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High-Speed Railway Opening, Industrial Symbiotic Agglomeration and Green Sustainable Development—Empirical Evidence from China

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Abstract: In recent years, China's transportation infrastructure has undergone significant changes. High-speed rail, as a new and favored mode of transportation, offers travelers convenience, efficiency, and punctuality, replacing many high-pollution transportation methods. Based on the characteristics of high-speed rail, this paper selects data from 30 provinces spanning from 1999 to 2019. It utilizes the double-difference method to evaluate the impact of high-speed rail opening on economic sustainability. It has been found that the introduction of high-speed rail contributes to economic sustainability during the examination period. The mechanism test also reveals that the opening of high-speed rail promotes green and sustainable development through the industrial agglomeration effect. In addition, the opening of high-speed rail (HSR) has a significant time lag effect and a spatial spillover effect on green sustainable development. The conclusion complements the theoretical framework regarding the impact of high-speed rail on the environment and regional economic sustainability. It also provides guidance for the efficient utilization of high-speed rail, which holds both theoretical and practical importance.

Keywords: high-speed rail; sustainable; economic growth; industrial symbiotic agglomeration; double-difference method; spatial spillover effect

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1. Introduction

Since 1978, China's economy has experienced tremendous development. At the beginning of the reform and opening up, China's total economic output was only slightly more than 360 billion yuan. However, by 2022, the total economic output had exceeded 120 trillion yuan, representing a growth of hundreds of times. Additionally, China's share of the global economy has risen from 1.7% in 1987 to 17%. Nevertheless, this high-speed growth has come at the expense of biodiversity and green space, which have both experienced significant reductions. Problems seriously damage the environment. The "GDP-only" theory has led to a depletion of resource reserves, a rise in hazy weather conditions, and an increase in emissions of various types of waste. In addition, the rapid urbanization process and the influx of population into cities have fueled urban consumption and led to issues such as traffic congestion, air pollution, noise pollution, and other problems. This contradicts the objective of promoting green and sustainable urban development. This indicates that the overall environmental situation in China is not optimistic, and various ecological and environmental problems are still prominent. Therefore, it is necessary to pursue economic growth while strengthening the protection of the ecological environment to achieve green and sustainable development in the region. The 14th Five-Year Plan proposes to continue implementing the new development concept, with a focus on prioritizing ecology in regional development. It also aims to actively promote low-carbon recycling and accelerate the green transformation of the energy sector. This reveals that to promote high-quality economic development, we must accelerate the construction of low-carbon and recycling industrial and economic systems promptly. This will help ensure that economic development becomes more rationalized and environmentally friendly. However, based on China's national conditions, such as its large population base, achieving economic development of high quality cannot be accomplished overnight. It requires gradual reform.

In recent years, China's transportation infrastructure has undergone significant changes. The introduction of high-speed rail as a new form of transportation has revolutionized the traditional concept of time and space, while also reducing production and transaction costs [1,2]. These changes have had a profound impact on China's regional economic growth. Because the improvement of transportation infrastructure greatly reduces transaction costs caused by geographical distance, it facilitates the active flow of production factors and expands the boundaries of the market, thereby improving the income level of residents [3–5]. Additionally, it also contributes to a certain extent in reducing the growth of carbon emissions. The emergence of high-speed rail has introduced a new avenue for economic development within the community. However, the current relevant studies have focused more on the impact of high-speed rail on macroeconomic development and have paid less attention to its impact on the green and sustainable growth of regional economies. Therefore, this paper will focus on research related to this perspective.

Can the introduction of high-speed rail contribute to the sustainable development of a green economy? Can studying the economics of high-speed rail provide policy support for sustainable regional economic growth, as well as carbon reduction initiatives? Unfortunately, there are not many studies of this nature in the academic field, Rather, the emphasis is placed on the perspectives of green total factor productivity [6,7], regional economic growth [8,9], innovation performance [10–12] and carbon emissions [13,14]. In recent years, there has been a growing emphasis among scholars on the importance of transportation accessibility (connectivity) for regional economic development, surpassing the traditional focus on transportation infrastructure. They found that high-speed rail is an important driver of environmental sustainability [15] in both developing and developed countries [16], with climate conditions playing an important mediating role [7]. This shift in research focus has led to a deeper exploration of the subject [17,18].

However, there is a dearth of theoretical evidence from academia regarding the impact of high-speed rail on the development of the green economy, as well as the time lag effect of high-speed rail on its economic function. Current studies have examined the impact of high-speed rail (HSR) on the regional economy but have paid less attention to its impact on environmental protection and the economy. Further in-depth studies are necessary to provide academic references for the sustainable development of the world economy, as well as for transportation changes in developing countries along the "Belt and Road". The study of the impact of the introduction of high-speed rail on the regional transportation system is also a commendable idea.

As a new form of industrial organization, there is still a lack of research on how the intermediary variable affects the opening of high-speed rail and the growth of the green economy [19]. With the acceleration of the industrialization process, environmental pollution problems are also spread all over China. As a clean means of transportation, high-speed rail has replaced the traditional transportation mode of gas-powered cars and buses, which is conducive to the study of green and sustainable development of cities. The industrial development presents a new feature of "interlinked, agglomeration and symbiosis" [20]. However, how to balance environmental protection and economic growth, the existing industrial symbiosis theory seems to solve the actual needs at this stage [21]. As Chertow et al. (2008) [22] said, strengthening the theoretical connection between symbiosis and agglomeration and empirically testing the benefits of symbiosis in agglomeration is an important future research direction. In addition, there are few existing studies on how the opening of high-speed rail affects the green and sustainable development of cities through industrial symbiosis and agglomeration. Therefore, this paper will study how the opening of high-speed rail affects the green and sustainable development of cities through industrial symbiosis and agglomeration.

Thus, this paper examines the impact of the opening of high-speed rail on the sustainable development of the regional green economy. This study selects data from 31 provinces spanning in China, from 1999 to 2019, and utilizes the double-difference method to assess this impact. Additionally, this paper explores the mechanism of industrial symbiosis and agglomeration in relation to the opening of high-speed rail and economic development. The contribution of this paper may lie in the following: first, the opening of high-speed rail plays a role as an intermediary mechanism in promoting the sustainable development of the green economy through industrial symbiotic agglomeration. Additionally, different types of industrial symbiotic agglomeration will have different mechanisms. Compared to existing transportation modes, high-speed rail offers several advantages such as faster running speed, increased convenience, and zero fuel consumption. These factors contribute to the reduction in carbon emissions, promoting green and sustainable development. Additionally, it is important to examine the specific economic impact of high-speed rail from a global perspective. Furthermore, considering the heterogeneity of different regions, it is crucial to explore the significant influence of high-speed rail on economic growth. This will enable policy makers to apply appropriate strategies based on local conditions and fully utilize the economic value of high-speed rail for economic development. This promotes the scientific and localized implementation of policies to fully utilize the economic value of high-speed rail in economic development. In the context of the "Belt and Road" initiative, China's infrastructure construction serves as a reference for countries along the route. Additionally, the "diffusion effect" of high-speed rail on the economy may result in a time-lag effect. Thirdly, the opening of high-speed rail may have a delayed impact on the economy due to the "diffusion effect." Additionally, there is a time-cycle process for the economic value of transportation infrastructure to be realized. By studying the time lag effect of high-speed rail on the economy, it offers valuable theoretical insights for maximizing the benefits of high-speed rail.

2. Theoretical Analysis and Assumptions

Research on the impact of high-speed rail on regional economy and green sustainable development has yielded abundant results. Compared to traditional transportation infrastructure, high-speed rail improves transportation efficiency and reduces travel time between regions. It also has significant advantages in terms of passenger load, punctuality, and safety performance [23–25]. Additionally, high-speed rail can better accommodate the flow of human resources. Currently, there are numerous studies on the economic value of transportation infrastructure and the transformation of the economic growth mode. However, there are significant disparities in research perspectives. One viewpoint argues that transportation infrastructure has a significant positive impact on economic growth [26–28], while the other viewpoint contends that the contribution of transportation infrastructure to economic growth is not significant [17,18,29].

Referring to the existing studies by related scholars [30], this paper aims to integrate environmental pollution and urban accessibility into the residents' consumption function. The goal is to investigate the connection between the introduction of high-speed rail and green sustainable development. In other words, the objective is to determine if there is a relationship between the two.

$$U_{it} = U(A_{it}, P_{it}, Z_{it}), A_{it} = A'_{it} - \overline{A}_{it} \tag{1}$$

where U_{it} denotes the utility function of representative residents of the city i at moment t, A'_{it} denotes the actual commuting time of residents of city i to reach other cities at moment t, $\overline{A}_{it}$ denotes the potential commuting time of residents of city i to reach other cities at moment t, and $\mathrm{A_{it}}$ denotes the degree of transportation smoothness between cities, i.e., the difference between the actual commuting time to reach other cities and the potential commuting time, and the greater the difference denotes the lower the degree of transportation smoothness. P_{it} denotes the degree of environmental pollution in city i at time t, and Z_{it} denotes other factors that may affect the utility of residents in city i at time t. We consider that the potential commuting time for residents of city i to reach other cities at moment t is affected by the level of high-speed rail infrastructure and the level of other transportation infrastructure, i.e., there are

$$\overline{A}_{it} = \overline{A}\left(H_{it}, X'_{ii}\right) \tag{2}$$

where H_{it} denotes the influence factor of the level of high-speed rail infrastructure on the accessibility of the residents of city i to other cities at moment t, and X'_{it} denotes the influence factor of other factors on the accessibility of the residents of city i to other cities at moment t. Since the level of environmental pollution in the city is not only affected by the transportation infrastructure such as cars and airplanes, some other factors, such as the proportion of the secondary industry structure, the green area of the city, and the size of the economy, will have an impact on the level of environmental pollution in the city, and these influencing factors we use X''_{ii} to represent them, and therefore P_{it} can be set as follows.

$$P_{it} = P\left(A'_{it}, X''_{it}\right) \tag{3}$$

In this paper, we refer to the work of Cropper (1981) to analyze the impact of intercity accessibility and environmental pollution on the utility function of residents [31]. We adopt the Cobb Douglas utility function for this analysis. Without loss of generality, we assume that the level of residents' utility follows the law of diminishing marginal utility. To emphasize the relevance of the theoretical model, we consider that other commodities have a negligible impact on consumer utility, meaning $Z_{it} = Z_0$ are assumed to be constant. Based on this, we define the specific form of the consumer utility function as Equation (4). Additionally, to facilitate further derivation of the model, we define the specific forms of the transportation accessibility function ($\overline{A}_{it}$) and the environmental pollution index (P_{it}) as Equations (5) and (6), respectively.

$$U_{it} = (A_{it})^{-\alpha}(P_{it})^{-\beta}Z_0^{\delta} \quad \alpha > 0, \beta > 0, \delta > 0 \tag{4}$$

$$\overline{A}_{it} = (H_{it})^{\eta} \times \left(X'_{it}\right)^{\varphi} \quad \eta > 0, \varphi > 0 \tag{5}$$

$$P_{it} = \left(A'_{it}\right)^{\gamma} \times \left(X''_{it}\right)^{k} \tag{6}$$

Equation (4) illustrates that the higher the degree of transportation accessibility and the lower the degree of environmental pollution, the higher the level of consumer utility. Equation (5) illustrates that the higher the level of construction of high-speed rail and other transportation facilities, the greater the accessibility of the city. Equation (6) reflects the relationship between the level of environmental pollution and the level of transportation infrastructure, as well as other influencing factors. Generally speaking, the continuous improvement of transportation infrastructure, particularly airports and highways, will result in a rise in automobile and airplane usage, thereby increasing the potential for air pollution. However, the ongoing development of high-speed rail and other eco-friendly transportation facilities can, to some extent, mitigate air pollution. Therefore, the impact of transportation infrastructure on air pollution depends on the relative significance of the influence of green transportation infrastructure compared to other forms of transportation infrastructure on environmental pollution.

From Equation (5), it can be seen that the degree of transportation access ($\overline{A}_{it}$) between cities is affected by the level of high-speed rail construction and the level of other transportation infrastructure. Now, in order to maximize the residents' utility, we need to find a reasonable solution A_{it}. Therefore, we must carry out the first-order derivation of the utility function U_{it} by A_{it}. The results are shown in Equation (7).

$$\frac{\partial U_{it}}{\partial A_{it}} = -\alpha(A_{it})^{-(\alpha+1)}(P_{it})^{-\beta}Z_0^{\delta} - \beta(A_{it})^{-\alpha}(P_{it})^{-(\beta+1)}\frac{\partial P_{it}}{\partial A'_{it}}\frac{\partial A_{it}}{\partial A_{it}}Z_0^{\delta} \tag{7}$$

where $\frac{\partial P_{it}}{\partial A'_{it}} = \gamma(A_{it})^{\gamma-1} \times (X_{it})^k$, $\frac{\partial A'_{it}}{\partial A_{it}} = 1$ is obtained by substituting into Equation (7) and collapsing:

$$\frac{\partial U_{it}}{\partial A_{it}} = -\alpha(A_{it})^{-(\alpha+1)}\left[(A'_{it})^{\gamma} \times (X_{it})^k\right]^{-\beta}Z_0^{\delta} - \beta\gamma(A_{it})^{-\alpha}\left[(A'_{it})^{\gamma} \times (X_{it})^k\right]^{-(\beta+1)}(A_{it})^{\gamma-1}(X'_{it})^k Z_0^{\delta} \tag{8}$$

$\alpha(A_{it})^{-(\alpha+1)}\left[(A'_{it})^{\gamma} \times (X_{it})^k\right]^{-\beta}Z_0^{\delta}$ denotes the direct impact of transportation access on residents' utility level. This is mainly influenced by the coefficient of transportation access α.$\beta\gamma(A_{it})^{-\alpha}\left[(A'_{it})^{\gamma} \times \left(X''_{it}\right)^k\right]^{-(\beta+1)} (A_{it})^{\gamma-1} (X''_{it})^k Z_0^{\delta}$ denotes the degree of pollution caused by transportation infrastructure, which indirectly affects residents' utility level through the coefficient of environmental pollution β and the coefficient of actual commuting time γ. As we aim to maximize the level of utility for residents, we make $\frac{\partial U_{it}}{\partial A_{it}} = 0$ adjustments after completing the project.

$$A'_{it} = -\frac{\beta\gamma A_{it}}{\alpha} \tag{9}$$

According to Equation (1), We have $A_{it} = A'_{it} - \overline{A}_{it}$, it can be obtained from this:

$$A'_{it} = \frac{\beta\gamma}{\alpha+\beta\gamma}\overline{A}_{it} \tag{10}$$

Substituting Equation (10) into Equation (6) gives:

$$P_{it} = (\frac{\beta\gamma}{\alpha+\beta\gamma})^{\gamma}(\overline{A}_{it})^{\gamma}(X''_{it})^k \tag{11}$$

Substituting Equation (5) into Equation (11) gives:

$$P_{it} = (\frac{\beta\gamma}{\alpha+\beta\gamma})^{\gamma}(H_{it})^{\gamma\eta}(X'_{it})^{\gamma\varphi}(X''_{it})^k \tag{12}$$

Taking the logarithm of Equation (12) gives:

$$lnP_{it} = \gamma ln\left(\frac{\beta\gamma}{\alpha+\beta\gamma}\right) + \gamma\eta(H_{it}) + \gamma\varphi ln(X'_{it}) + Kln(X''_{it}) \tag{13}$$

Sin α, β, γ all are constants, then (13) can be further simplified as:

$$lnP_{it} = cons + \gamma\eta ln(H_{it}) + \lambda\sum lnX_{it} \tag{14}$$

where cons represents a constant, H_{it} signifies the level of high-speed rail construction, and $\gamma\eta$ denotes a coefficient. Given that η represents the level of accessibility between the opening of a high-speed rail and the city, and it is generally assumed that the opening of a high-speed rail improves accessibility ($\eta > 0$), the focus of concern lies solely on the variable γ. If $\gamma < 0$, there exists an inverse relationship between the introduction of high-speed rail and the level of pollution in urban areas. This implies that the construction of high-speed rail facilitates the environmentally-friendly development of cities, i.e., $\gamma\eta < 0$. This indicates that if $\gamma > 0$, there is a positive correlation between the introduction of high-speed rail and the pollution level of cities, suggesting that the construction of high-speed rail hinders the environmentally-friendly development of cities, i.e., $\gamma\eta > 0$. This suggests that the introduction of high-speed rail impedes the environmentally-friendly development of cities, despite its potential to enhance the accessibility level of each city. The construction of high-speed rail infrastructure not only expands regional capital investment channels but also facilitates the development of industrial clusters and industrial symbiosis agglomeration. This generates positive externalities such as geographic agglomeration, knowledge spillover, infrastructure and labor sharing. Additionally, high-speed rail infrastructure offers advantages such as cyclic integration, technological externalities, and incremental new remuneration. These benefits achieve a harmonious balance between economic and environmental considerations, aligning with the current trend of economic development. As a consequence, this paper presents the subsequent hypotheses:

Hypothesis 1a: *The opening of high-speed rail strengthens green and sustainable development*.

Hypothesis 1b: *The introduction of high-speed rail hinders green sustainable development.*

Hypothesis 2: *The opening of high-speed rail enhances green sustainable development through the agglomeration of industrial symbiosis with heterogeneity.*

Hypothesis 3: *Various levels of industrial symbiotic agglomeration have diverse impacts on the implementation of high-speed rail (HSR) and the promotion of green sustainable development*.

Figure 1 below shows the framework of this paper.

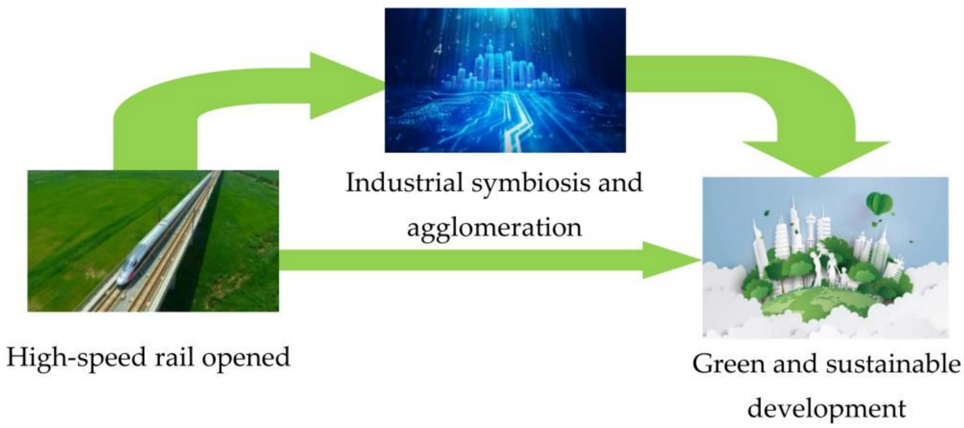

Figure 1. Guiding conceptual framework of this study.

3. Model Construction and Variable Selection

3.1. Model Construction

The use of the double-difference method first requires identifying and addressing whether the timing of the high-speed rail opening aligns with a natural experiment. Therefore, it is necessary to examine the parallel trend of high-speed rail opening and economic development to determine if the effect can be assessed using the double-difference method. It can be observed from Figure 2. that the control group and the experiment exhibit a parallel trend in the green sustainable development from 1999 to 2019. However, a significant difference in effect is evident after 2007, when the HSR officially opened. Therefore, this paper chooses to use the double-difference method to identify the effect of the opening of high-speed rail on economic development in a more effective and feasible manner.

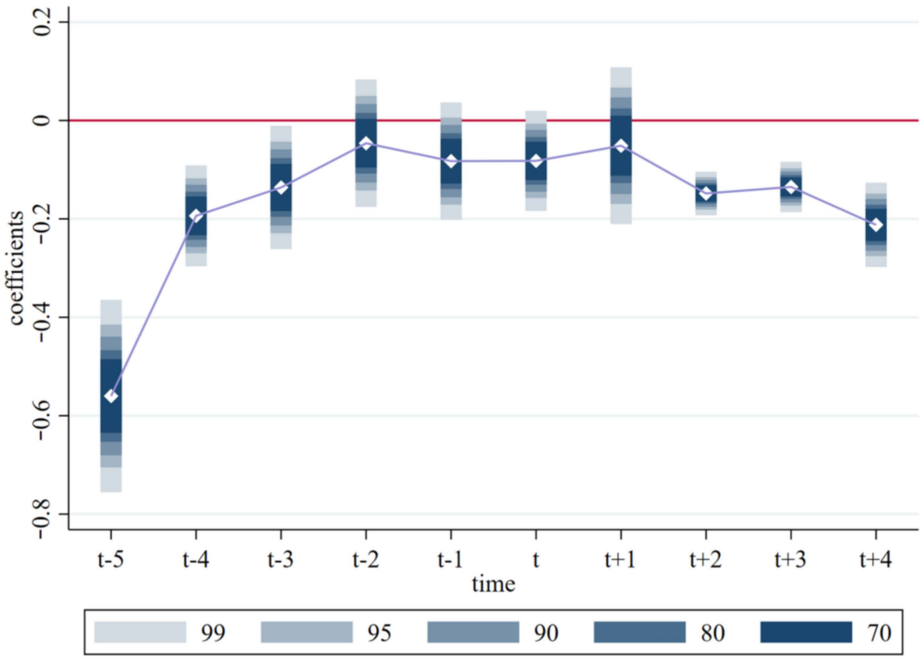

Figure 2. Change in the average value of green sustainable development of high–speed rail opening and non–opening provinces.

The economic effect of HSR opening can be assessed by the difference in economic development of the treatment group of provinces before and after the opening of HSR using the double-difference method.

$$Gedl_{it} = \alpha_0 + \alpha_t(treat_{it} \times post_{it}) + \sum_{i=1}^{N} \beta X_{it} + \varepsilon_{it} + \mu_{it} \quad (15)$$

where $Gedl_{it}$ denotes the degree of green sustainable development of province i at time period t; $treat_{it}$ is an individual dummy variable that reflects the opening of high-speed rail in province i in year t. It takes the value of 1 if the province is open and 0 if it is not; $post_{it}$ denotes the time dummy variable, which represents the year after the opening of high-speed rail. In this case, the year 2007 is considered the time of policy shocks, with a value of 1 after 2007 and 0 otherwise; and the interaction term $treat_{it} \times post_{it}$ X_{it} represents the treatment effect. The control variable is a crucial component of the model as it regulates the relevant variables that impact the green and sustainable development of the economy. The random error term is denoted as ε_{it}, and the fixed effect term μ_{it} is used to control for the province. Additionally, the economic value of the opening of high-speed rail is assumed to have a certain time cycle on green sustainable development. Therefore, this paper adopts the assumption that there is a lagging effect of the opening of high-speed rail on green sustainable development. Following the approach of Wang et al. (2019) [27], this paper employs model (2) to analyze the impact of the opening of high-speed rail on regional economic development and its changing trend:

$$Gedl_{it} = \alpha_0 + \sum_{year=2010}^{N} \alpha_t(treat_{it} \times post_{it}) + \sum_{i=1}^{N} \beta X_{it} + \varepsilon_{it} + \mu_{it} \quad (16)$$

where "year" is an annual dummy variable, taking the values from 2010 to 2019. α_t represents the coefficient of interest in this study, helping to identify the time-varying trend of the opening of the high-speed rail on green sustainable development. The definitions of the other variables in the model are consistent with the above description.

3.2. Variable Selection and Data Source Description

3.2.1. Variable Selection

The core explanatory variable is the level of green sustainable development. Referring to the research conducted by Guo & Ma (2017) [32] and other scholars, the index for measuring the level of green sustainable development capacity is constructed using the comprehensive graphical method of fully aligned polygons. A higher value of the index indicates a higher level of green sustainable development in a region. The opposite indicates a low level of economic development in this region. The indicator system is formulated based on six sub-capacity systems, namely survival support capacity, economic support capacity, environmental support capacity, social support capacity, innovation support capacity, and transformation support capacity. This construction is both comprehensive and scientifically grounded.

The main explanatory variable is the opening of high-speed rail. The main variable selected is the dummy variable indicating whether high-speed railways were opened in each province of China from 1999 to 2019. The exclusion of a sample spanning almost three years in this study was motivated by the need to avoid the counterintuitive implications arising from a nationwide shutdown caused by the outbreak of the epidemic. The main study uses an interaction term as the explanatory variable. The dummy variable for the time of high-speed rail opening measures the structural changes in the treatment group and green economic development before and after the opening of high-speed rail. The dummy variable for the city of high-speed rail opening measures the difference in economic development between provinces that have opened high-speed rail and those that have not. Figure 3 shows China's high-speed and intercity railway networks and stations in recent years.

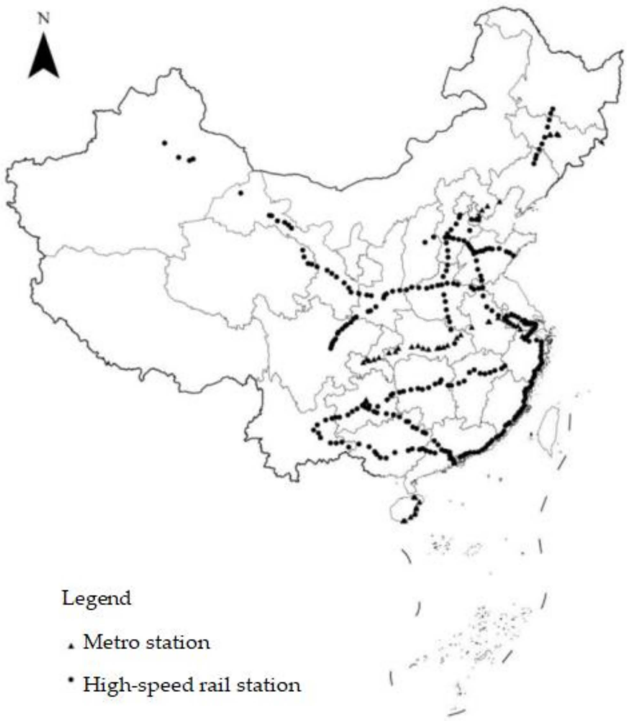

Figure 3. China's high-speed and intercity railway network and stops (2019). Note: The base map is from the standard map website of the Ministry of Natural Resources (http://bzdt.ch.mnr.gov.cn, accessed on 22 August 2019), review number GS2019 (1822), and there are no modifications to the base map.

The control variables mainly include the degree of economic development (GDP) expressed as GDP per capita, which aims to alleviate the problem of non-normal distribution;

the level of openness to the outside world (OR), which is expressed using the ratio of a province's exports to its GDP; the level of education (EDU), which is expressed using the ratio of the number of students enrolled in general higher education schools in the region to the total population; the rate of urbanization (UR), which is expressed by using the rate of urbanization in a province; the degree of financial development (FIN), which is expressed using the balance of RMB deposits of financial institutions as a proportion of GDP; and the degree of three-waste management (WT), i.e., the proportion of investment in the management of solid waste, wastewater, and exhaust gas as a proportion of GDP, as shown in Table 1.

Table 1. Summary of indicator selection.

Name	Symbolic	Description	Source	References
Green sustainability	GEL	Green sustainability index	China Statistical Yearbook, Provincial Statistical Yearbook, Provincial Statistical Bulletin	[6,32,33]
High-speed rail opening city	X	Dummy variable, assigned values 0 and 1 according to whether high-speed rail is opened or not	12306 website	[9,34,35]
Degree of economic development	GDP	GDP per capita	China Statistical Yearbook	[6,36]
Level of openness to the outside world	OR	Ratio of exports to GDP of a province	China Statistical Yearbook	[37]
Level of education EDU	EDU	Ratio of the number of students enrolled in general higher education institutions to the total population	China Statistical Yearbook	[13]
Urbanization rate	UR	Urbanization rate	China Statistical Yearbook	[38]
Level of financial development	FIN	Balance of RMB deposits in financial institutions as % of GDP	China Statistical Yearbook, Financial Yearbook of Provinces	[9]
Degree of three-waste management	WT	Investment in solid waste, waste water and waste gas management as a share of GDP	Yearbook, Provincial Statistical Yearbook, Provincial Statistical Bulletins	[39]

3.2.2. Data Sources

The real starting point of China's high-speed railway was in 1990 when the Report on the Plan of Beijing-Shanghai High-speed Railway Line was officially completed that year. Later, around whether to build a high-speed railway, what standard to build a standard high-speed railway, when to start the construction of high-speed railway, "construction party", "delayed construction", "maglev" had a protracted war of public opinion. This stage began in 1990 and ended in 1998, mainly in the ideological enlightenment stage of high-speed rail.

On 16 August 1999, China's first high-speed railway shen (Yang) passenger center (404 km, 200 km/h) started construction (officially opened on 12 October 2003). Qin and Shenyang passenger railway is a milestone in the development history of China's railway. It is the starting point of China's high-speed railway. It is the first fast railway passenger dedicated line of 200 km per hour. During this period, it also experienced the research and development peak of domestic EMU, and produced a large number of excellent domestic EMU models represented by China Star and Pioneer Blue Arrow. Therefore, the time range chosen for this study started in 1999.

The reason why the year selected in this study ended in 2019 was the outbreak of COVID-19 in China in 2020. During these three years, the epidemic had a serious impact on the construction of high-speed rail and residential travel in China. In particular, the national grounding regulations, namely "not necessary, do not go out", which had a great impact on this study. Therefore, this study finalized the years 1999–2019. The empirical analysis in this paper utilizes panel data from 30 provinces and municipalities in China, covering the period from 1999 to 2019. Tibet, which does not have high-speed railways, as well as Hong Kong, Macao, and Taiwan, are excluded from this study. Additionally, in order to reduce heteroscedasticity, this paper will apply a logarithmic treatment to each variable, as derived from the formula. However, since the high-speed rail opening city is a binary variable (0 or 1), logarithmic treatment will not be applied to them. The following table presents the descriptive statistics of the variables. The raw data used in the empirical study are all from the China Statistical Yearbook, China Urban Yearbook, and China Environmental Statistical Yearbook. The data on high-speed rail openings are sourced from the "12306 website" and other publicly available data. These data have been compiled in Table 2 below.

Table 2. Descriptive statistics of main variables.

Var	N	Mean	SD	Min	Max	Skewness	Kurtosis
GEL	630	11.34374	1.672288	8.633531	18.36703	1.274298	5.251386
did	630	0.4095238	0.4921367	0	1	0.3679794	1.135499
GDP	630	3.348406	2.859711	0.2457844	25.04468	1.917759	9.768803
OR	630	2.384436	0.8900156	0.5194266	5.052831	0.6587333	2.548088
EDU	630	2.627069	0.5823533	0.9249219	4.772524	−0.7502563	3.195674
UR	630	3.890704	0.3111633	3.061052	4.506454	−0.2044338	2.678433
FIN	630	3.742889	0.202724	2.445746	4.437003	−0.2174174	7.863322
WT	630	4.549923	1.212923	0.8329091	6.85909	−0.379081	2.687132

3.2.3. Data Description

From Table 2 above, the data illustrate the status of each variable. It is observed that the larger pair exhibits a significant difference in mean and variance, denoted as GEL. This discrepancy can be attributed to the considerable heterogeneity in the green sustainability index across different regions, aligning with the fact that the smallest pair displays a difference denoted as DID. This difference is primarily due to the composition of zero and one values. All the values in the dataset exhibit a positive trend and are generally measured on a consistent scale, with the exception of Gross Domestic Product (GDP). Furthermore, with regard to skewness and windiness, all variables fall within acceptable ranges, except for GDP, which exhibits a significant skewness.

4. Empirical Results and Analysis

4.1. Baseline Regression Results

In this part, the econometric model expressed in Equation (15) was regressed using the double-difference method by Stata16 software, and the results are shown in Table 3. It is based on the estimation results of the opening of high-speed rail on green sustainable development while further controlling for time and province. In Table 3, it can be seen that after incorporating the relevant control variables, the introduction of high-speed rail still has a significant positive impact on green sustainable development. This finding aligns with the research of Li et al. (2020); Sun and Li (2021) and Huang et al. (2020) [8,11,13], which demonstrates that the implementation of high-speed rail (HSR) contributes to sustainable economic development and the transition towards a greener economy. As a result, Hypothesis 1a is supported. In addition, the experimental results show that higher education hinders green and sustainable development. Traditionally, many higher education systems are more focused on areas such as technology, business and economics, where research and funding may flow more to support traditional industries, while ignoring environmental science, sustainable development and social science, and ignoring the urgency of global environmental challenges, which is not conducive to green and sustainable development.

Table 3. Baseline regression results.

Variables	GEL
DID	0.184 *** (0.0474)
GDP	0.0156 * (0.00937)
OR	0.287 *** (0.0618)
EDU	0.165 *** (0.0455)
UR	0.0257 (0.294)
FIN	0.287 *** (0.109)
WT	−0.301 *** (0.0458)
Constant	10.06 *** (1.263)
Observations	630
R-squared	0.969

Note: *** denotes significant within 1 percent and * denotes significant within 10 percent.

4.2. Heterogeneity Analysis

In order to study the impact of the opening of high-speed rail on the green sustainable development of different regions, this paper categorizes the provinces of the country into four regions: the eastern region, the northeastern region, the central region, and the western region. According to the relevant information from the National Bureau of Statistics, the specific divisions of the eastern, central, western, and northeastern regions involved in the statistics are as follows: The results of the sub-regional regression analysis indicate that, with the exception of the western region, the introduction of high-speed rail in both the central and western regions has a significant positive effect on green sustainable development. These findings are largely consistent with the results of the national analysis. The reason why the opening of high-speed rail in the western region does not significantly contribute to green sustainable development is due to the steep terrain. In comparison to the central and eastern regions, the western region requires a higher capital investment for the construction of high-speed rail. Additionally, the utilization rate of high-speed rail in the western region is relatively low, resulting in limited spillover and agglomeration effects. As a result, sustainable development in the western region is hindered. From the results of controlling variables processing, it is evident that a higher regional education level contributes to the enhancement of green sustainable development. Moreover, an improvement in the regional education level leads to the concentration of high-quality talents, thereby facilitating the promotion of green sustainable development in central and western China. Please refer to Table 4 for further details. This finding aligns with the research by Vickerman (2015); Jia et al. (2017) and Chen & Haynes (2017) [40–42], which suggests that the introduction of high-speed rail has varying effects on regional development.

Table 4. Heterogeneity analysis: regional analysis.

Variables	Eastern	Northeastern	Central	Western
DID	0.175 * (0.0967)	0.173 *** (0.0618)	0.104 ** (0.0439)	0.0401 (0.0917)
GDP	−0.00306 (0.0331)	−0.317 *** (0.0448)	0.0551 (0.0374)	0.00594 (0.0171)
OR	0.353 (0.251)	0.147 ** (0.0679)	0.188 *** (0.0598)	0.551 *** (0.108)
EDU	0.468 *** (0.157)	0.394 ** (0.190)	0.174 (0.7621)	0.117 (0.741)
UR	0.0754 (0.339)	6.452 *** (0.904)	0.319 (0.491)	0.530 (0.724)
FIN	−0.00293 (0.101)	0.360 * (0.188)	0.449 *** (0.158)	1.451 *** (0.315)
WT	−0.145 * (0.0773)	−0.234 ** (0.102)	−0.200 *** (0.0449)	0.0721 (0.104)
Constant	9.630 *** (1.617)	−13.43 *** (3.444)	8.404 *** (2.178)	3.480 (3.546)
Observations	210	63	126	231
R-squared	0.977	0.991	0.991	0.973

Note: *** denotes significant within 1 percent, ** denotes significant within 5 percent, and * denotes significant within 10 percent.

4.3. Robustness Tests

4.3.1. Control Variable Lagged Terms

Control variables are lagged by one period. To address the potential endogeneity problem and account for the possible inverse effect between the selected variables and the opening of high-speed rail, a lag of one period is applied to all control variables. The regression is then re-run, and the empirical results are presented in the columns of Table 5. It can be observed that the signs and significance of the coefficients are generally consistent with the Baseline regression results. However, the control variables being lagged by one period weaken the degree of control, leading to a slight increase in the estimated coefficients. Once again, the robustness of this paper's findings has been verified.

4.3.2. Narrowing the Sample Period

The regression in this paper is primarily based on the full sample from 1999 to 2019. However, it is worth noting that the high-speed rail was only opened in 2007. Therefore, the period of the sample before the opening of the high-speed rail may be excessively long. For the sake of robustness and to ensure protection from the financial crisis, the sample time period selected is 2010–2019, as shown in Table 5. The empirical findings are largely consistent with those of the previous paper.

Table 5. Estimation results with one period lag.

Variables	Control Variable Lagged Terms	Narrowing the Sample Period
DID	0.182 *** (0.0440)	0.188 *** (0.0439)
L_GDP	0.0440 *** (0.00966)	0.0490 *** (0.00968)
L_OR	0.228 *** (0.0571)	0.214 *** (0.0554)
L_UR	0.174 (0.274)	0.158 (0.266)
L_FIN	0.355 *** (0.0805)	0.341 *** (0.0807)
L_WT	0.116 (0.0909)	0.133 (0.0829)
Constant	−0.273 *** (0.0468)	−0.242 *** (0.0466)
Observations	11.53 ***	11.27 ***
R-squared	(0.897)	(0.864)

Note: *** denotes significant within 1 percent.

5. Mechanism Test of the Impact of the Opening of High-Speed Rail on Green Sustainable Development

As demonstrated by the fundamental findings of the aforementioned study, high-speed rail has a direct influence on green sustainable development. However, does high-speed rail also have an indirect impact on green sustainable development through other factors? Relevant studies have shown that transportation infrastructure is conducive to promoting the transfer of industries with comparative advantage between regions [43–45].

Here, we hypothesize that industrial symbiotic agglomeration plays a crucial role as a mediating variable in the impact of high-speed rail on green sustainable development. Industrial symbiotic agglomeration is a novel concept that seeks to emulate the functioning of natural ecosystems. Symbiotic agglomeration, as viewed through an economic lens, pertains to the tangible interconnection among economic entities. In an abstract context, it signifies the association between symbiotic units within a specific symbiotic environment, following a particular pattern of symbiotic agglomeration [19]. The location quotient method is used to study the level of industrial agglomeration and its characteristics from a regional perspective. In this study, we adopt the location quotient method to measure the level of manufacturing agglomeration in each province. The calculation is as follows: According to Liu et al. (2022); Zhang et al. (2020) and Wang et al. (2022) [19,46,47], there are three types of industrial symbiotic agglomeration modes: mutually beneficial industrial symbiotic agglomeration (All), partially beneficial industrial symbiotic agglomeration (part), and non-symbiotic agglomeration (None). The level of manufacturing agglomeration in each province is classified into three categories based on the following ranges: 0–30%, 31–60%, and 61–100%.

Table 6 presents the results of the analysis. Column (1) displays the total mediation effect. Column (2) provides the estimation results of the impact of the opening of high-speed rail on the level of unsymbiotic agglomeration (None). Column (3) presents the results of the regression treatment of the opening of high-speed rail on the symbiotic agglomeration of biased industries (Part). Lastly, column (4) indicates the estimation results of the impact of the opening of high-speed rail on the level of symbiotic agglomeration of mutual-beneficial industries (All). Combined with the preceding benchmark regression findings, it can be observed that the introduction of high-speed rail has a positive and statistically significant influence on the co-dependent clustering of mutually advantageous industries. However, it does not have a significant impact on the clustering of non-co-dependent industries and partially co-dependent industries. In fact, it even has a negative effect on the clustering of non-co-dependent industries. This observation suggests that varying degrees of industrial symbiotic agglomeration can result in different mediating effects. The implementation of high-speed rail systems facilitates the interconnection of various industries, leading to mutually beneficial industrial symbiotic agglomeration. This integration allows for the sharing of infrastructure resources and a reduction in transportation energy consumption, ultimately promoting green and sustainable development.

Table 6. Mediating mechanism test of high-speed rail opening on green sustainable development.

Variables	ISA	None	Part	All
DID	0.308 ** (0.151)	−0.131 (0.0867)	0.00654 (0.0562)	0.677 ** (0.326)
GDP	0.0473 (0.0308)	−0.0121 (0.0105)	0.0153 (0.0203)	0.0671 (0.0889)
OR	0.0416 (0.160)	−0.0566 (0.0544)	−0.150 ** (0.0670)	0.300 (0.255)
EDU	0.282 (0.192)	0.0175 (0.104)	−0.00513 (0.177)	0.236 (0.296)
UR	0.173 (1.154)	−0.144 (0.480)	0.403 (0.551)	−1.544 (2.056)
FIN	0.506 (0.551)	−0.625 ** (0.280)	−0.109 (0.106)	0.732 (0.787)
WT	−0.146 (0.115)	−0.122 (0.0880)	−0.0676 (0.0527)	0.481 ** (0.204)
Constant	6.042 (6.624)	12.02 *** (2.090)	8.351 *** (2.570)	9.723 (11.16)
Observations	630	168	132	322
R-squared	0.580	0.695	0.445	0.432

Note: *** denotes significant within 1 percent and ** denotes significant within 5 percent.

6. Further Analysis

6.1. Time Lag Effect of the Opening of High-Speed Rail on Green Sustainable Development

Transportation infrastructure has a significant impact on the green and sustainable development of the economy. However, it is difficult to observe a significant impact on economic growth in the short term, such as within a one-year period. By considering relevant research perspectives, it can be assumed that the opening of high-speed rail has a certain time lag effect on the impact of green and sustainable development. To ensure that this time lag effect is indeed caused by the opening of high-speed rail and not by other factors, further investigation is necessary. In this regard, this study refers to the research method used by Xu et al. (2022) [48] and other similar research methods. The provided text is empty. We conduct a regression analysis on the core explanatory variables with a one-period lag. The outcomes of the national and sub-regional interventions are displayed in the subsequent table.

According to the findings presented in Table 7, the coefficients for all regions in the national sample demonstrate a positive relationship between the opening of high-speed rail and green sustainable development. This suggests that the implementation of high-speed rail positively impacts sustainable environmental practices. The significance of the opening of high-speed rail varies across different regions of China. While it is not significant in the western and central regions, it is indeed significant in the eastern and northeastern regions. This suggests that the eastern and northeastern regions experience a certain time lag effect in terms of high-speed rail development.

Table 7. Time lag effect of the opening of high-speed rail on the impact of green sustainable development.

Variables	Eastern	Northeastern	Central	Western
L.DID	0.198 ** (0.0886)	0.133 *** (0.0473)	0.0703 (0.0466)	0.128 (0.0972)
GDP	−0.0197 (0.0342)	−0.344 *** (0.0383)	0.0356 (0.0349)	0.00508 (0.0128)
OR	0.286 (0.252)	0.146 ** (0.0625)	0.173 *** (0.0616)	0.476 *** (0.102)
EDU	0.160 (0.100)	0.00692 (0.404)	0.00136 (0.127)	0.00938 (0.0788)
UR	0.139 (0.392)	6.586 *** (0.780)	0.179 (0.624)	1.193 (0.825)
FIN	−0.0182 (0.0980)	0.173 (0.130)	0.400 ** (0.153)	0.820 *** (0.280)
WT	−0.159 ** (0.0755)	−0.146 ** (0.0696)	−0.192 *** (0.0480)	0.0852 (0.0945)
Constant	9.413 *** (1.823)	−15.00 *** (2.905)	9.154 *** (2.850)	3.225 (3.569)
Observations	200	60	120	220
R-squared	0.978	0.993	0.991	0.975

Note: *** denotes significant within 1 percent and ** denotes significant within 5 percent.

6.2. Spatial Spillover Effects of the Opening of High-Speed Railways Affecting Green Sustainable Development

Inter-regional socio-economic activities are typically accompanied by noticeable spatial correlation. The spatial econometric model can effectively consider the spatial correlation characteristics and eliminate the estimation bias that may arise from spatial interaction effects, thereby improving the accuracy of empirical results. To evaluate the model fitting effect, the optimal econometric model for this paper was selected based on the methodology used by Gao & Wang (2023) [49]. The specific settings are as follows:

$$Gedl_{it} = \alpha + \beta_0 X + \beta_1 C_{it} + \rho \sum_{j=1}^{N} W_{ij} Gedl_{it} + u_i + \lambda_t + \varepsilon_{it}$$

$$\varepsilon_{it} = \lambda \sum\nolimits_{j=1}^{N} W_{it} \varepsilon_{it} + \tau_{it} \quad (17)$$

Equation (1) denotes green sustainable development. The main explanatory variable is the accessibility of high-speed rail, which is represented by the logarithm of the total mileage of high-speed rail. If the number of high-speed rail mileage is not available, the logarithm of the number of highway mileage can be used, as suggested by Lin et al. (2021) and Lin (2017) [2,50]. There are also several control variables. The coefficients in the constant term and the independent variable regression represent the constant term and the coefficients of the independent variable, respectively. The spatial weighting matrix denotes the area effect, and the time effects are also denoted; they are random disturbance terms. The coefficients represent spatial terms. Regarding the spatial weight matrix, this paper refers to relevant literature on practices for constructing the geographic distance weight matrix. This matrix reflects the spatial correlation characteristics among regions.

Firstly, global Moran's I index was calculated to assess the spatial dependence of green sustainable development among provinces. The results indicate that Moran's I index is negative for each weight matrix and passes the 1% significance level test. This suggests a significant spatial dependence on green sustainable development among provinces. As depicted in the table provided, Moran's I index demonstrates a generally fluctuating downward trajectory. The declining trend in the spatial correlation coefficient may be attributed to the limitations imposed by the original transportation system, which restricted economic activities to be closely exchanged between neighboring cities. However, with the introduction of high-speed railroads, particularly the sixth railroad speed increase, the economic links between cities have significantly transcended geographic boundaries. As a result, these economic links are no longer confined to neighboring areas alone, thereby contributing to the observed decline in the spatial correlation coefficient. The aforementioned analysis highlights the importance of considering the spatial correlation characteristics of cities and utilizing spatial econometric models to examine the spatial impact effects of the introduction of high-speed railways on green sustainable development. This is demonstrated in Table 8.

Table 8. Trend of Moran's I index under geographic distance weight matrix.

Year	I	E(I)	Sd(I)	Z	*p*-Value
1999	−0.0894	−0.0345	0.0168	−3.2631	0.0011
2000	−0.1123	−0.0345	0.0169	−4.6063	0.0000
2001	−0.1128	−0.0345	0.0169	−4.6218	0.0000
2002	−0.1139	−0.0345	0.0170	−4.6824	0.0000
2003	−0.1145	−0.0345	0.0170	−4.7162	0.0000
2004	−0.1144	−0.0345	0.0170	−4.7079	0.0000
2005	−0.1142	−0.0345	0.0170	−4.6983	0.0000
2006	−0.1135	−0.0345	0.0170	−4.6540	9.9000
2007	−0.1136	−0.0345	0.0170	−4.6495	0.0000
2008	−0.1132	−0.0345	0.0170	−4.6287	0.0000
2009	−0.1167	−0.0345	0.0170	−4.8287	0.0000
2010	−0.1167	−0.0345	0.0170	−4.8202	0.0000
2011	−0.1155	−0.0345	0.0170	−4.7561	0.0000
2012	−0.1136	−0.0345	0.0170	−4.6498	0.0000
2013	−0.1126	−0.0345	0.0170	−4.5880	0.0000
2014	−0.1113	−8.0345	0.0170	−4.5149	0.0000
2015	−0.1131	−0.0345	0.0170	−4.6190	0.0000
2016	−0.1147	−0.0345	0.0170	−4.7083	0.0000
2017	−0.1153	−0.0345	0.0170	−4.7448	0.0000
2018	−0.1138	−0.0345	0.0170	−4.6612	0.0000
2019	−0.1122	−0.0345	0.0171	−4.5461	0.0000

Next, the estimation of spatial measures is conducted. As shown in Table 9, the estimated coefficient of HSR accessibility (X) displays a positive value and demonstrates statistical significance according to the conducted significance test. The analysis uncovers a significant spatial clustering and correlation of green sustainable development. Meanwhile, the weight interaction observed in the spatial econometric model continues to exhibit a significant positive relationship. This implies that there is a noteworthy inhibitory effect on green sustainable development when considering the enhancement of high-speed rail accessibility, even after accounting for the spatial interaction effect. The establishment of China's high-speed rail network has led to the interdependent clustering of industries and the consolidation of resources in certain regions, consequently hindering the environmentally sustainable development of other regions.

Table 9. Spatial measurement results.

Variables	Main	Wx	Spatial	Variance
DID	0.147 *** (0.0499)	−0.279 (0.178)		
GDP	0.0115 (0.0103)	−0.110 *** (0.0419)		
OR	0.246 *** (0.0390)	−0.000205 (0.103)		
EDU	0.189 *** (0.0319)	−0.0179 (0.0513)		
UR	−0.225 (0.195)	−3.583 *** (0.924)		
FIN	0.353 *** (0.0903)	1.034 ** (0.432)		
WT	−0.339 *** (0.0400)	0.114 (0.189)		
rho			−0.00309 (0.141)	
sigma2_e				0.0935 *** (0.00527)
Observations	630	630	630	630
R-squared	0.506	0.506	0.506	0.506
Number of code	30	30	30	30

Note: *** denotes significant within 1 percent and ** denotes significant within 5 percent.

7. Conclusions and Implications

Based on the economic characteristics of high-speed rail, this paper selects data from 30 provinces between 1999 and 2019. It employs the double-difference method to assess the impact of the introduction of high-speed rail on green sustainable development. This study finds that the introduction of high-speed rail contributes to the improvement of environmentally sustainable economic development during the study period. Furthermore, a heterogeneity test reveals that the introduction of high-speed rail significantly promotes environmentally sustainable economic development in the eastern, central, and western regions. It also facilitates agglomeration through the horizontal mechanism of symbiotic agglomeration among various industries. This study also finds that the introduction of high-speed rail has a significant time lag effect on the sustainable green development of the economy. Furthermore, the opening of high-speed rail has a gradual positive impact on the sustainable green development of the economy in the central and western regions. The following conclusions and insights have been drawn. During the study period, the opening of high-speed rail has a significant direct effect on the green and sustainable development of the economy. Additionally, it promotes industrial symbiosis and agglomeration, further strengthening the relationship between urban and rural areas in the central and western regions. This enables full industrial symbiosis and agglomeration during the process of industrialization, reduces transportation costs, shares infrastructure construction, and decreases pollutant emissions. Consequently, the opening of high-speed rail contributes to the improvement of the green and sustainable development of the economy. This, in turn, enhances the green and sustainable development of the economy. Secondly, the heterogeneity test reveals that the introduction of high-speed rail in the central and western regions promotes the comprehensive, environmentally friendly, and sustainable development of the economy. Finally, with time, the impact of high-speed rail on the green sustainable development of the economy has shown a trend of initially increasing and then decreasing on a national scale. However, for the central and western regions, the effectiveness of its effects has gradually increased over time. This indicates that high-speed rail is effectively utilizing the comparative advantages of industries in these regions to enhance the green sustainable development of the economy. Finally, the opening of the high-speed rail (HSR) has an impact on the spatial spillover effect of green sustainable development. Therefore, at the policy level, there should be a strong emphasis on further developing the construction of high-speed railways in central and western China. This is of immense value and significance for promoting green and sustainable economic development, as well as for fully implementing and solidifying the concept of green development, such as the idea that "green water and green mountains are as valuable as gold and silver mountains".

First, we should strengthen regional planning and increase the number of high-speed rail lines in underdeveloped areas. At present, the construction of the high-speed rail network primarily focuses on connecting prefecture-level cities to provincial capital cities. However, many counties still lack efficient transportation infrastructure. It is important to consider the strategic placement of high-speed rail lines through these counties, particularly in the design of connections between small and medium-sized cities and county high-speed rail stations. This will significantly contribute to the socio-economic development of the relatively underdeveloped areas along the region's economy. Especially the relatively underdeveloped areas along the route are abundant in tourism resources. However, transportation is inconvenient in these areas. The construction of a high-speed rail line in such regions promotes local tourism, economic development, and the movement of goods and people. This development is of great significance for achieving green and sustainable economic growth.

Secondly, it plays a role in the industrial aggregation and diffusion of high-speed rail. The development of high-speed railroads plays a role in the economic growth and connectivity of neighboring cities, as well as the efficient flow and distribution of goods and services along the rail line. It promotes the transfer of industries from developed regions to the central and eastern parts of the country, the optimization and adjustment of the regional industrial structure, the employment of rural residents in the surrounding areas, the improvement of their family income, and the promotion of green and sustainable economic development.

Thirdly, increase the involvement of local governments in the development of high-speed rail. As the primary beneficiaries of regional high-speed railway lines, local governments should actively participate in high-speed railway construction and leverage the investment enthusiasm of regional urban investment companies and enterprises with diverse economic backgrounds. This will ensure that the investment funds for local high-speed railway sections are fully secured. In conjunction with the current central poverty alleviation policy, it is crucial for the relevant functional departments to prioritize providing financial and monetary support to the central and western regions during the construction of high-speed railways. This will enable the full utilization of the high-speed railways' potential value, facilitate the transfer of industries with comparative advantages, and ultimately promote economic development in the central and western regions. Additionally, it will contribute to the green and sustainable development of the economy in these regions.

In addition, it is important to acknowledge that this paper is not without its research limitations. Due to limited data availability, acquiring county-level data at a more granular level poses challenges, resulting in a research sample size of only 30. Consequently, future research endeavors will aim to expand this sample size. In addition, an intriguing aspect to explore is the heterogeneity of industrial symbiotic agglomeration across various industries. These areas of investigation can be pursued in future research endeavors.

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