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Analysis of the Influence of High - Tech industry Agglomeration on Sulfur Dioxide Emissions in Yangtze River Delta

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Abstract: ***This article mainly studies the impact of high-tech industry agglomeration on sulfur dioxide emissions in the Yangtze River Delta region. By establishing an index system, it is found that the development level of high-tech industry in different regions of the Yangtze River Delta is obviously different, among which Anhui province has the lowest level , and Shanghai and Jiangsu province have the highest level . In further empirical analysis, this paper uses panel data regression analysis, found that the high-tech industry agglomeration level of sulfur dioxide emissions have influences on inverted "U" type, namely with the improvement of agglomeration level, sulfur dioxide emission levels fall after rise, and in recent years, the population is not the key factors influencing the sulfur dioxide emission levels in Yangtze river delta, The secondary industry is still an important factor affecting sulfur dioxide emissions.***

Keywords: High-tech industry; High-tech industry; Sulfur dioxide emission; Empirical analysis.

1. INTRODUCTION

1.1 Research background and research significance

The rapid development of the Chinese economy relies primarily on excessive resource exploitation and substantial input of production factors, leading to significant resource waste and environmental pollution while promoting industrialization (Xu and Tan, 2020). Traditional industries in China, dominated by low-tech manufacturing, belong to labor and resource-intensive sectors with low energy efficiency, emitting large amounts of waste gases, which are detrimental to sustainable development and do not align with the goal of "peak carbon emissions and carbon neutrality". In an era where technology increasingly becomes a decisive force in international competition, traditional industries are no longer the main driver of national competitiveness. Therefore, there is an increasingly urgent need domestically to promote industrial optimization and upgrading, and advance green sustainable development.

High-tech industries represent vital sectors of cutting-edge technology and play crucial roles in enhancing socio-economic development and improving regional environmental governance. According to the "China High-Tech Industry Statistical Yearbook" (Manufacturing), high-tech industries mainly include six categories: pharmaceutical manufacturing, aerospace equipment manufacturing, electronic and communication equipment manufacturing, computer and office equipment manufacturing, medical instrument and equipment manufacturing, and information chemical manufacturing (Bin, Chen, and Li, 2024). The 2020 "Government Work Report" explicitly stated the need to actively promote the development of high-tech industries, strengthen cooperation in regional advantageous industries, and fully leverage the agglomeration effects and competitive advantages of high-tech industries. High-tech industries can not only improve regional economic development but also promote technological innovation for environmental governance, serving as the core competitive industries in the new era.

The Yangtze River Delta region, administratively consisting of Shanghai, Jiangsu, Zhejiang, and Anhui provinces, is fertile in land, densely populated, and has become an "important window" in the new era. It exhibits high levels of openness to the outside world, strong scientific innovation capabilities, and rapid economic development, representing one of the typical regions of China's economy. According to the 2017 "Industrialization Bluebook: China's Industrialization Process Report (1995-2015)", the industrialization level of the Yangtze River Delta region ranked first among the nine economic regions, approaching the post-industrialization stage. However, relying on a long-term energy-consuming industrial development model, extensive industrial gas emissions have become a significant constraint on the high-quality integrated development process of the Yangtze River Delta.

Future manufacturing development is inevitably moving towards knowledge-intensive high-tech industries (Chen, Xu, and Wang, 2022). Sulfur dioxide, as a primary indicator of gas emissions, can indirectly reflect the level of environmental pollution in a region. Therefore, studying the impact of high-tech industry agglomeration on sulfur dioxide emissions in the Yangtze River Delta region is of strategic significance in the field of regional development.

This paper takes the provincial-level administrative regions of the Yangtze River Delta as research samples to examine the relationship between high-tech industry agglomeration and sulfur dioxide emissions, effectively assessing the role of high-tech industry agglomeration in sustainable development and highlighting the environmental effects of high-tech industry agglomeration. Based on the basic situation of the Yangtze River Delta region, it is essential to formulate reasonable industrial policies and strategies tailored to local conditions, providing a basis and recommendations for proposing the most suitable level of high-tech industry agglomeration to promote regional green sustainable development, and offering references for the integration of regional development and environmental governance in other areas.

1.2 Research methods and research content

The present study begins with theoretical analysis and literature review to formulate hypotheses. Subsequently, data related to high-tech industry agglomeration levels and sulfur dioxide emissions in the Yangtze River Delta region are collected from various statistical yearbooks. The current levels of both variables are then assessed, followed by inter-provincial and inter-temporal comparisons. Descriptive statistics are applied to the collected data to observe the differences in high-tech industry agglomeration levels and sulfur dioxide emissions among different provinces and the changes over different years.

Furthermore, a econometric model is established to regress panel data, examining the impact of various variables on sulfur dioxide emission intensity. This analysis aims to elucidate the mechanism of action between high-tech industry agglomeration and sulfur dioxide emissions, determining the optimal level of high-tech industry agglomeration. Additionally, the study investigates regional differences among provincial-level areas, providing theoretical support for the integration of economic development and environmental governance in the Yangtze River Delta region.

2. THEORETICAL BASIS

2.1 High-tech industry agglomeration effect

In Alfred Marshall's theory of industrial agglomeration, the concept of "agglomeration" was first introduced to describe the geographical proximity and concentration of enterprises and industries, suggesting that agglomeration can generate positive externalities (Becattini, 2002). Marshall proposed three reasons for industrial spatial agglomeration: first, the emergence of localized economies of scale; second, the development of specialized economies; and third, the creation of favorable local production systems. According to Marshall's theory of industrial location, industrial agglomeration exhibits three externalities: scale effects of specialized labor, scale effects of intermediate inputs, and spillover effects of technological knowledge diffusion. High-tech industry agglomeration particularly benefits from the spillover effects of technological knowledge diffusion.

Industrial agglomeration entails both positive and negative externalities. For conventional industries, the impact of industrial agglomeration on the environment follows an "N" shaped curve. Initially, industrial agglomeration leads to a large influx of population, increasing ecological pressure and sulfur dioxide emissions. Subsequently, through the emergence of scale effects, production efficiency improves, and pollution decreases. However, excessive levels of industrial agglomeration may lead to negative externalities outweighing the positive ones brought by scale effects. High population density exacerbates regional environmental pressure, resulting in traffic congestion, overexploitation of resources, energy shortages, hindering technological progress, decreasing production efficiency, and exacerbating emissions of industrial pollutants.

High-tech industries, being knowledge-intensive, are primarily driven by scientific and technological advancements. In the initial stages of agglomeration, high-tech industries experience mainly congestion effects, as the entry of multiple enterprises brings in a significant labor force, increasing regional population. However, at this stage, high-tech industries still require substantial research and development investments, which can lead to resource waste and energy consumption, aggravating environmental pollution. As the level of high-tech industry agglomeration increases, the industry matures, technological levels rise, and scale effects become prominent. Transaction costs and production costs decrease, while competition among industries within the agglomeration region leads to advancements in regional innovation levels and overall factor productivity, resulting in reduced gas emissions and positive environmental benefits.

Based on the knowledge spillover effects brought about by high-tech industry agglomeration, high levels of high-tech industry agglomeration can effectively drive the improvement of surrounding areas' industrial technological levels, enhancing the overall regional competitiveness. The improvement in technological levels also leads to the adoption of more advanced clean technologies. High agglomeration facilitates the diffusion of clean technologies to surrounding areas, improving environmental pollution and promoting the level of environmental governance in neighboring regions.

2.2 Spatial Gini coefficient

The Gini coefficient is a statistical indicator proposed based on the Lorenz curve to measure the fairness of income distribution. Krugman applies the Lorenz curve and the Gini coefficient, in a similar manner, to determine the evenness of industry distribution across regions and proposes the spatial Gini coefficient (Arbia 2001). The calculation formula is as follows:

$$G = \sum_{i=1}^{n} (S_i - X_i)^2$$

S_i represents the ratio of a certain industry's relevant indicators in region i to the corresponding national indicators, and X_i denotes the ratio of the relevant indicators in region i to the national averages. A higher value of the spatial Gini coefficient indicates a higher degree of clustering, generally considered significant if the value exceeds 0.5, suggesting a high level of industry clustering. However, the spatial Gini coefficient does not take into account specific industry scales and regional differences. Therefore, in specific calculations, significant errors may occur, limiting its ability to accurately measure the distribution level of industries across the overall space.

2.3 location entropy

The location entropy, also known as the regional concentration index of production, is used to describe the specialization level and distribution of industries in a region, as well as the clustering level and position of a certain industry within the region. The calculation formula is as follows:

$$LQ = \frac{Xi}{Ei} \Big/ \frac{\sum X}{\sum E}$$

Where LQ represents the location entropy of high-tech industries in various provinces within the Yangtze River Delta, X_i denotes the number of employees in the high-tech industry in provincial region i, E_i represents the total number of employees in provincial region i, $\sum X$ represents the total number of employees in the high-tech industry nationwide, and $\sum E$ represents the total number of employees nationwide. A higher value of location entropy indicates a higher degree of clustering of high-tech industries in the region. It is evident that location entropy is not an absolute indicator but a relative one. However, given the large database and high level of overall economic capacity and development in China, using the national average as a reference to calculate location entropy has significant value as a reference point.

3. DATA AND METHODS

3.1 Data source and explanation

The empirical data in this study utilizes panel data from Shanghai, Jiangsu, Zhejiang, and Anhui provinces from 2011 to 2019. Data sources include the "China High-Tech Industry Yearbook," "China Statistical Yearbook," "China Environmental Yearbook," as well as provincial statistical yearbooks. Due to missing data for 2018 in the "China High-Tech Industry Yearbook," the median imputation method is employed.The explanation of relevant variables is as follows:

(1) High-tech industry clustering level (LQ): Considering that the spatial Gini coefficient may not reflect the actual location situation in practical operations, while the location entropy indicator is more general and accurate in measuring the clustering level of industries in a certain area, this study uses location entropy to calculate the clustering level of high-tech industries. A higher value of location entropy indicates a higher degree of clustering of high-tech industries in the region. The location entropy is based on the national level, and a value greater than 1 indicates that the clustering level in the region exceeds the national average.

(2) Sulfur dioxide emission intensity index (sp): This study uses the sulfur dioxide emission intensity index to reflect the relative level of sulfur dioxide emissions in the Yangtze River Delta region. Firstly, the per capita sulfur dioxide emissions for each province in the Yangtze River Delta are calculated using the formula $UEi = Ei/Pi$, where Ei is the sulfur dioxide emissions of each province in the Yangtze River Delta, and Pi is the total population of each province in the Yangtze River Delta. Then, the per capita sulfur dioxide emissions for each province are logarithmically transformed. A higher value of the sulfur dioxide emission intensity index indicates a higher level of sulfur dioxide emissions.

(3) Other control variables:

Secondary industry ratio (sec): This study measures the proportion of the secondary industry to the total output value in each province. The secondary industry is the main industry causing "industrial waste." A higher proportion of the secondary industry indicates more sulfur dioxide emissions.

Population growth rate (pr): Measured by the net increase in population divided by the population of the previous year in each region. The population growth rate often indirectly reflects a region's policies, environment, and economy.

Technological level (t): Measured by the proportion of scientific and technological expenditure in each region's annual fiscal expenditure to general public budget expenditure. The technological level often reflects the level of environmental governance.

Economic development level (A): Measured by per capita GDP in each region. Generally, a higher economic development level indicates that governments and enterprises are more willing to improve environmental pollution.

Foreign direct investment (FDI): Measured by the logarithm of the actual utilization of foreign direct investment. Foreign direct investment may lead to pollution transfer effects or promote the scientific and technological level of the region, providing more advanced and cleaner technologies to improve the ecological environment.

Population size (P): Measured by the logarithm of the number of permanent residents in the region in a year. The denser the population, the greater the regional pressure.

3.2 Research hypothesis

According to the Environmental Kuznets Curve hypothesis, it is speculated that there is a similar inverted "U" shape relationship between the clustering of high-tech industries and sulfur dioxide emissions (Han et al., 2021). Initially, as the clustering of high-tech industries increases, the crowding effect brought about by labor concentration exacerbates environmental pollution. Then, with the increase in clustering level, after surpassing a certain threshold, the technological level significantly improves, and the spillover effects of knowledge and economies of scale become apparent. The increase in clustering of high-tech industries will then lead to a reduction in sulfur dioxide emissions.

In general, industrial clustering will exacerbate sulfur dioxide emissions when the clustering level exceeds a certain value, as the negative externalities of industrial clustering outweigh the positive ones, thereby intensifying sulfur dioxide emissions. However, high-tech industries, with scientific and technological advancement as their core competitiveness, will exhibit a inverted "U" shape relationship with sulfur dioxide emissions. Higher levels of clustering will bring about more advanced technological levels, resulting in better governance of sulfur dioxide emissions.

Among other variables, the level of economic development may initially increase sulfur dioxide emissions before decreasing them. The proportion of the secondary industry remains an important factor affecting sulfur dioxide emission levels; the higher the proportion of the secondary industry, the more industrial waste is generated, leading to more severe environmental pollution. Due to the existence of a critical threshold for ecological carrying capacity, the expansion of population size will increase environmental pressure, resulting in environmental pollution. The improvement in technological level tends to drive the development of cleaner technologies, enhance environmental governance, and reduce gas emissions.

4. SITUATION ANALYSIS

4.1 Calculation of high-tech industry agglomeration in the Yangtze River Delta region

Utilizing Location Quotient to Calculate the Agglomeration Level of High-Tech Industries in Zhejiang Province, Jiangsu Province, Anhui Province, and Shanghai Municipality from 2011 to 2019. It can be observed that Jiangsu Province and Shanghai Municipality exhibit a high level of agglomeration in high-tech industries, significantly surpassing the national average, and they also show a declining trend over the years. On the other hand, Anhui Province demonstrates a relatively low level of agglomeration in high-tech industries, but it displays an increasing trend year by year. Zhejiang Province's agglomeration level in high-tech industries is slightly higher than the national average and shows a rising trend over the years (Wang et al., 2020).

4.2 Sulfur dioxide emissions in the Yangtze River Delta region

The per capita sulfur dioxide emissions of each province are linearly standardized within the range of [0,1]. Since sulfur dioxide is a negative indicator, the calculation formula spi=[max(UEi)-UEi]/[max(UEi)-min(UEi)] is adopted, where UEi represents the original value of the indicator, max(UEi) and min(UEi) are respectively the maximum and minimum values of pollutant i among all provinces nationwide, and spi represents the standardized value. The higher the standardized value of sulfur dioxide emission intensity, the lower the sulfur dioxide emission level, indicating more effective environmental management. It can be calculated that in the Yangtze River Delta region from 2011 to 2019, the minimum value of sulfur dioxide emissions is 0.7666, and the maximum value is 0.9852. This indicates that the sulfur dioxide emission level in the Yangtze River Delta region is much lower than the national average, indicating effective control of industrial exhaust emissions. This region serves as a typical area for the coordinated and sustainable development of China's economy and ecology, with Shanghai emitting the least and Jiangsu emitting the most sulfur dioxide. Observing from the perspective of yearly changes, sulfur dioxide emissions have decreased year by year overall. Among them, the reduction in sulfur dioxide emissions in Shanghai and Zhejiang is most significant, while the reduction rate of sulfur dioxide emissions in Anhui and Jiangsu is slightly lower than the national average, resulting in a slight decrease in the standardized sulfur dioxide indicator (Qian, Cao, and Huang, 2020).

5. EMPIRICAL ANALYSIS

5.1 Econometric model building

In 1971, Ehrlich et al. proposed the IPAT model (Chertow, 2000), which remains a dominant model in academic research on the environmental pollution effects globally. Therefore, this study employs the IPAT model to investigate the impact of high-tech industry agglomeration on sulfur dioxide emissions. The expression of the IPAT model is as follows:

$$I_{it} = \alpha P_{it}^{a} A_{it}^{b} T_{it}^{c} \mu$$

I represents the degree of environmental pollution, P represents the population size, A represents the level of economic development, T represents the technical level, and represents the random disturbance term.

Based on this model and to mitigate the impact of data, logarithmic transformation is applied to the data to establish a specific model. This model investigates the effects of population and economic development level on sulfur dioxide emissions. Additionally, the square term of economic development level is introduced to verify if there exists an inverted "U"-shaped effect of economic development level on sulfur dioxide emissions. Thus, Model 1 is formulated as follows:

$$\ln sp = \alpha_1 pr + \alpha_2 A + \alpha_3 P + a_4 A^2 + \mu$$

After incorporating the high-tech industry agglomeration term and its square term into the analysis to investigate the potential existence of an inverted "U"-shaped nonlinear relationship, the econometric Model 2 is formulated as follows after modifications and adjustments:

$$\ln sp = \alpha_1 lq + \alpha_2 lq^2 + \mu$$

After gradually incorporating the variables of the proportion of the secondary industry, scientific and technological capabilities, and actual utilization of foreign investment into the analysis, four specific models are obtained to examine their respective relationships with sulfur dioxide emissions:

$$\ln sp = \alpha_1 pr + \alpha_2 A + \alpha_3 P + a_4 A^2 + \alpha_5 lq + \alpha_6 lq^2 \mu$$
$$\ln sp = \alpha_1 lq + \alpha_2 lq^2 + \alpha_3 pr + \alpha_4 A + \alpha_5 P + \alpha_6 sec + \mu$$
$$\ln sp = \alpha_1 lq + \alpha_2 lq^2 + \alpha_3 pr + \alpha_4 A + \alpha_5 P + \alpha_6 sec + \alpha_7 t + a_8 A^2 + \mu$$
$$\ln sp = \alpha_1 lq + \alpha_2 lq^2 + \alpha_3 pr + \alpha_4 A + \alpha_5 P + \alpha_6 sec + \alpha_7 t + \alpha_8 FDI + a_9 A^2 + \mu$$

5.2 Descriptive statistics of variables

From Table 1, it can be observed that the average level of high-tech industry agglomeration in the Yangtze River Delta urban agglomeration is 1.33, indicating a relatively high level of agglomeration. This is mainly due to the higher agglomeration level of cities such as Taizhou and Zhenjiang in Jiangsu Province, which has driven the overall high-tech industry agglomeration level in the Yangtze River Delta region. Conversely, cities such as Suzhou and Huainan in Anhui Province exhibit lower levels of agglomeration, thereby lowering the overall high-tech industry agglomeration level in the Yangtze River Delta. The variance of high-tech industry agglomeration is 0.705, indicating relatively low dispersion of this data in the Yangtze River Delta region, suggesting overall stability.

The variance of per capita sulfur dioxide emissions is relatively high, at 82.73, with maximum and minimum values of 519.3 tons per 10,000 people and 3.149 tons per 10,000 people, respectively. This indicates significant regional disparities in sulfur dioxide emission levels, with high dispersion.

Foreign direct investment, the proportion of the secondary industry, and investment in science and technology have relatively small variances, suggesting minor differences among prefecture-level cities.

Table 1: Descriptive statistics of variables

Variable	Number	Average value	Variance	Minimum value
P	369	6.084	0.608	4.301
sp	369	83.97	82.73	3.149
sec	369	0.478	0.0747	0.270
pr	369	4.855	4.539	-8.700
t	369	0.0338	0.0199	0.00438
A	369	10.99	0.607	9.219
FDI	369	11.38	1.226	8.396
lq	369	1.330	0.705	0.217

5.3 Empirical analysis

A Hausman test was conducted on the model, revealing a p-value below 0.05. Consequently, a fixed effects model was chosen to enhance the explanatory power of the model for the overall population. To mitigate potential multicollinearity among variables, control variables were sequentially added to the baseline model. The results indicated a significant F-statistic, which increased with the addition of each variable, suggesting a good level of reliability for the model.

Table 2: Regression results

	Model1	Model2	Model3	Model4	Model5	Model6	Model7
A	11.415***		6.183***	4.644**	3.529*	3.455*	4.996***

	(4.85)		(2.72)	(2.37)	(1.94)	(1.90)	(2.66)
A^2	-0.600***		-0.338***	-0.240***	-0.195**	-0.190**	-0.257***
	(-5.54)		(-3.22)	(-2.64)	(-2.32)	(-2.26)	(-2.96)
lq		0.682**	0.520*	0.493**	0.634***	0.603***	0.623***
		(2.28)	(1.95)	(2.14)	(2.97)	(2.82)	(2.90)
lq^2		-0.453***	-0.310***	-0.287***	-0.307***	-0.298***	-0.308***
		(-5.47)	(-4.14)	(-4.44)	(-5.15)	(-4.97)	(-5.14)
sec				7.334***	5.557***	5.745***	5.708***
				(10.72)	(8.23)	(8.39)	(8.32)
P					-1.893***	-1.886***	-1.819***
					(-7.50)	(-7.49)	(-7.26)
prate						0.013	0.014*
						(1.52)	(1.68)
t							1.485
							(0.46)
FDI							-0.222***
							(-2.78)
Con	-42.785***	10.105***	-16.981	-15.467	3.557	3.563	-3.219
	(-3.34)	(45.16)	(-1.38)	(-1.46)	(0.35)	(0.35)	(-0.31)
R^2	0.393	0.354	0.499	0.579	0.685	0.688	0.695

Model 1 introduced economic development and its squared term on the basis of the original reference model, aiming to examine the existence of the Environmental Kuznets Curve (EKC) in the Yangtze River Delta region. The results indicated that the economic development level term was significantly positive at the 1% level, while its squared term was significantly negative at the 1% level. This suggests a rising-then-falling trend in sulfur dioxide emissions with increasing per capita GDP, indicating the presence of an inverted "U" shaped impact, thereby confirming the existence of the EKC in the Yangtze River Delta urban agglomeration.

Model 2 primarily investigated the impact of high-tech industry agglomeration and its squared term on sulfur dioxide emissions. Empirical results revealed an inverted "U" shaped relationship, consistent with expectations, yet with an R-squared value of only 0.354, indicating poor explanatory power of the model. Thus, it's necessary to incorporate more domestic variables to verify their correlation and examine other factors influencing sulfur dioxide emissions to better explain the relationship between high-tech industry agglomeration and sulfur dioxide emissions.

Model 3 combined Models 1 and 2. Regression results showed that high-tech industry agglomeration also exhibited an inverted "U" shaped relationship with sulfur dioxide emissions and was significant at the 1% level. This reaffirmed the previous hypothesis that high-tech industry agglomeration initially promotes and then inhibits sulfur dioxide emissions. Similarly, economic development level in Model 3 also demonstrated an inverted "U" shaped relationship with sulfur dioxide emissions at the 1% level, indicating robust results. The R-squared value of this model was 0.499, significantly higher than Models 1 and 2, proving the model's excellent explanatory power.

Model 4 introduced the proportion of the secondary industry, with results showing that the proportion of the secondary industry was significantly positive at the 1% level, with a coefficient of 7.334, indicating a substantial impact. This suggests that the proportion of the secondary industry remains a primary factor influencing sulfur dioxide emissions.

Model 5 added the population size variable, revealing that population size was significantly negative at the 1% level, with a relatively large coefficient of -1.89. This indicates that an increase in population size not only does not lead to an increase in sulfur dioxide emissions but actually reduces sulfur dioxide emissions. One explanation is that in today's society with advanced transportation systems and increased population mobility, population size is closely related to economic development level, which in turn inhibits sulfur dioxide emissions. Moreover, an increase in population size stimulates demand for ecological environment, promoting environmental governance and reducing sulfur dioxide emissions. Additionally, in Model 5, the coefficient of the proportion of the secondary industry slightly decreased, indicating a weakened impact of the secondary industry on sulfur dioxide emissions under the influence of population size.

Model 6 incorporated the population growth variable, revealing that the population growth variable was not significant, with a small coefficient, and the model's R-squared value increased only by 0.03, indicating virtually no improvement in model reliability. This suggests that population growth is no longer a factor influencing sulfur dioxide emissions.

Model 7 added the variables of scientific and technological input and foreign direct investment (FDI). Scientific and technological input exhibited a positive but insignificant coefficient in the regression, possibly because scientific and technological input did not effectively translate into clean technologies but rather focused more on other research projects, such as the development of production capacity for enterprises, leading to increased sulfur dioxide emissions. Results showed that FDI was significant at the 1% level, with a negative coefficient, indicating that FDI reduced sulfur dioxide emissions. This could be because FDI does not directly affect sulfur dioxide emissions but rather acts on sulfur dioxide emissions through influencing other factors, such as providing clean energy and technology. Apparently, for the Yangtze River Delta region, FDI projects mainly focus on high-tech industries, thus avoiding the pollution transfer effects seen in lower-end industries.

5.4 Robustness check

To ensure the robustness of the regression results, the sulfur dioxide emission intensity indicator in the regression model was replaced with per capita sulfur dioxide emissions, and the regional emission total was transformed into regional emission levels. Robustness tests were conducted on the same prefecture-level city samples. Table 3 presents the results.

Table 3: Robustness check

	Model1	Model2	Model3	Model4	Model5	Model6
A	10.074***		4.835**	3.565*	3.489*	5.205***
	(4.56)		(2.31)	(1.91)	(1.87)	(2.70)
A^2	-0.537***		-0.275***	-0.194**	-0.189**	-0.263***
	(-5.29)		(-2.84)	(-2.24)	(-2.18)	(-2.96)
lq		0.739***	0.565**	0.543**	0.513**	0.537**
		(2.65)	(2.29)	(2.48)	(2.33)	(2.44)
lq^2		-0.465***	-0.324***	-0.304***	-0.295***	-0.306***
		(-6.01)	(-4.69)	(-4.95)	(-4.78)	(-4.98)
sec				6.051***	6.229***	6.131***
				(9.28)	(9.40)	(9.24)
prate					0.013	0.014
					(1.44)	(1.59)
t						2.222
						(0.68)
FDI						-0.253***
						(-3.09)
Con	-41.730***	3.971***	-15.952	-14.703	-14.628	-21.609**
	(-3.48)	(19.05)	(-1.41)	(-1.46)	(-1.45)	(-2.12)
R^2	0.411	0.382	0.531	0.630	0.632	0.643

The results of the robustness tests indicate that the main variables in each model are generally consistent with the empirical results. Specifically, from Model 6, it can be observed that after adjusting the explanatory variable to per capita sulfur dioxide emissions, the coefficient of the proportion of the secondary industry has increased slightly. This suggests that the impact of the secondary industry on regional sulfur dioxide emissions levels is stronger when considering emissions per capita rather than total emissions.

Additionally, the absolute value of the coefficient for foreign direct investment (FDI) has also slightly increased, indicating that FDI can better reduce regional sulfur dioxide emissions levels. These findings provide further support for the initial empirical results and reinforce the conclusion that adjusting the explanatory variable to per capita sulfur dioxide emissions enhances the understanding of the effects of industrial structure and foreign direct investment on regional sulfur dioxide emissions levels.

6. MAIN CONCLUSIONS AND POLICY RECOMMENDATIONS

In the Yangtze River Delta region, the impact of high-tech industry agglomeration on sulfur dioxide emissions also exhibits an inverted "U" shaped pattern. Specifically, from 2011 to 2019, both Jiangsu Province and Shanghai Municipality were situated on the right side of the inverted "U" shape, indicating that increased levels of high-tech industry agglomeration were associated with reduced sulfur dioxide emissions. On the other hand, Anhui Province and Zhejiang Province consistently remained on the left side of the inverted "U" shape, signifying that higher levels of high-tech industry agglomeration were correlated with increased sulfur dioxide emissions.

Regression results reveal that scientific and technological investment in the Yangtze River Delta region does not significantly affect sulfur dioxide emissions. This could be due to the majority of scientific and technological investment being allocated towards research and experimentation, rather than towards environmental pollution control, thus lacking the necessary technical support for environmental governance. Within the model, industrial structure exhibits the greatest impact on sulfur dioxide emissions, highlighting the enduring significance of industrial structure as the most crucial factor influencing environmental pollution in contemporary times.

The Yangtze River Delta region boasts formidable technological capabilities, and foreign direct investment (FDI) does not lead to pollution transfer effects but rather enhances scientific and technological proficiency, thereby positively contributing to environmental governance.

It is recommended that the government vigorously promote the development of high-tech industries in the Yangtze River Delta region, increase investment in science and technology, establish technology-driven industrial clusters, leverage high-tech industries to propel low-tech industries, and utilize emerging industries to drive traditional industries forward. Shanghai Municipality and Jiangsu Province, positioned at a stage where higher levels of high-tech industry agglomeration yield more pronounced environmental governance effects, should continue developing high-tech industries, expand technological investment, strengthen industrial clustering, and facilitate the realization of energy conservation and emission reduction goals. Meanwhile, Anhui Province and Zhejiang Province, situated at a stage where higher levels of high-tech industry agglomeration lead to increased sulfur dioxide emissions, should focus on enhancing high-tech industry agglomeration levels to surpass the inflection point, rather than relying on the environmental governance effects of high-tech industries, in order to enhance regional competitiveness, optimize industrial structure, improve ecological environment, and promote economic development.

The government should vigorously promote high-quality development, reduce the proportion of the secondary industry, regulate high-emission factories, accelerate industrial transformation and upgrading, and provide policy support for the development of energy conservation and emission reduction industries. By prioritizing science and technology as a core competitive advantage, efforts should be made to expedite the construction of technology-driven high-tech industries, increase the transformation of scientific and technological investment into environmental governance, develop clean energy sources, and improve resource utilization.

Focusing on provincial-level administrative regions within the Yangtze River Delta as the research subjects may lack persuasiveness when examining individual cities. While this approach effectively elucidates the overall situation of high-tech industries and sulfur dioxide emissions in the region and its provinces, it fails to precisely investigate the circumstances of each city.

Future research could delve deeper into various economic regions across the country to explore the environmental governance effects of high-tech industry agglomeration in different regions, conduct comparative analyses, identify regional development disparities, determine optimal levels of agglomeration across regions, and study the factors influencing high-tech industry agglomeration levels, thereby providing research support for accelerating high-tech industry agglomeration.

Currently, the role of high-tech industry agglomeration in the Yangtze River Delta region in influencing sulfur dioxide emissions is not dominant. The primary factor influencing sulfur dioxide emissions remains the proportion of the secondary industry, indicating that pollutant discharge levels among enterprises in the secondary industry remain relatively high, and the agglomeration of high-tech industries has yet to facilitate the adjustment and optimization of industrial structure. Future studies may explore how high-tech industry agglomeration can drive energy conservation and emission reduction in surrounding industries and how scientific and technological investment can be effectively utilized to improve the ecological environment. In-depth research on the nationwide mechanisms of the role of high-tech industry agglomeration in environmental governance can provide valuable recommendations for sustainable development across different regions of the country.

REFERENCES

[1] Arbia, Giuseppe. 2001. "The Role of Spatial Effects in the Empirical Analysis of Regional Concentration." Journal of Geographical Systems 3 (3): 271–81. https://doi.org/10.1007/pl00011480.
[2] Becattini, Giacomo. 2002. "From Marshall's to the Italian 'Industrial Districts'. A Brief Critical Reconstruction." In Contributions to Economics, 83–106. https://doi.org/10.1007/978-3-642-50007-7_6.
[3] Bin, Zheng, W Chen, and Lianshui Li. 2024. "Research on the Agglomeration and Spatiotemporal Development of China's Green High-Tech Industries." Green and Low-Carbon Economy, March. https://doi.org/10.47852/bonviewglce42022352.
[4] Chen, Yufan, Yi Xu, and Fuyuan Wang. 2022. "Air Pollution Effects of Industrial Transformation in the Yangtze River Delta From the Perspective of Spatial Spillover." Journal of Geographical Sciences 32 (1): 156–76. https://doi.org/10.1007/s11442-021-1929-6.
[5] Chertow, Marian. 2000. "The IPAT Equation and Its Variants." Journal of Industrial Ecology 4 (4): 13–29. https://doi.org/10.1162/10881980052541927.
[6] Han, Zongwei, Sheng Jiao, Xiang Zhang, Fei Xie, Jing Ran, Rui Jin, and Shan Xu. 2021. "Seeking Sustainable Development Policies at the Municipal Level Based on the Triad of City, Economy and Environment: Evidence From Hunan Province, China." Journal of Environmental Management 290 (July): 112554. https://doi.org/10.1016/j.jenvman.2021.112554.
[7] Qian, Yuan, Hui Cao, and Si-Min Huang. 2020. "Decoupling and Decomposition Analysis of Industrial Sulfur Dioxide Emissions From the Industrial Economy in 30 Chinese Provinces." Journal of Environmental Management 260 (April): 110142. https://doi.org/10.1016/j.jenvman.2020.110142.
[8] Wang, Lu, Yusheng Xue, Meng Chang, and Changsheng Xie. 2020. "Macroeconomic Determinants of High-tech Migration in China: The Case of Yangtze River Delta Urban Agglomeration." Cities 107 (December): 102888. https://doi.org/10.1016/j.cities.2020.102888.
[9] Wang, Shuhong, Xiaoqing Wang, and Suisui Chen. 2022. "Global Value Chains and Carbon Emission Reduction in Developing Countries: Does Industrial Upgrading Matter?" Environmental Impact Assessment Review 97 (November): 106895. https://doi.org/10.1016/j.eiar.2022.106895.
[10] Xu, Lu, and Junlan Tan. 2020. "Financial Development, Industrial Structure and Natural Resource Utilization Efficiency in China." Resources Policy 66 (June): 101642. https://doi.org/10.1016/j.resourpol.2020.101642.
[11] Yeh, Ago, and M. Ng. 1994. "The Changing Role of the State in High-Tech Industrial Development: The Experience of Hong Kong." Environment and Planning C-Government and Policy 12 (4): 449–72. https://doi.org/10.1068/c120449.
[12] Zhang, Fan, Xiangzheng Deng, Fred Phillips, Chuanglin Fang, and Chao Wang. 2020. "Impacts of Industrial Structure and Technical Progress on Carbon Emission Intensity: Evidence From 281 Cities in China." Technological Forecasting and Social Change 154 (May): 119949. https://doi.org/10.1016/j.techfore.2020.119949.