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Original Research

Effects of Petrochemical Industry Agglomeration and Green Technology Innovation on Eco-Efficiency: an Analysis Based on Provincial Data in China

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Abstract

China is currently at a critical stage in transitioning from a large petrochemical country to a powerful one. To clarify the relationship between the development of the petrochemical industry and local ecological economy and explore the scientific development path for the industry, this paper analyzes the influence of petrochemical industry agglomeration on local ecological efficiency. By using panel data from 30 provincial units between 2012 and 2021, the study also investigates the mediating effect of green technology innovation on this relationship. Results show that the agglomeration of China's petrochemical industry positively affects local ecological efficiency. However, given some issues such as separation of production and innovation activities within the industry, a negative correlation exists between the agglomeration level of the petrochemical industry in China and the level of green technology innovation. Consequently, the agglomeration of China's petrochemical industry cannot enhance ecological efficiency through the mediating effect of green technology innovation level. The substantial resource consumption by green technology innovation has not translated into effective ecological economic benefits, which has increased the burden on ecological functions and resulted in a negative effect on ecological efficiency. The research conclusions and proposed measures hold significant implications for the scientific planning of the development of China's petrochemical industry, as well as for promoting regional economic growth and ecological construction.

Keywords: ecological efficiency, green technology innovation, mediating effect, petrochemical industry agglomeration

Introduction

The petrochemical industry, which uses oil and natural gas as raw materials, is an important basic raw materials industry in China. In 2021, the industry's business revenue reached 189,389.8 billion yuan, accounting for 14% of the total industrial business revenue, making it an important part of China's industrial economy. However, as a traditional industrial sector, the petrochemical industry is characterized by high energy consumption, high emissions, and resource dependence. In 2021, the industry's total energy

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consumption reached 1,095.4 million tons of standard coal, accounting for 31% of total industrial energy consumption.

Industrial agglomeration is a spatial organization form based on the deepening division of labor [1]. To form development advantages, most industries show a trend of spatial agglomeration of economic entities and supporting systems, including the petrochemical industry. The expansion of production scale within a region can lead to the growth of economic benefits; however, it also increases the local ecological burden in terms of resource consumption and environmental pollution. Given the petrochemical industry's high energy consumption and high emission characteristics, the agglomeration phenomenon has prompted many scholars to conduct related research. Some have measured and evaluated the petrochemical industry's agglomeration level in specific regions (Han et al., 2017 [2]; Sun et al., 2014 [3]), whereas others have conducted studies on the effect of the industry on regional economies (Wu et al., 2017 [4]) and regional ecological environments (Bai et al., 2016 [5]). However, few studies have been conducted from the perspective of the effect of petrochemical industry agglomeration on the comprehensive benefits of regional economic and ecological environment. As an effective tool for measuring comprehensive economic and ecological benefits, ecological efficiency opens up a new way for the research of the regional effect of petrochemical industry agglomeration.

At present, China suffers from severe overcapacity in basic chemicals and structural contradictions in high-end new materials and functional chemicals. The country is at a critical stage of transitioning from a large petrochemical country to a powerful one [6]. The effect of petrochemical industry agglomeration on local ecological efficiency must be investigated to firmly implement sustainable development concepts, explore the scientific development path for the petrochemical industry, and coordinate the relationship between the industry's development and local ecological economy.

Theoretical Mechanism

Influence Mechanism of Industrial Agglomeration on Ecological Efficiency

Upon reviewing the existing literature, many scholars have conducted studies on the effect of industrial agglomeration on ecological efficiency. The main research perspectives can be summarized into the following aspects.

Industrial agglomeration positively affects ecological efficiency. It generates scale, technical, structural, and competition and cooperation effects [7]. When the interaction between these effects is continuously optimized and improved, it can positively influence ecological efficiency [8]. Industrial agglomeration can reduce enterprise search costs by eliminating regional segmentation effects caused by geographical distance and effectively integrating production factors. It can also improve resource allocation efficiency by improving and sharing infrastructure. In terms of undesirable output, enterprises focus on following unified environmental regulations and standardized pollution treatment procedures, reducing unit pollution control costs through shared environmental protection facilities and technologies. In industrial agglomeration areas, competition among enterprises leads to improved product and service quality through internal optimization of production processes and innovation, ultimately securing a dominant position in the industrial value chain [9]. Structural adjustments and healthy competition promote reasonable specialization and cooperation arrangements within a region, benefiting enterprise growth and regional economic development. Industrial agglomeration removes barriers to factor flow, enhances exchanges and cooperation between enterprises, and shortens cognitive distance. This process promotes industrial technological innovation by exerting the spillover effect of knowledge and technology. Positive externalities of technological innovation are mainly reflected in two aspects: enhancing product added value and improving resource utilization efficiency while reducing environmental pollution [10]. In addition, industrial agglomeration provides an opportunity to maximize resource utilization and develop local circular economy.

Industrial agglomeration negatively affects ecological efficiency. According to the input–output nature of industrial industries, such as mining and manufacturing, the agglomeration phenomenon's production scale expansion increases resource consumption and pollutant emissions [11]. Negative environmental externalities contribute to regional ecological function degradation and increased environmental governance costs. At the same time, the crowding effect caused by industrial agglomeration results in economic disorder, unhealthy competition, resource allocation imbalance, and other issues. In this case, production units cannot achieve coordinated development, and their investment choice costs and sunk costs transform into economic losses, which inhibits regional economic development.

A nonlinear relationship exists between industrial agglomeration and ecological efficiency. The industrial agglomeration process is a dynamic game between positive and negative externalities. The effects of dominant externalities on ecological efficiency may differ across various agglomeration stages, resulting in a nonlinear relationship between industrial agglomeration and ecological efficiency [12].

Generally, the influence of industrial agglomeration on ecological efficiency is complex, and different industries show significant differences in different life cycle stages [13]. On the basis of the above theoretical mechanism analysis, the first research hypothesis is proposed in this paper: petrochemical industry agglomeration positively affects local eco-efficiency.

Influence Mechanism of Industrial Agglomeration and Green Technology Innovation on Eco-Efficiency

On the basis of the influence mechanism analysis above, technological innovation may serve as an effective intermediary for industrial agglomeration to affect ecological efficiency. Industrial agglomeration can stimulate green technology innovation in enterprises through scale and knowledge spillover effects. Conversely, the geographical agglomeration of production units leads to a crowding effect of knowledge rather than a concentration of technological innovation [14]. In addition, industrial agglomeration may cause innovation path dependence and cognitive self-locking, which restricts the improvement of innovation ability. Innovation activities are knowledge-intensive and may be geographically separated from production activities when considering location conditions. The agglomeration of different types of industry can have significantly different effects on green technology innovation. Green technology innovation often reflects the strategic orientation of industry development. Enterprises exhibit varying demands and intentions for green technology innovation at different stages of the industrial agglomeration life cycle. In the initial stage, enterprises within the cluster area experience disorganized development. Pollution treatment costs are high due to environmental regulation constraints and the lack of supporting facilities. As a result, companies may be locked into a low-cost strategy and not actively engage in green technology adoption and related innovation activities.

Different from traditional technological innovation that seeks to maximize economic benefits, green technological innovation adheres to ecological principles and ecological economic laws, aiming to achieve positive ecological and environmental outcomes. It places greater emphasis on improving resource allocation efficiency and reducing environmental pollution through active source management, process control, terminal treatment, and recycling [15]. When considering the potential environmental benefits of green technology innovation, it is crucial to recognize its high input, high risk, and external economic characteristics [16]. The comprehensive benefit transformation of green technology innovation also exhibits a time lag.

In sum, whether green technology innovation can achieve equilibrium in the game between economic benefits and ecological environment constraints is worth exploring. On the basis of the above theoretical mechanism analysis, the second research hypothesis is proposed in this paper: petrochemical industry agglomeration has a mediating effect on eco-efficiency through green technology innovation.

Research Design

Mediating Model Construction

This analysis aims to determine whether the petrochemical industry in China can promote the development of green technology innovation through industrial agglomeration and further influence regional eco-efficiency. On the basis of the above theoretical mechanism, an econometric model is constructed to test the overall effect of petrochemical industry agglomeration on regional eco-efficiency, as shown as follows:

$$EE_{it} = C_1 + \alpha_1 AG_{it} + \alpha_j Control_{it} + \mu_{1i} + \delta_{1t} + \varepsilon_{1it} \tag{1}$$

where the explained variable EE_{it} is the ecological efficiency in year t of province i; the core explanatory variable AG_{it} is the agglomeration degree of petrochemical industry agglomeration in year t of province i; $Control_{it}$ represents a set of control variables, including the level of economic development, the level of land urbanization, the level of government support for science and technology, the intensity of environmental regulation, and the level of opening-up; C_1 is a constant term; α_1 represents the influence coefficient of petrochemical industry agglomeration on regional eco-efficiency; α_j represents the coefficients of each control variable; μ_{1t} and δ_{1t} represent individual fixed effect and time fixed effect, respectively; and ε_{1it} is a random error term.

To further study the indirect effect of petrochemical industry agglomeration on eco-efficiency through green technology innovation, a mediating effect model is constructed to test the transmission mechanism, as shown as follows:

$$GT_{it} = C_2 + \beta_1 AG_{it} + \beta_j Control_{it} + \mu_{2i} + \delta_{2t} + \varepsilon_{2it} \tag{2}$$

$$EE_{it} = C_3 + \varphi_1 GT_{it} + \varphi_2 AG_{it} + \varphi_j Control_{it} + \mu_{3i} + \delta_{3t} + \varepsilon_{3it} \tag{3}$$

Model (2) is the analysis equation of green technology innovation, where the mediating variable green technology innovation (GT) is taken as the explained variable; GT_{it} represents the green technology innovation level in year t of province i; core explanatory variable AG_{it} represents the agglomeration degree of petrochemical industry agglomeration; $Control_{it}$ represents a set of control variables, including the advanced degree of industrial structure, the level of government support for science and technology, the intensity of environmental regulation, and the level of opening-up; C_2 is a constant term; β_1 represents the influence coefficient of petrochemical industry agglomeration on the level of green technology innovation; β_j represents the coefficients of each control variable; μ_{2i} and δ_{2t} represent individual fixed effect and time fixed effect, respectively; and ε_{2it} is a random error term.

The mediating variables green technology innovation level (GT) and the core explanatory variable agglomeration degree of petrochemical industry (AG) are included in the regression model (Model (3)). $Control_{it}$ represents a set of control variables, with variable selection similar to that of Model (1); φ_1 represents the influence coefficient of the mediating variable, namely, the mediating effect; φ_2 represents the influence coefficient of the agglomeration degree of petrochemical industry as the core explanatory variable; μ_{3i} and δ_{3t} represent individual and time fixed effects, respectively; and ε_{3it} is a random error term.

The mediating effect is tested as follows. If coefficients α_1 and β_1 are significant and φ_2 decreases accordingly or is notably lower than α_1, then a mediating effect exists, that is, the theoretical mechanism and research hypothesis above are tenable.

Variable Explanation

Explained Variable. The explained variable is regional eco-efficiency (EE). Ecological efficiency is an evaluation method that considers economic and environmental benefits and reveals the balance degree of comprehensive benefits achieved by individual resource allocation. It needs to evaluate the relative effectiveness of decision-making units based on multiple input and output indicators. The Super-SBM model provides an ideal paradigm for its measurement, as shown as follows [17]:

$$min\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}}{x_{ik}}}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\frac{y^d}{y_{sk}^d}+\sum_{q=1}^{r_2}\frac{\overline{y^u}}{y_{qk}^u}\right)};$$

$$\text{s.t.}\begin{cases}\bar{x} \geq \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j; \overline{y^d} \leq \sum_{j=1,\neq k}^{n} y_{sj}^d\lambda_j;\\ \overline{y^d} \geq \sum_{j=1,\neq k}^{n} y_{qj}^d\lambda_j; \bar{x} \geq x_k; \overline{y^d} \leq y_k^d; \overline{y^u} \geq y_k^u;\\ \lambda_j \geq 0; i=1,2,\dots,m; j=1,2,\dots,n;\\ s=1,2,\dots,r_1; q=1,2,\dots,r_2;\end{cases} \tag{4}$$

where ρ is the green innovation efficiency value of high-tech industry; n is the number of provincial units; m is the number of inputs; r_1 and r_2 represent the number of expected and unexpected outputs, respectively; and x, y^d, and y^u correspond to the elements of the input matrix, expected output matrix, and unexpected output matrix, respectively.

The input indexes of eco-efficiency include energy, water, labor, and capital inputs. Energy input index is measured by total energy consumption in a region; water input index is measured by total water consumption in a region; the labor input index is measured by the number of employed persons in a region at the end of the year; and the capital input index is expressed by the capital stock in a region, which is calculated by the perpetual inventory method. $K_t = I_i/p_i + (1-\delta) K_{t-1}$, where K is the capital stock, I is the total social investment in fixed assets, and ρ is the price index of fixed asset investment; 2011 is taken as the base period for price reduction, δ is the depreciation rate and is set at 9.4% in reference to the study by Da et al. [18].

The output index of ecological efficiency includes desirable output and undesirable outputs. Expected output is the economic benefit, expressed by gross regional product, with 2011 as the base period for constant price treatment. Waste water, waste gas, and solid waste are common indicators of undesirable environmental output. Waste water is expressed in terms of chemical oxygen demand, waste gas is expressed in terms of sulfur dioxide emissions, and solid waste refers to the amount of common industrial solid wastes generated.

Core Explanatory Variable. The core explanatory variable is the agglomeration degree of petrochemical industry (AG). The petrochemical industry mentioned in this study includes five sectors: petroleum and natural gas extraction; processing of petroleum, coal, and other fuels; manufacture of raw chemical materials and chemical products; manufacture of chemical fibers; and manufacture of rubber and plastic products. The related indexes of the petrochemical industry are the sum of the related indexes of the five sectors. The measurement methods of industrial agglomeration level mainly include location entropy, spatial Gini coefficient, and Ellison–Glaeser agglomeration index. Each of these indexes has its own advantages and disadvantages. In this study, in terms of data collection and applicability, location entropy can meet the requirements for measuring the agglomeration degree of the petrochemical industry. Therefore, location entropy is selected as the measurement model for the level of petrochemical industry agglomeration, that is,

$$AG_i = \frac{E_{ij}/E_i}{E_{kj}/E_k} \tag{5}$$

where E_{ij} is the business revenue of petrochemical enterprises above designated size in region i, E_i is the business revenue of industrial enterprises above designated size in region i, E_{kj} is the business revenue of petrochemical enterprises above designated size in China, and E_k is the business revenue of industrial enterprises above designated size in China.

Mediating Variable. The mediating variable is green technology innovation level (GT). In this study, according to the Green and Low-carbon Technology Patent Classification System issued by the State

Intellectual Property Office and the relevant reference search formula, the patent retrieval and analysis system is used to search from three branches: petroleum low-carbon exploitation, clean petrochemical and transformation, and natural gas exploitation and transformation. The number of green and low-carbon technology patent applications is used to describe the green technology innovation level of the regional petrochemical industry.

Control Variable. The level of economic development (EC) is measured by the logarithm of the constant price of GDP per capita. The level of government support for science and technology (GS) is measured by the proportion of science and technology expenditure in general public budget expenditure. Land urbanization level (UR) is measured by the proportion of urban area to land area. Environmental regulation intensity (ER) is measured by the proportion of investment in pollution control projects to industrial added value. The level of opening-up (OP) is measured by the proportion of foreign investment in gross regional product. The advanced degree of industrial structure (TH) is determined by the proportion of added value of tertiary industry in gross regional product.

Data Source and Processing

The data used in this study are panel data of 30 provincial-level regions in China from 2012 to 2021 (excluding Tibet, Hong Kong, Macao, and Taiwan), and the data mainly come from the China Statistical Yearbook, China Industrial Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Statistical Yearbook and statistical yearbook of provinces, municipalities, and autonomous regions. The number of green and low-carbon technology patent applications is collected through the patent retrieval and analysis system of the State Intellectual Property Office. Data that cannot be obtained directly are retrieved by converting the data above. Missing data can be completed by interpolation method.

Variable Measurement Result

Measurement Results of the Agglomeration Level of the Petrochemical Industry

Taking 2012-2021 as the main study period (excluding 2017 and 2018 due to lack of data), the agglomeration degree of the petrochemical industry of 30 provincial units in China was measured by location entropy, and the results are shown in Table 1. China's petrochemical industry agglomeration has a certain tendency of resource endowment. During the study period, the petrochemical industry agglomeration degree of 10 provincial units in Liaoning, Heilongjiang, Zhejiang, Shandong, Hainan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang has always been more than 1. The petrochemical industry of these provincial units occupies a relatively important position in the local industrial economy, forming the petrochemical industry agglomeration. Hainan and Xinjiang are the most prominent, and the agglomeration degree of the petrochemical industry is always above 2. From the perspective of spatial distribution, northwest China is the most concentrated area of petrochemical industry, and north, northeast, and east China are also the main distribution areas of petrochemical industry agglomeration, whereas central and southwest China have a low level of petrochemical industry agglomeration. From the perspective of time, the concentration level of petrochemical industry in Inner Mongolia and Shanghai is gradually enhanced during the study period, whereas that of Jiangsu is gradually weakened.

Measurement Results of Ecological Efficiency

In this paper, the Super-SBM model is used to measure the eco-efficiency of 30 provincial units throughout the study period, with the results presented in Table 2. A significant variation exists in the eco-efficiency of China's provincial units, and the spatial distribution is uneven. Throughout the study period, some provincial units experienced an increase in eco-efficiency values, whereas others experienced a decrease. However, the majority of regions maintained relatively stable eco-efficiency values. Five provincial units, including Beijing, Tianjin, Shanghai, Jiangsu, and Zhejiang, consistently had eco-efficiency values higher than the national average during the study period. In addition, Inner Mongolia has maintained high eco-efficiency since 2013. These regions are characterized by their ability to generate greater economic value with lower resource and environmental costs. From a spatial distribution perspective, the average eco-efficiency in north and east China consistently surpasses the national average. northwest China is highly sensitive to ecological factors. As a critical area for industrial relocation from the eastern coastal regions, northwest China continues to face significant challenges in ecological and environmental governance [19], resulting in poor average eco-efficiency performance. In terms of time, the average eco-efficiency in northeast China experienced a notable increase during the study period. Conversely, the average eco-efficiency in south China exhibited a downward trend, with Guangdong experiencing the most significant decrease in eco-efficiency.

Results and Analysis

Regression Analysis of Petrochemical Industry Agglomeration on Eco-Efficiency

The regression analysis is conducted according to Model (1) and considering the regional differences

Table 1. Results of agglomeration degree of China's petrochemical industry from 2012 to 2021.

Region		2012	2013	2014	2015	2016	2019	2020	2021
North China	Beijing	0.52	0.45	0.45	0.40	0.34	0.31	0.27	0.26
	Tianjin	1.10	1.04	0.98	0.95	1.03	1.22	1.08	1.17
	Hebei	0.80	0.81	0.80	0.86	0.87	0.87	0.89	0.81
	Shanxi	0.77	0.77	0.70	0.72	0.74	0.96	1.01	0.92
	Inner Mongolia	0.79	0.89	1.00	1.00	1.04	1.05	1.18	1.21
Northeast China	Liaoning	1.16	1.17	1.18	1.34	1.57	2.07	2.04	1.93
	Jilin	0.74	0.81	0.72	0.70	0.67	0.67	0.68	0.70
	Heilongjiang	2.02	1.88	1.89	1.53	1.49	1.90	1.76	1.82
Eastern China	Shanghai	0.94	1.01	0.95	0.94	0.94	0.98	1.03	1.05
	Jiangsu	1.04	1.06	1.08	1.12	1.14	0.98	0.93	0.89
	Zhejiang	1.26	1.29	1.27	1.23	1.23	1.23	1.25	1.25
	Anhui	0.64	0.65	0.68	0.70	0.71	0.76	0.82	0.78
	Fujian	0.76	0.76	0.86	0.85	0.82	0.87	0.98	0.95
	Jiangxi	0.75	0.72	0.71	0.73	0.76	0.59	0.64	0.61
	Shandong	1.34	1.37	1.42	1.47	1.54	1.83	1.76	1.83
Central China	Henan	0.67	0.65	0.65	0.66	0.67	0.70	0.74	0.70
	Hubei	0.84	0.87	0.92	0.94	0.94	0.80	0.85	0.86
	Hunan	0.80	0.79	0.77	0.79	0.75	0.72	0.73	0.69
South China	Guangdong	0.81	0.82	0.79	0.76	0.74	0.71	0.73	0.75
	Guangxi	0.81	0.74	0.71	0.66	0.65	0.61	0.51	0.58
	Hainan	2.64	2.21	2.54	2.49	2.50	2.81	2.65	2.64
Southwest China	Chongqing	0.52	0.48	0.46	0.48	0.48	0.44	0.46	0.47
	Sichuan	0.78	0.76	0.81	0.85	0.86	0.84	0.86	0.84
	Guizhou	0.80	0.78	0.81	0.91	0.81	0.67	0.60	0.79
	Yunnan	0.80	0.74	0.71	0.77	0.71	0.88	0.86	0.87
Northwest China	Shaanxi	1.73	1.68	1.68	1.58	1.39	1.36	1.23	1.22
	Gansu	1.51	1.31	1.24	1.10	1.00	1.26	1.23	1.18
	Qinghai	1.46	1.32	1.34	1.44	1.40	1.44	1.48	1.46
	Ningxia	1.37	1.51	1.51	1.73	1.87	1.63	1.76	1.93
	Xinjiang	3.11	2.98	2.87	2.52	2.42	2.34	2.19	2.22

of provincial unit samples. The units are divided into seven groups: north, northeast, east, central, south, southwest, and northwest China for regional heterogeneity analysis. Table 3 displays the regression results.

Core Explanatory Variable. The estimated regression coefficient of the petrochemical industry's agglomeration degree for the entire country is positive and passes the 5% significance level test. This result indicates a positive proportional relationship with eco-efficiency, supporting the first hypothesis proposed in this paper. From a national perspective, the petrochemical industry's agglomeration may produce positive scale, technical, structural, and competition and cooperation effects, ultimately positively affecting local eco-efficiency. The estimated regression coefficient for north China is positive and passes the 10% significance level test, indicating that petrochemical industry agglomeration in north China can balance economic development and ecological environmental constraints, generating favorable economic and environmental benefits. Although the estimated regression coefficient

Table 2. Results of eco-efficiency of provincial units in China from 2012 to 2021.

Region	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Beijing	1.1664	1.1697	1.1580	1.1618	1.1781	1.1574	1.2171	1.2128	1.2227	1.2860
Tianjin	1.0989	1.1058	1.1125	1.1137	1.1233	1.1258	1.1205	1.1101	1.1143	1.1033
Hebei	0.4273	0.4048	0.3903	0.3825	0.3708	0.3864	0.3812	0.3867	0.3806	0.3832
Shanxi	0.3481	0.3327	0.3175	0.3035	0.2855	0.3026	0.3156	0.3292	0.3310	0.3440
Inner Mongolia	0.4722	1.0433	1.0351	1.0336	1.0264	1.0235	1.0259	1.0279	1.0210	1.0240
Liaoning	0.4238	0.3972	0.3895	0.3916	0.4021	0.4206	0.4384	0.5273	1.0017	1.0163
Jilin	0.4477	0.4234	0.4165	0.4343	0.4310	0.4277	0.4334	0.4389	0.4292	0.4352
Heilongjiang	0.3147	0.3347	0.3330	0.3366	0.3453	0.3455	0.3457	0.3822	0.3723	0.3783
Shanghai	1.0686	1.0720	1.0733	1.0747	1.0773	1.0859	1.0790	1.0628	1.0640	1.0558
Jiangsu	1.0810	1.0020	0.5923	0.6020	0.5348	0.5277	0.5166	1.0075	1.0034	1.0105
Zhejiang	0.6517	0.6690	0.6398	0.6322	0.5774	0.5930	0.5990	0.6214	0.5928	0.5965
Anhui	0.4103	0.3973	0.3971	0.3888	0.3637	0.3613	0.3399	0.3486	0.3417	0.3455
Fujian	0.4621	0.4928	0.4925	0.4880	0.4622	0.4585	0.4317	0.4466	0.4533	0.4643
Jiangxi	0.3925	0.3805	0.3707	0.3606	0.3553	0.3554	0.3548	0.3585	0.3557	0.3574
Shandong	0.5796	0.5365	0.5321	0.5172	0.5019	0.5084	0.5071	0.5222	0.5048	0.5279
Henan	0.4210	0.3861	0.3847	0.3837	0.3883	0.3957	0.4021	0.4163	0.3889	0.3980
Hubei	0.4050	0.4175	0.4119	0.4109	0.3973	0.3965	0.3942	0.3998	0.3732	0.3769
Hunan	0.4226	0.4564	0.4570	0.4619	0.4427	0.4463	0.4346	0.4277	0.4341	0.4316
Guangdong	1.0288	0.6904	0.6661	0.6527	0.6076	0.5668	0.5431	0.5494	0.5011	0.4975
Guangxi	0.3730	0.3789	0.3765	0.3671	0.3578	0.3460	0.3369	0.3331	0.3189	0.3142
Hainan	0.4476	0.4393	0.4108	0.4056	0.4064	0.3709	0.3625	0.3619	0.3247	0.3312
Chongqing	0.4282	0.4242	0.4259	0.4533	0.4520	0.4586	0.5007	0.5104	0.4789	0.4994
Sichuan	0.4038	0.3776	0.3850	0.3909	0.3717	0.3674	0.3691	0.3729	0.3558	0.3543
Guizhou	0.2550	0.2696	0.2651	0.2657	0.2483	0.2436	0.2458	0.2478	0.2427	0.2413
Yunnan	0.2961	0.3056	0.3058	0.3042	0.2875	0.2832	0.2856	0.3021	0.2889	0.2888
Shaanxi	0.4378	0.3948	0.3896	0.3861	0.3762	0.3653	0.3677	0.3676	0.3574	0.3604
Gansu	0.2603	0.2544	0.2465	0.2444	0.2442	0.2430	0.2517	0.2645	0.2431	0.2524
Qinghai	0.2674	0.2643	0.2562	0.2503	0.2369	0.2343	0.2352	0.2357	0.2318	0.2300
Ningxia	0.2553	0.2595	0.2526	0.2441	0.2376	0.2321	0.2356	0.2420	0.2467	0.2498
Xinjiang	0.2160	0.2145	0.2122	0.2076	0.2071	0.2006	0.2084	0.2170	0.2023	0.2081
China	0.5088	0.5098	0.4899	0.4883	0.4766	0.4743	0.4760	0.5010	0.5059	0.5121
North China	0.7026	0.8113	0.8027	0.7990	0.7968	0.7992	0.8120	0.8133	0.8139	0.8281
Northeast China	0.3954	0.3851	0.3796	0.3875	0.3928	0.3979	0.4059	0.4495	0.6011	0.6099
Eastern China	0.6637	0.6500	0.5854	0.5805	0.5532	0.5557	0.5469	0.6239	0.6165	0.6226
Central China	0.4162	0.4200	0.4179	0.4188	0.4094	0.4129	0.4103	0.4146	0.3988	0.4022
South China	0.6165	0.5029	0.4845	0.4752	0.4572	0.4279	0.4142	0.4148	0.3816	0.3809
Southwest China	0.3458	0.3442	0.3454	0.3535	0.3399	0.3382	0.3503	0.3583	0.3416	0.3460
Northwest China	0.2873	0.2775	0.2714	0.2665	0.2604	0.2551	0.2597	0.2654	0.2563	0.2601

of the petrochemical industry's agglomeration degree in northeast, central, south, southwest, and northwest China does not pass the significance test, it still shows a positive correlation with ecological efficiency. The estimated regression coefficient of the petrochemical industry's agglomeration degree in east China is negative and passes the 5% significance level test, indicating a negative effect on eco-efficiency in east China. As an economically developed region, petrochemical industry agglomeration in east China increases the ecological environmental burden, and the economic benefits generated by production scale expansion cannot compensate for the negative environmental externalities.

Control Variable. From a national perspective, government support for science and technology negatively affects eco-efficiency, particularly in south and northwest China. This phenomenon may be due to the current scientific and technological innovation activities consuming considerable resources but have not yet effectively transformed into comprehensive economic and environmental benefits. Scientific and technological innovation activities aimed at pursuing economic benefits cannot coordinate the relationship with resource constraints and environmental protection. Although scientific and technological progress drives economic development, it also indirectly leads to energy consumption rebound. In addition, the unreasonable allocation of scientific and technological resources may hinder the release of enterprise innovation vitality.

From a national perspective, environmental regulations positively affect eco-efficiency, especially in north China. China's environmental protection policies and regulations have not produced negative "one-size-fits-all" effects, limiting the industry's healthy development. Environmental regulation achieves favorable economic and environmental benefits and effectively compensates the cost of environmental governance by forcing the closure or punishment of enterprises with excessive energy consumption and pollution, and by encouraging enterprises to adopt and use cleaner production processes and technologies.

From a national perspective, land urbanization negatively affects ecological efficiency, particularly in the northeast and northwest regions. As urban scale expands, a significant amount of agricultural and forestry land is converted into urban planning land or industrial land, and the change in land property has not achieved favorable green economic benefits. The scale effect of land urbanization results in a surge in energy consumption and pollution emissions, and land use driven by economic interests has low efficiency. The process of land urbanization has not resolved the conflict between urban economic development and environmental constraints. The southwest region exhibits regional heterogeneity. Land urbanization in southwest China has achieved a successful green economy transformation, positively affecting eco-efficiency.

The estimated regression coefficient of the influence of economic development level on eco-efficiency in south China and northwest China is negative. Hence, the economic development mode in those regions still maintains its rough characteristics, and industries with high energy consumption, high pollution, and low added

Table 3. Model (1) regression results for each region in China.

	China		North China		Northeast China		Eastern China	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
AG	0.1001**	2.2700	0.5892*	2.0500	0.2611	0.8900	-0.4946**	-2.6500
EC	0.0883	0.3900	0.1683	0.8500	-0.1321	-0.0600	-0.0728	-0.6400
OP	-0.0024	-0.9500	-0.1902	-1.0100	-0.4463*	-1.9900	0.2498*	2.0100
GS	-0.0425***	-2.9700	0.0344	0.4100	0.0522	0.2700	0.0238	0.8200
ER	0.0530*	1.8100	0.2781**	2.6100	0.5557	1.2700	-0.0725	-0.6200
UR	-0.0292**	-2.0900	0.0244	0.4300	-0.1413**	-2.5500	-0.0533	-1.4000
	Central China		South China		Southwest China		Northwest China	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
AG	0.1155	0.7800	0.0394	0.2600	0.0258	0.4800	0.0081	0.7300
EC	0.5479	1.1400	-0.3108*	-2.1600	0.0165	0.4100	-0.0439**	-2.4100
OP	-0.1103	-0.8800	-0.0007	-0.2600	-0.1119	-1.7100	-0.0348	-0.9400
GS	-0.0195	-1.1200	-0.0578**	-2.3400	-0.0095	-0.4100	-0.0278**	-2.3700
ER	-0.0398	-0.5300	-0.1603	-1.4000	0.0378	1.2900	-0.0035	-0.7600
UR	-0.0283	-0.8700	-0.1556	-1.7000	0.0263**	2.1800	-0.0164**	-2.6800

Note: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

value have contributed significantly to local economic development. Imbalance patterns, such as resource misallocation, may also weaken the positive effect of economic development level on eco-efficiency [20].

The influence of the level of opening-up on eco-efficiency also shows regional heterogeneity. The estimated regression coefficient of the opening-up level in northeast China is negative, confirming the hypothesis of "pollution paradise." The northeast region has undertaken high-energy-consuming and highly polluting industrial transfers in the international market, causing damage to the local ecological environment. The estimated regression coefficient of the opening-up level in east China is positive, and opening-up has stimulated the region's economic vitality. Foreign investment is an important source of external knowledge and provides opportunities for local businesses to learn and develop. The introduction of efficient and advanced products, technologies, and management concepts can help enterprises accelerate industrial transformation and upgrading, improve environmental protection enthusiasm, and produce favorable ecological and economic benefits.

Regression Analysis of Petrochemical Industry Agglomeration on Green Technology Innovation

The regression analysis is conducted according to Model (2), and the regression results are reported in Table 4.

Core Explanatory Variable. The estimated regression coefficient of the agglomeration degree of the petrochemical industry in China is negative, passing the 10% significance level test. Thus, a negative correlation exists between the agglomeration level of the petrochemical industry in China and the level of petrochemical green technology innovation, particularly in north China. The petrochemical industry, which uses oil and natural gas as raw materials, has its industrial agglomeration influenced by resource distribution. China's land oil and gas resources are primarily located in the economically underdeveloped western and northern regions. The construction of petrochemical industry facilities is subject to strict environmental regulations in terms of geographical location. Elements needed for innovation activities, such as talent, capital, infrastructure, and achievement transformation platforms, are typically concentrated in economically developed areas, causing a separation between production and innovation activities in China's petrochemical industry. For example, Beijing, China's political, economic, and scientific innovation center, has the lowest petrochemical industry agglomeration level but the highest number of patent applications for petrochemical green low-carbon technology. China's petrochemical industry is dominated by large state-owned enterprises with geographically separated R&D and production departments. The industry monopoly and lack of marketization caused by state-owned enterprises may also lead to a lack of innovation within the petrochemical industry. Petrochemical industry agglomeration may also cause innovation path dependence and cognitive self-locking, restricting enterprises' innovation ability improvement. In addition, this study's measurement of petrochemical industry agglomeration level reflects the regional industrial scale concentration degree and cannot reflect the industrial agglomeration stage. At present, China's petrochemical product overcapacity and insufficient high-end petrochemical product supply capacity indicate that petrochemical industry agglomeration is in its initial stage, with enterprises locked in a low-cost strategy, making it difficult to achieve green technology innovation breakthroughs.

Control Variable. From a national perspective, the advanced nature of the industrial structure negatively affects petrochemical green technology innovation, particularly in south China. The petrochemical industry involves traditional mining and manufacturing industries, and tertiary industry development has a crowding-out effect on the petrochemical industry, affecting its green technology innovation level. North China exhibits regional heterogeneity, with the advanced nature of the industrial structure promoting local petrochemical industry green technology innovation. The tertiary industry's sustainable development concept profoundly influences society's production and lifestyle, thereby improving environmental protection requirements for the traditional petrochemical industry and generating a driving force for enterprises' green technology innovation. The tertiary industry's low-carbon green attributes can be transferred to the petrochemical industry along the industrial chain.

The estimated regression coefficient of the influence of the opening-up level on green technology innovation in the petrochemical industry in north, northeast, east, and northwest China is negative. In terms of high-end petrochemical products, China has consistently been at a market competition disadvantage with foreign enterprises, and local petrochemical product quality stability struggles to meet downstream demand. Market opening may increase the crowding-out effect on the local petrochemical industry. In addition, path dependence on foreign advanced technology may also limit local independent innovation research and development.

The influence of government support for science and technology on petrochemical industry green technology innovation exhibits regional heterogeneity. The northwest region shows a positive influence. Northwest China is a significant petrochemical industry agglomeration area, and government support for science and technology can be accurately and effectively allocated to the petrochemical industry and green research and development, stimulating local petrochemical enterprises' green technology innovation vitality. South China shows a negative influence. The petrochemical industry's economic influence in

Table 4. Model (2) regression results for each region in China.

	China		North China		Northeast China		Eastern China	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
AG	-13.4783*	-1.8000	-35.7913*	-1.9500	-5.7130	-0.5200	-11.3782	-0.3800
TH	-0.5533***	-2.7800	0.6580*	1.7800	-0.1996	-0.4300	1.1020	1.3300
OP	0.1568	0.3400	-27.5401**	-2.7000	-24.9759*	-2.1100	-80.1935***	-3.8000
GS	-2.0491	-0.9200	0.1015	0.0100	1.5408	0.1200	-5.2795	-1.0200
ER	3.5380	0.7800	3.0794	0.3600	-5.0158	-0.2900	35.4070*	1.8400
	Central China		South China		Southwest China		Northwest China	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
AG	-53.8876	-0.8400	-3.4775	-0.0800	-32.3781	-0.5800	5.8453	1.1000
TH	-0.2832	-0.4600	-8.0079*	-2.2300	1.0978	1.2900	0.0722	0.3100
OP	14.1837	0.2600	0.8066	0.9300	-69.0424	-1.3800	-32.9936**	-2.3500
GS	-0.3690	-0.0600	-16.1416*	-1.9300	-20.1702	-1.0800	10.6876**	2.0700
ER	91.0995***	3.3900	26.8231	0.9000	-13.9877	-0.5800	-0.1582	-0.0700

Note: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

south China is weak, and the local government gives less priority to supporting the petrochemical industry's science and technology. Traditional industries are less sensitive to government support for science and technology. Resource allocation imbalance has inhibited the local petrochemical industry's green innovation vitality.

Environmental regulation in east and central China positively affects petrochemical industry green technology innovation. Environmental regulation constraints can stimulate local petrochemical enterprises to conduct independent green technology innovation, helping achieve energy conservation and emission reduction ecological needs while realizing economic benefits to compensate for environmental protection costs.

Mediating Effect Analysis

The regression analysis is conducted according to Model (3), and the regression results are reported in Table 5. From the perspective of the whole country, the estimated regression coefficient of influence of green technology innovation level on eco-efficiency φ_1 is −0.0011, and passes the significance level test of 1%. The estimated regression coefficient of the influence of the agglomeration degree of petrochemical industry on eco-efficiency is 0.095, and passes the significance level test of 5%. The coefficient α_1 in Model (1) and β_1 in Model (2) are significant, and the coefficient φ_2 in Model (3) is correspondingly reduced and lower than α_1, which proves that mediating effect exists. The second research hypothesis proposed in this paper is valid. Petrochemical industry agglomeration can influence eco-efficiency through the mediating effect of green technology innovation. China's petrochemical industry agglomeration may positively affect local eco-efficiency through positive scale, structural, and competition effects. However, China's petrochemical industry agglomeration has not been able to form a good technical effect, mainly due to the separation of production and innovation activities, trapped in the primary stage of agglomeration, innovation path dependence, and cognitive self-locking. In other words, the influence of petrochemical industry agglomeration on eco-efficiency is positive, but it is not achieved through the mediating variable of green technology innovation.

Moreover, the estimated regression coefficient of the influence of green technology innovation level on eco-efficiency is significantly negative. Thus, the current green technology innovation level cannot sufficiently enhance eco-efficiency. The extensive resource consumption by green technology innovation has not been converted into effective ecological economic benefits, which fails to compensate for the risk cost and instead increases the burden of ecological functions. The level of green technology innovation in east China also exhibits the same effect on eco-efficiency.

Robustness Test

On the basis of Models (1)–(3), the robustness of the regression results is tested by replacing the control variables and changing the sample size. The coefficients' direction for core explanatory variables and intermediary variables remained unchanged and significant, demonstrating that this study's results are robust. On the basis of relevant research, the selected

Table 5. Model (3) regression results for each region in China.

	China		North China		Northeast China		Eastern China	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
AG	0.0950**	2.2900	0.6464*	1.9100	0.2273	0.7300	-0.5355***	-3.2400
GT	-0.0011***	-2.7600	0.0010	0.3400	0.0032	0.6700	-0.0030***	-3.3200
EC	0.0463	1.1900	0.1395	0.6300	-0.6493	-0.2500	-0.0139	-0.1400
OP	-0.0020	-0.8000	-0.1721	-0.8600	-0.3960	-1.6000	0.0661	0.5400
GS	-0.0389***	-3.0400	0.0396	0.4500	0.0913	0.4300	0.0179	0.7000
ER	0.0337	1.3000	0.2738**	2.4900	0.5480	1.1900	0.0411	0.3800
UR	-0.0312**	-2.3200	0.0271	0.4600	-0.1590*	-2.4900	-0.0717**	-2.1000
	Central China		South China		Southwest China		Northwest China	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
AG	0.0238	0.2100	0.0378	0.2400	0.0191	0.3900	0.0118	1.0600
GT	-0.0001	-0.1500	-0.0002	-0.2200	-0.0005*	-2.0800	-0.0006	-1.4900
EC	0.0258	0.6600	-0.3094*	-2.0600	0.0090	0.2400	-0.0397**	-2.2000
OP	-0.1439	-1.5300	-0.0007	-0.2400	-0.1098*	-1.8200	-0.0632	-1.5500
GS	-0.0046	-0.3900	-0.0584**	-2.2500	-0.0307	-1.3100	-0.0238*	-2.0200
ER	-0.0514	-0.7500	-0.1565	-1.3000	0.0330	1.2200	-0.0031	-0.6900
UR	-0.0152	-0.7500	-0.1517	-1.5600	0.0384***	3.0700	-0.0190***	-3.0500

Note: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

control variables mainly include the standard value of per capita GDP, the urban population's proportion in the total population, the energy conservation and environmental protection expenditure proportion in general public budget expenditure, the government public budget proportion in GDP, the number of patent applications per 10,000 people, the per capita urban road area, the college student population proportion, the per capita private car ownership, and the per capita number of households with Internet broadband access.

Research Conclusion and Suggestion

Main Research Conclusions

This paper, based on panel data from 30 provincial units in China from 2012 to 2021, measures the agglomeration level of the petrochemical industry and local ecological efficiency. It demonstrates the effect of petrochemical industry agglomeration on local ecological efficiency and the mediating effect of green technology innovation on this influence. The main conclusions are as follows.

The direct effect of petrochemical industry agglomeration on ecological efficiency. Petrochemical industry agglomeration in China positively affects the improvement of ecological efficiency level. It can coordinate the relationship between economic development and ecological environment constraints, creating favorable economic and environmental benefits. However, east China exhibits regional heterogeneity, where petrochemical industry agglomeration negatively affects ecological efficiency. The expansion of production scale increases the burden of ecological functions, and economic benefits cannot compensate for the negative environmental externalities.

The effect of petrochemical industry agglomeration on green technology innovation. Petrochemical industry agglomeration in China negatively affects green technology innovation, particularly in north China. The primary reason is that resource distribution influences the agglomeration of the petrochemical industry in China, leading to the geographical separation of production and innovation activities. China's petrochemical industry, dominated by large state-owned enterprises, suffers from industry monopoly and lack of marketization, resulting in innovation deficiencies. Petrochemical industry agglomeration can also create innovation path dependence and cognitive self-locking, limiting enterprises' innovation ability improvement. China's petrochemical industry agglomeration is still in its initial stage, with companies locked in a low-cost strategy, making it challenging to achieve green technology innovation breakthroughs.

The mediating effect of petrochemical industry agglomeration on eco-efficiency through green technology innovation. Although China's petrochemical industry agglomeration can positively affect local ecological efficiency, it has not formed a good technical effect and cannot improve ecological efficiency through the mediating effect of enhancing green technology innovation level. The substantial resources consumed by green technology innovation have not been converted into effective ecological economic benefits, which cannot compensate for the risk cost, increase the ecological function burden, and negatively affect ecological efficiency.

Suggestions

On the basis of the above analysis and conclusions, this paper presents the following suggestions.

Continuously optimize the positive scale, structural, and competitive effects of petrochemical industry agglomeration. Properly manage the relationship between petrochemical industry agglomeration and local environmental regulation, refining restriction items to avoid a one-size-fits-all approach, and maximizing the positive scale effect of petrochemical industry agglomeration. Arrange the regional industrial structure scientifically, catalyze horizontal and vertical enterprises in the petrochemical industry chain to form a "collaborative flow," and achieve complementary advantages. Create a production collaboration network that facilitates knowledge sharing and interactive learning. The government provides an institutional environment through policy guidance and market-oriented mechanism reforms, fostering market forces, breaking the monopoly situation dominated by large state-owned enterprises in China's petrochemical industry, bridging the gap between production and innovation activities, releasing positive technical effects, and continuously promoting local ecological efficiency improvement.

Clarify the petrochemical industry's role in the local industrial economy and promote petrochemical industry agglomeration development according to local conditions. Manage the competitive and cooperative relationships between local and foreign enterprises. Actively learn and introduce efficient management processes and green innovation technologies to drive the improvement of their own operational and innovation ability. Relevant enterprises focus on breaking through key core technologies in the petrochemical industry, accelerating the green, high-end, differentiated, and refined reform of the supply side of local petrochemical products. Promote the development of petrochemical industry toward low energy consumption, low environmental externalities, and high added value; achieve domestic petrochemical product market competitiveness improvement; occupy a dominant position in the industrial value chain; and reap economic and environmental benefits. Firmly support green technology innovation development in the petrochemical industry and understand the nonlinear law of green technology innovation development. Promote the development of China's petrochemical industry agglomeration to a higher stage, escape innovation path dependence and cognitive self-lock, overcome technical constraints of high-end petrochemical products, and break the green technology innovation dilemma in the petrochemical industry. Relevant government departments need to improve resource allocation efficiency for science and technology, accurately allocate resources to the petrochemical industry and green research and development, and stimulate the initiative of independent innovation of enterprises. Strengthen the construction of innovation infrastructure and environmental protection facilities in petrochemical industry agglomeration areas, reduce resource consumption intensity in green technology innovation processes, standardize pollution emission treatment, reduce environmental burden, and accelerate the transformation of ecological economy externalities of green technology innovation.

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Conflict of Interest

The authors declare no conflict of interest.

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