182	0.4525
W*Open	–	–	–	–	0.0002	0.0007
W*Edu	–	–	–	–	0.0329	0.0495
Fixed time	YES		YES		YES	
Ind. fix.	YES		YES		YES	
Variance	0.0006***	0.0001	0.0006***	0.0001	0.0005***	0.0000
R^2		0.425		0.4110		0.8756
Log-L		679.9281		680.7646		701.2415
N		300		300		300

Note: *** = significant at 1%; ** = significant at 5%; * = significant at 10%; R^2 = coefficient of determination; N = number of observations; Variance = Variance sigma2_e; Ind. fix. = individual fixation

Source: authors' own estimations

4.4 Regression result analysis of SDM model

Constructing the SDM model to analyse the impact of GTI on HQED, columns (1)–(3) show the influencing coefficients of GTI on the HQED of the region under the time fixed effect, individual effect and double fixed effect, respectively. Columns (4)–(6) represent the spatial spillover coefficients of GTI to other regional economies under the time fixed effect, regional effect and double fixed effect, respectively (Table 9).

Table 9: SDM model results

Variable	Stat.	(1)	(2)	(3)	(4)	(5)	(6)
		Wx					
GTI	**coef.** **p value**	0.0219* (6.28)	0.0299*** (2.53)	0.0557*** (3.38)	−0.0008 (−1.88)	0.0783** (−0.07)	−0.0559 (2.95)
Fci	**coef.** **p value**	0.0777* (3.01)	0.0808* (2.13)	0.0467** (2.27)	0.216* (−0.90)	0.289** (2.54)	−0.0284 (3.20)
Gov	**coef.** **p value**	0.0333 (3.68)	0.0309 (1.48)	0.0874*** (1.41)	−0.204*** (−6.39)	−0.158* (−4.71)	−0.498*** (−2.56)
St	**coef.** **p value**	0.0941 (0.62)	0.122 (1.28)	0.0651 (1.59)	−0.334** (−3.54)	0.0021 (−2.75)	−1.078*** (0.01)
Urb	**coef.** **p value**	−0.003 (6.57)	−0.143 (−0.02)	0.940*** (−0.85)	−0.625 (4.84)	0.182 (−1.63)	1.839*** (0.40)
Open	**coef.** **p value**	−0.0002 (1.38)	0.0002 (−0.54)	0.0009 (0.54)	−0.0014* (−4.38)	0.0002 (−2.54)	−0.0053*** (0.25)
Edu	**coef.** **p value**	0.0435* (−6.94)	0.0392* (2.20)	−0.107*** (0.67)	0.0404 (−10.54)	0.0329 (0.79)	−0.555*** (0.67)
Spatial rho	**coef.** **p value**	0.103 (−2.64)	−0.0989 (1.15)	−0.251** (−1.02)	0.103 (−2.64)	−0.0989 (1.15)	−0.251** (−1.02)
Variance sigma2_e	**coef.** **p value**	0.0006*** (12.02)	0.0005*** (12.24)	0.0046*** (12.25)	0.0006*** (12.02)	0.0005*** (12.24)	0.0046*** (12.25)
N		300	300	300	300	300	300
R^2		0.957	0.688	0.690	0.957	0.688	0.690

Note: *** = significant at 1%; ** = significant at 5%; * = significant at 10%; Main = coefficient of influence of the variable on the region; Wx = spatial spillover coefficient of the variable to other regions, rho = spatial spillover coefficient of the interpreted variable to the surrounding area

Source: authors' own estimations

Based on the regression results of the SDM model, a joint significance test is performed to test the regional fixed effect. The time fixed effect and the double fixed effect are the three effects most suitable for the study. The test result shows that the p value is 0.0003 for the regional fixed effect and the bidirectional fixed effect tests. In the double fixed-effects test, the p value is 0.0000, which is significant at the 1% level. This allows us to reject the null hypothesis, and the regression results of the double fixed-effects model prevail.

4.5 Effect decomposition

The SDM model is decomposed by effect decomposition, in which the direct effect indicates the degree of influence of GTI on the region's HQED. The indirect effect is the degree of influence of one unit of GTI change in the surrounding area on the HQED of the region. The total effect indicates the degree of influence of the variable change for all regions on the HQED of the interpreted variable in the region.

Table 10: Empirical results of SDM model effect decomposition

Variable	Stat.	Direct	Indirect	Total
GTI	coef.	0.0289***	0.0688***	0.0977***
	p value	(0.0091)	(0.0231)	(0.0243)
Fci	coef.	0.0740**	0.267***	0.341***
	p value	(0.0341)	(0.0815)	(0.0895)
Gov	coef.	0.0356*	−0.149**	−0.113*
	p value	(0.0212)	(0.0590)	(0.0603)
St	coef.	0.120*	−0.0125	0.108**
	p value	(0.0730)	(0.1920)	(0.2040)
Urb	coef.	−0.141	0.207	0.0663
	p value	(0.1666)	(0.4524)	(0.4417)
Open	coef.	0.0002*	0.0001*	0.0003*
	p value	(0.0004)	(0.0007)	(0.0007)
Edu	coef.	0.0387*	0.0253*	0.0639*
	p value	(0.0200)	(0.0451)	(0.0444)
N		300		
R^2		0.690		

Note: *** = significant at 1%; ** = significant at 5%; * = significant at 10%; R^2 = coefficient of determination; N = number of observations

Source: authors' own estimations

The results of the effect decomposition of the SDM model (Table 10) show that the region's coefficient of GTI on the region's HQED is 0.0289, at a significance level of 1%. This confirms that the GTI in the region has a positive role in promoting the HQED of the region. The coefficient of the GTI development level in the surrounding area and the HQED of the region is 0.0688, at a significance level of 1%. It also has a promoting effect on the surrounding areas. In addition, the impact of the GTI and development level of all regions on the HQED level of the region also passes the 1% significance test. It further shows that the effect of GTI on HQED is obvious.

4.6 Control variables

Firstly, the direct and indirect effects of transportation infrastructure are significantly positive. This proves that transport infrastructure is conducive to the HQED of the region and has a spillover effect on the economic development of the surrounding areas. Secondly, financial support plays a significant role in promoting the HQED of the region. However, it has a significant inhibitory effect on the economic development of the surrounding areas. Thirdly, the direct effect and total effect of the industrial structure are significantly positive. It confirms that optimising and upgrading the industrial structure is one of the important links for the economy to achieve high-quality development. The spatial spillover effect of the industrial structure is insignificant, indicating that China's current industrial structure has a weak driving capacity for the surrounding areas. Fourthly, the direct and indirect effects of opening up to the outside world on HQED are positive. This confirms that deepening the degree of opening up to the outside world and the smooth flow of foreign circulation are conducive to achieving HQED. Fifthly, the direct and indirect effects of education level are significantly positive, indicating that the higher the level of education, the higher the people's quality of life and the higher the quality of the economy to achieve HQED; coupled with the factors of population mobility, the improvement of education level will also drive the HQED level of the surrounding areas.

4.7 Regional heterogeneity analysis

According to the different economic development levels, China's overall territory is divided into Eastern, Central and Western Regions. Thus, the SDM model is constructed to analyse the interregional effects using a nested weight matrix (Table 11).

GTI in the Eastern Region promotes HQED, but the role of the Central and Western Regions is not significant and shows a negative effect. To better explore the heterogeneity between regions and further decompose the effects, the study finds that the direct effects in the Eastern Region are more obvious. This could be explained by the fact that the economic infrastructure in the Eastern Region is relatively developed, which is conducive to the use of advanced digital technologies to promote economic development, such as the continuous development of the digital economy through artificial intelligence and cloud computing. At the same time, the average education level of residents in the Eastern Region is higher, the knowledge stock is richer, and the cognitive ability of technological innovation is stronger, so the spatial spillover effect of GTI can be more fully exerted. The direct effect on the Central and Western Regions is negative, which could be due to the low level of economic development in the Central and Western Regions and the slow development speed. As a consequence, it could hinder GTI development.

Table 11: Heterogeneity analysis results

Variable	Stat.	Eastern Region	Central Region	Western Region
GTI	**coef.**	0.0499***	−0.00469	−0.00155
	p value	(0.0179)	(0.0091)	(0.0097)
W*GTI	**coef.**	0.0843*	0.0261*	−0.00109
	p value	(0.0437)	(0.0214)	(0.0325)
Direct effects	**coef.**	0.0469**	−0.00712*	−0.00118
	p value	(0.0185)	(0.0087)	(0.0099)
Indirect effects	**coef.**	0.0709*	0.0225*	−0.00117
	p value	(0.0372)	(0.0153)	(0.0217)
Total effect	**coef.**	0.118***	0.0153*	−0.00235
	p value	(0.0376)	(0.0197)	(0.0231)

Note: *** = significant at 1%; ** = significant at 5%; * = significant at 10%
Source: authors' own estimations

4.8 Robustness test

The regression results of the double fixed-effect SDM model using the adjacent spatial weight matrix (replacing the nested spatial weight matrix), the economic distance spatial weight matrix, and the geospatial weight matrix are presented in Table 12. The signs of each explanatory variable are consistent with the previous results, suggesting that the spatial effect of GTI on HQED is robust.

Table 12: Robustness test results

Variable	Stat.	Adjacent space matrix	Geospatial matrix	Economic distance matrix
GTI	coef. p value	0.0294*** (0.0088)	0.00741* (0.0094)	0.0326*** (0.0088)
W*GTI	coef. p value	0.00409 (0.0191)	−0.203*** (0.0715)	0.0711*** (0.0275)
Direct effects	coef. p value	0.0298*** (0.0090)	0.0181* (0.0098)	0.0310*** (0.0090)
Indirect effects	coef. p value	0.00530* (0.0188)	−0.104*** (0.0335)	0.0565** (0.0228)
Total effect	coef. p value	0.0351* (0.0211)	−0.0860** (0.0348)	0.0875*** (0.0235)
Ind. fix. Fixed time	coef. p value	Yes Yes	Yes Yes	Yes Yes
Log-L		703.4675	714.3749	714.3749
R^2		0.8127	0.8855	0.6974
N		300	300	300

Note: *** = significant at 1%; ** = significant at 5%; * = significant at 10%; R^2 = coefficient of determination; N = number of observations; Ind. fix. = individual fixation

Source: authors' own estimations

5. Discussion and Conclusions

This paper used panel data from 30 provinces in China from 2010 to 2019 to construct an index system to measure the HQED of China's economy from the view of innovation, coordination, sustainability, greenness and sharing, and constructed an SDM model to study the impact and spillover effect of GTI on HQED. Considering the findings, the following conclusions can be highlighted. Firstly, GTI and HQED have a strong positive spatial correlation. The increase in GTI improves HQED by 0.0977. In addition, all the analysed variables positively contribute to HQED, excluding Gov. GTI in the region plays a positive role in promoting the HQED of the region, which is confirmed at the 1% significance level, and the extension of GTI in the region provokes the growth of HQED by 0.0289. Considering the test of regional heterogeneity, GTI in the Eastern Region makes the largest contribution to promoting HQED. Nevertheless, the role of GTI in the Central and Western Regions is not significant and negative. The growth of GTI by 1 provokes an increase in HQED by 0.0499 points for the Eastern Region.

The spillover effect in the Western Region is not obvious. Considering the core findings, China could develop the following suggestions for promoting GTI to achieve HQED.

1. Continue to implement the innovation-driven development strategy, formulate relevant policies for GTI according to local conditions, and maximise the driving effect of GTI on the HQED of the regions. At the same time, the government should deepen the scientific and technological system reform, strengthen support for innovative enterprises, create a GTI environment, increase financial support for education, improve the innovation environment, and improve the supply of high-level innovative talent in the region. Furthermore, it is necessary to optimise the structure of innovation input, pay more attention to the investment in common technologies in the industry and innovative elements in important key areas, and effectively improve the ability of independent innovation. The government should strengthen the integration of the innovation chain, industrial chain and capital chain, and guide the formation of a virtuous circle between technological innovation and HQED.
2. Accelerate the process of coordinating technological innovation and environmental regulation in different regions. For the Eastern Region, the level of economic development is high, and the allocation efficiency is relatively high for the regional production factor agglomeration. Thus, to promote HQED, the government should pay more attention to the improvement of technological innovation, further stimulate the vitality of regional innovation, and realise the role of GTI in promoting HQED. While raising the level of technological innovation, the Central Region should strengthen the construction of HQED. The Western Region should pay more attention to green technological innovation and environmental regulation and use green technological innovation to guide and encourage the innovative development of enterprises. It is necessary to promote the construction of the institutional environment through green technological innovation, make technological innovation and the institutional environment a virtuous circle, and jointly promote the HQED of the Eastern, Central and Western Regions.
3. Encourage green investment in green technology – the government should provide tax incentives, subsidies and other financial support to companies that invest in green technology. This will help create a favourable investment environment for investors in green technology.
4. Provide relevant financial support – it is necessary to improve the policies on grants allocation, loans and other forms of financial assistance that can help lower the costs of innovation and facilitate the development of new technologies.
5. Promote international cooperation and knowledge sharing – the government should work with international organisations and other countries to share knowledge and best practices in green technology. This can include promoting technology transfers, joint research and development, and partnerships between Chinese and foreign stakeholders.

6. Develop a highly qualified workforce – the government should invest in education and training programmes to develop the necessary skills for GTI. It will help build a skilled workforce that can drive innovation in the sector.
7. Strengthen intellectual property protection to encourage innovation and technology development. It will ensure that companies are adequately rewarded for their innovation efforts.

This study has limitations that could be considered in future investigations. The study period is from 2010 to 2019, which is limited to considering the latest trends in economic development and shocks, particularly the COVID-19 pandemic. Furthermore, it requires enlarging the number of variables that could stimulate or restrict the extension of GTI for HQED. In addition, it is necessary to extend the object of investigation by incorporating other Asian countries to provide a comparison analysis and identify the best policies for stimulating HQED.

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