



Spatial correlation and influencing factors of industrial agglomeration and pollution discharges: a case study of 284 cities in China

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Abstract

Exploring the spatial correlation characteristics and influencing factors of industrial agglomeration and pollution discharge, which is of great significance to reduce industrial pollution discharge and promote China's construction of an ecological civilization. Taking 284 prefecture-level cities in China in 2017 as the research object, this study used spatial autocorrelation analysis method to explore the spatial agglomeration characteristics and spatial correlation of industrial agglomeration and industrial pollution discharge, and spatial econometric analysis method was used to explore the main factors affecting industrial pollution discharge. The research results showed that the level of industrial agglomeration in China exhibited a spatial distribution characteristic of "high in the east and low in the west". The total discharge and discharge intensity of industrial pollutants showed a spatial pattern of "high in the north and low in the south" in general, and industrial agglomeration, total discharge, and discharge intensity of industrial pollution showed significant spatial autocorrelation. Moreover, industrial agglomeration had a strong local spatial correlation with the total and intensity of industrial wastewater, industrial SO₂, and industrial smoke and dust, and the main agglomeration types were high agglomeration-low pollution, low agglomeration-high pollution, and low agglomeration-low pollution. In addition, industrial agglomeration had a positive impact on the total industrial wastewater discharge, and had a negative impact on the total industrial smoke and dust discharge, industrial wastewater discharge intensity, industrial SO₂ discharge intensity, and industrial smoke and dust discharge intensity.

Keywords Industrial agglomeration · Pollution discharge · Spatial correlation · Spatial econometric analysis · China

Introduction

Since the Reform and Opening more than 40 years ago, China's industrialization process has been significantly accelerated, which has effectively promoted China's rapid economic

growth. While promoting China's rapid economic growth, industry has produced a large number of environmental pollutants such as industrial wastewater, waste gas, and smoke and dust, causing serious pollution to the ecological environment, which is not conducive to human physical and mental health and the sustainable development of economy and society (Dong et al. 2019a). In order to alleviate the ecological and environmental problems caused by industrial pollution discharges, the Chinese government has taken a series of environmental protection measures to reduce pollution discharge (Zhao et al. 2012). However, owing to the vast territory of China, there are obvious regional differences among different regions in terms of physical geographical environment, economic development level, and industrial structure (Shen et al. 2017; Zheng et al. 2019). There is an obvious spatial mismatch between pollution discharge levels and industrial agglomeration (Liu et al. 2018a, 2018b).

Industrial agglomeration refers to the process of high concentration of the same industry in a specific geographical area and the continuous convergence of industrial capital

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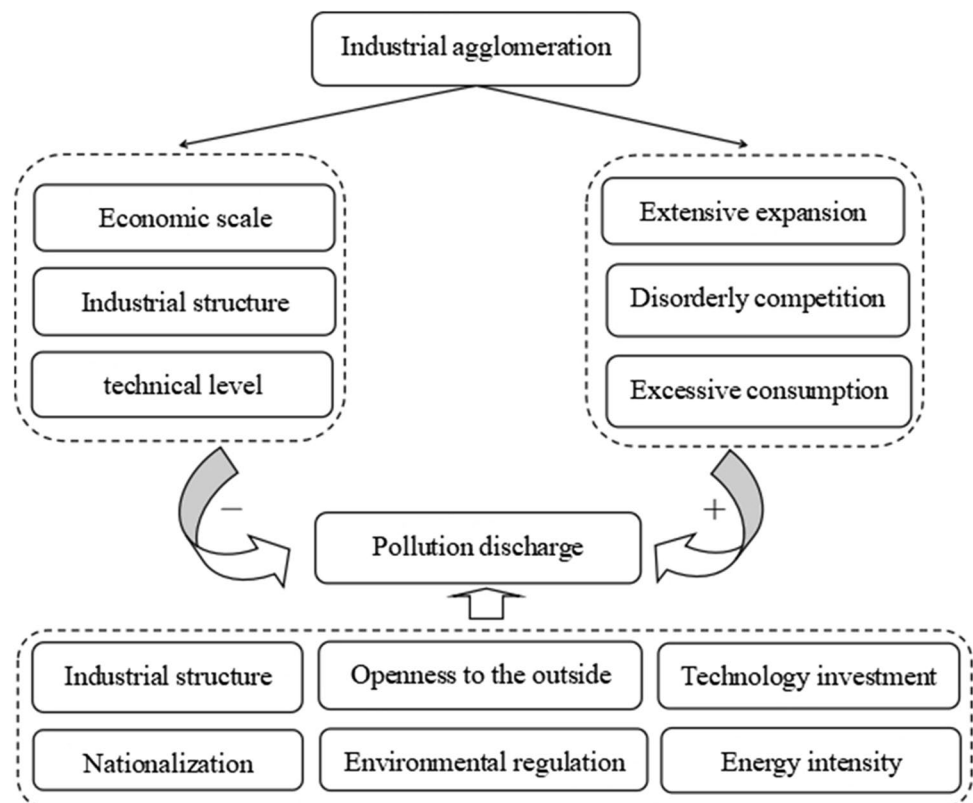
elements in the spatial scope. Industrial agglomeration can reduce the production costs of industrial enterprises, increase scale returns, and improve production efficiency, thereby improving the efficiency of local resource allocation and promoting economic growth (Shen and Peng 2020; Zheng and Lin 2018). Affected by the effect of agglomeration economy, in order to obtain higher economic benefits, enterprises often choose centralized distribution to enhance their ability to resist risks and promote their own better development (Ning et al. 2016). However, excessive industrial agglomeration may lead to waste of resources, rising production costs, and environmental damage, which is not conducive to regional economic development and ecological environment protection (Liu and Wang 2017).

At present, scholars have not reached an agreement on the relationship between industrial agglomeration and industrial pollution, mainly focusing on the following three views: (1) Industrial agglomeration may lead to the increase of regional pollution discharges, which has a negative impact on the ecological environment. For example, Xiao and Shen (2019) analyzed the correlation between population, industrial agglomeration, and environmental pollution, and found that industrial agglomeration can aggravate environmental pollution. Dong et al. (2019b) studied the influence of industrial agglomeration on pollution agglomeration by using the GTWR model, and the research results showed that industrial agglomeration at the national level can lead to

an increase in industrial pollution discharges. (2) Industrial agglomeration is conducive to reducing regional pollution discharges, which has a positive impact on the ecological environment. For example, Otsuka et al. (2014) took Japanese manufacturing industry as a research case; it was found that industrial agglomeration can reduce industrial pollution discharges by improving energy efficiency. Ke and Yu (2014) found that the knowledge and technology spillover effect produced by industrial agglomeration, which is conducive to the technology upgrading of surrounding enterprises. (3) The relationship between industrial agglomeration and pollution discharges is uncertain. For example, Wang et al. (2018) found an inverted U-shaped relationship between industrial agglomeration and carbon discharge by studying the impact of manufacturing agglomeration scale on carbon discharge. He et al. (2014) found that the relationship between industrial agglomeration and pollution discharge is uncertain, with nonlinear or multiple threshold characteristics. Cheng (2016) explored the relationship between manufacturing agglomeration and environmental pollution, and found that manufacturing agglomeration can aggravate environmental pollution, while environmental pollution can inhibit manufacturing agglomeration.

The externality theory is an important basis for understanding the relationship between industrial agglomeration and industrial pollution (Fig. 1). According to the externality theory, externalities are divided into positive externalities

Fig. 1 Impact mechanism framework of pollution discharge



and negative externalities (Hong et al. 2020; Tian et al. 2020). In the process of affecting economic scale, industrial structure, and technological level, industrial agglomeration will produce positive and negative environmental externalities, and then affect the ecological environment by affecting pollution discharges. On the one hand, industrial agglomeration may promote the increase of economic scale, the upgrading of industrial structure and technological level, and produce positive externalities of the environment, which is conducive to reducing industrial pollution discharges and have a positive impact on the ecological environment. For example, (1) industrial agglomeration is conducive to the centralized treatment of pollutants, reduce the cost of industrial discharge reduction, and then realize the scale effect of pollution control (Glaeser and Kahn 2010). (2) In order to maintain their own competitiveness, industrial agglomeration enables enterprises to continuously innovate and improve the level of industrial technology, so as to realize the effect of industrial competition (Krugman 1991). (3) Industrial agglomeration is conducive to strengthen the exchange and cooperation between different enterprises, and then form the demonstration effect and technology spillover effect among enterprises. On the other hand, excessive industrial agglomeration may lead to extensive expansion of enterprises, disorderly competition, and increased energy consumption, resulting in negative externalities of the environment, which will aggravate industrial pollution discharges and have a negative impact on the ecological environment (Dong et al. 2019b). For example, (1) industrial agglomeration may lead to an increase in regional energy and resource consumption (Wang et al. 2015; Zheng and Kahn 2013). (2) Due to disorderly competition and similar industries, industrial agglomeration may lead to vicious competition effect in adjacent regions (Wang and Nie 2016). (3) With the enhancement of industrial agglomeration effect, enterprises may turn to extensive expansion mode, resulting in increased energy consumption and pollution discharges (Chen et al. 2018). In addition, industrial structure, openness to the outside, technology investment, and environmental regulation may affect industrial pollution discharge by improving production technology, improving pollution treatment technology and strictly implementing pollution discharge standards (Liu et al. 2022b).

Taking 284 prefecture-level cities in China as the research objects, this paper explored the spatial distribution characteristics and spatial correlation of industrial agglomeration and pollution discharge, as well as the influencing factors of industrial pollution discharges. Compared with the existing studies, this study was advanced in the following two aspects: (1) taking prefecture level cities as the research scale, the research object was more specific. This study analyzed the spatial distribution characteristics and spatial correlation of industrial agglomeration and pollution discharge

in 284 prefecture level cities in China. (2) When analyzing the influencing factors of pollution discharge, the spatial effect was fully considered. The spatial econometric model based on spatial effect was used to analyze the impact of industrial agglomeration on the total and intensity of industrial pollution discharge.

The other parts of this paper were arranged as follows: the “Research setting and methodology” section explained the research data and methods, the “Results” section introduced the main research results, the “Discussion” section was an in-depth discussion on the research results, and the “Conclusion and policy suggestions” section summarized the research results and put forward policy suggestions.

Research setting and methodology

Industrial agglomeration

Industrial agglomeration can measure the degree of industrial concentration in a specific region. The traditional indicators of industrial agglomeration mainly include Gini coefficient and Herfindahl index. What is more, many scholars also use density to measure the agglomeration level of regional geographical things. However, location entropy can better reflect the degree of industrial agglomeration in a certain region and the calculation method is more concise and convenient. Therefore, based on the research method of location entropy, this paper constructed an industrial agglomeration model, the formula for the calculation is as follows:

$$Agg_t = \frac{Ind_t / Area_t}{\sum_{t=1}^n Ind_t / \sum_{t=1}^n Area_t} \quad (1)$$

where Agg_t referred to the industrial agglomeration level in area t ; Ind_t referred to the total industrial output value of region t ; $Area_t$ referred to the land area of region t ; $\sum_{t=1}^n Ind_t$ referred to the sum of the total industrial output of all the regions under study; $\sum_{t=1}^n Area_t$ referred to the sum of all the land regions under study.

Methods

Spatial autocorrelation analysis

The global spatial autocorrelation analysis method (Chen et al. 2021) was used to analyze the spatial autocorrelation, and local spatial autocorrelation of industrial agglomeration level, total and intensity of pollution discharge. The calculation formula of global spatial autocorrelation Moran's I is as follows (Moran 1948):

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x}) \times (x_j - \bar{x})}{\left(\sum_{i=1}^n \sum_{j=1}^n w_{ij} \right) \times \sum_{i=1}^n (x_i - \bar{x})^2} \tag{2}$$

where I is the global Moran index; n is the number of units in the analysis space; x_i and x_j are the observed values of space unit i and j , respectively; \bar{x} is the average value of observation values of all space units; w_{ij} is the spatial weight matrix of spatial unit i and j , respectively.

Local spatial autocorrelation (LISA) (Anselin 2010) was used to analyze the degree of local spatial correlation of industrial agglomeration and pollution discharge. Local Moran's I was adopted, and its formula is as follows:

$$I_i = \frac{(x_i - \bar{x}) \sum_{j=1}^n w_{ij} (x_j - \bar{x})}{\sum_{j=1, j \neq i}^n \left(\frac{x_j^2}{n-1} - \bar{x}^2 \right)} \tag{3}$$

where I_i is the local Moran value of spatial unit i , the meanings of other variables are the same as those in Eq. (2).

In this paper, bivariate spatial autocorrelation analysis method was used to analyze the spatial correlation characteristics of industrial agglomeration and industrial pollution discharge intensity, including global bivariate spatial autocorrelation and local bivariate spatial autocorrelation. Global bivariate spatial autocorrelation was used to reflect the degree of spatial correlation and difference between industrial agglomeration and pollution discharge intensity. Local bivariate spatial autocorrelation was used to identify local association patterns in different regions, and the calculation formula is as follows:

$$I_{ab} = \frac{n \sum_{i=1}^n \sum_{j \neq i}^n W_{ij} Z_i^a Z_j^b}{(n-1) \sum_{i=1}^n \sum_{j \neq i}^n W_{ij}}, I_i^{ab} = Z_i^a \sum W_{ij} Z_j^b \tag{4}$$

where I_{ab} is the global Moran index, I_i^{ab} is the local Moran index, and Z_i^a is the industrial agglomeration level of unit i . Z_j^b is the discharge intensity of industrial pollutants in j area; W_{ij} is the spatial weight matrix.

Spatial econometric model

The traditional OLS regression model does not consider the spatial effect in the calculation process, while spatial econometric model can fully reflect the influence of relevant indicators on industrial pollution discharge under the spatial effect. There are two types of basic spatial econometric

models: spatial lag model (SLM) and spatial error model (SEM) (Anselin 1988).

SLM mainly reflects whether the adjacent regions have spillover effect on the study area, that is, the influence of the industrial pollution discharge intensity of the adjacent regions on the industrial pollution discharge intensity of the observation area. The specific formula is as follows:

$$y = \rho W_y + \beta X + \varepsilon, \tag{5}$$

where y refers to the dependent variable represented by the discharge intensity of the three pollutants; ρ refers to the spatial lag term of the dependent variable y ; W refers to the spatial weight matrix; β refers to the autocorrelation regression coefficient; X refers to the matrix composed of parameters of independent variables; ε refers to error.

SEM mainly reflects the spatial dependence in the disturbance error term, which was used to measure the influence degree of the error impact of the dependent variable in the neighboring area on the regional industrial pollution discharge intensity, that is, some spatial elements that may be ignored have influence on the regional pollution discharge intensity through the error term. Its expression is as follows:

$$y = \beta X + \varepsilon, \varepsilon = \lambda W_\varepsilon + \mu \tag{6}$$

where ε refers to the random error term; μ refers to the random error term of normal distribution; λ refers to the spatial error coefficient.

Dependent and independent variables

Industrial wastewater, industrial SO₂, and industrial smoke and dust are the main pollutants in the process of industrial production. Owing to the purpose of industrial development is to promote economic growth, it is of great practical significance to study the total industrial pollution discharge and the pollution discharge intensity considering the industrial economic output. In this paper, the total industrial pollution discharge representing the amount of industrial pollution discharge and the industrial pollution discharge intensity considering industrial economic output were determined as the dependent variables. Industrial agglomeration was identified as the core explanatory variable to explore its spatial impact on industrial pollution discharges, and drawing on existing research results (Guan and Xu 2016; Ha et al. 2020), industrial structure, energy intensity, technology investment, openness to the outside, nationalization, and environmental regulation were selected as control variables. The spatial econometric model was used to explore the influencing factors of the total and intensity of industrial pollution discharge. The meanings of relevant variables and descriptive statistics are as follows (Table 1 and Table 2):

Table 1 Related variables and their meanings

	Variables	Definition	Codes
Dependent variables	Total wastewater discharge	Total industrial wastewater discharge	<i>Twater</i>
	Total SO ₂ discharge	Total industrial SO ₂ discharge	<i>Tso₂</i>
	Total smoke and dust discharge	Total industrial smoke and dust and dust discharge	<i>Tsoot</i>
	Wastewater discharge intensity	Wastewater discharge per 10,000 yuan of industrial output value	<i>Rwater</i>
	SO ₂ discharge intensity	SO ₂ discharge of 100 million yuan of industrial output value	<i>Rso₂</i>
	Smoke and dust discharge intensity	Smoke and dust discharge per 100 million yuan of total industrial output value	<i>Rsoot</i>
Core explanatory variables	Industrial agglomeration	Industrial agglomeration level	<i>agg</i>
Control variables	Industrial structure	The proportion of secondary industry	<i>ind</i>
	Energy intensity	Industrial electricity consumption	<i>eci</i>
	Technology investment	Technology expenditure proportion	<i>tec</i>
	Openness to the outside	The proportion of FDI	<i>fdi</i>
	Nationalization	Proportion of domestic enterprises	<i>nat</i>
	Environmental regulation	Sulfur dioxide treatment rate	<i>env</i>

Table 2 Variable descriptive statistics

Variables	Max	Min	Mean	Std.Dev
Industrial agglomeration level	56.216	0.008	2.199	4.604
Proportion of domestic enterprises /%	100.000	34.427	87.780	12.984
The proportion of secondary industry /%	70.500	12.190	44.760	9.538
Industrial electricity consumption/100 million kw·h	798.180	0.383	71.141	101.542
Technology expenditure proportion/%	16.560	0.068	1.646	1.917
Proportion of foreign direct investment/%	11.909	0.001	1.697	1.795
Sulfur dioxide treatment rate/%	99.445	0.098	73.466	21.042

- Industrial structure. The secondary industry is dominated by heavy chemical enterprises. In the process of production, heavy chemical enterprises will produce a large number of environmental pollutants such as industrial wastewater, sulfur dioxide, and smoke. Therefore, the higher the proportion of the secondary industry, the higher the industrial pollution discharge (Cheng 2016). Therefore, the proportion of the secondary industry was selected as the index affecting industrial pollution discharge.
- Energy intensity. In the process of production, local enterprises often consume a large amount of energy as fuel, which will release a large number of environmental pollutants in the process of combustion, resulting in an increase in local pollution discharges (Li et al. 2020). Moreover, industrial power consumption can indirectly reflect the energy consumption in the process of industrial production. Therefore, industrial electricity consumption was selected as the index affecting industrial pollution discharge.
- Technology investment. Scientific and technological investment can improve the production efficiency and pollutant treatment efficiency of enterprises by promoting the upgrading of production technology and the renewal of enterprise equipment, so as to reduce industrial pollution discharges (Wang et al. 2018). Therefore, the proportion of technology expenditure was selected as the index affecting industrial pollution discharge.
- Openness to the outside. The higher the degree of opening to the outside world of a country, the more conducive it is to attract foreign-funded enterprises to join (He 2007). On the one hand, foreign direct investment will increase local development funds, promote the upgrading of enterprise production facilities, and then reduce industrial pollution discharges. On the other hand, the products brought by foreign-funded enterprises may be the backward production capacity eliminated by developed countries, resulting in an increase in local pollution discharges. Therefore, the proportion of foreign direct investment was selected as the index affecting industrial pollution discharge.
- Nationalization. As a production and operation mode with Chinese characteristics, state-owned enterprises are the backbone of national economic development. Some scholars believe that state-owned enterprises have strong bargaining power and good relationship between gov-

ernment and enterprises, which may cause more serious environmental pollution by evading the supervision of environmental protection departments (Wu et al. 2018). Other scholars believe that most of China’s state-owned enterprises are large-scale and belong to enterprises under the key supervision of the environmental protection department. They are subject to stricter supervision in pollution control and discharge reduction, so they cause less pollution to the ecological environment (Song et al. 2022). Therefore, the proportion of state-owned enterprises was selected as the index affecting industrial pollution discharge.

- Environmental regulation. The environmental policies of local governments can have an important impact on the pollution discharges of local enterprises (Hong et al. 2020). In order to create a healthy and good ecological environment, local government departments often strengthen the environmental control of local enterprises, which leads to the reduction of local pollution discharges. It is difficult to obtain the data of industrial wastewater and industrial smoke and dust treatment rate. Therefore, sulfur dioxide treatment rate was selected as the index affecting industrial pollution discharge.

Data sources

Taking 284 prefecture-level cities of China in 2017 as the research section, the industrial data and influencing factor index data used in this study were obtained from the China City Statistical Yearbook (2018), the China Statistics Yearbook (2018), and the related provinces (autonomous regions and municipalities directly under the central government) Statistical Yearbook 2018. Due to the data of some cities were not available, the final number of research cities was 284. In order to unify the standard and avoid calculation error, the actual utilized foreign capital in 2017 was converted according to the exchange rate of US dollar into RMB in that year.

Results

Spatial distribution characteristics of industrial agglomeration

The spatial distribution of industrial agglomeration in China was shown in Fig. 2. On the whole, the industrial agglomeration level in China presented a spatial distribution pattern of “high in the east and low in the west”. The industrial agglomeration level in the eastern coastal regions was relatively high, while the industrial agglomeration level in

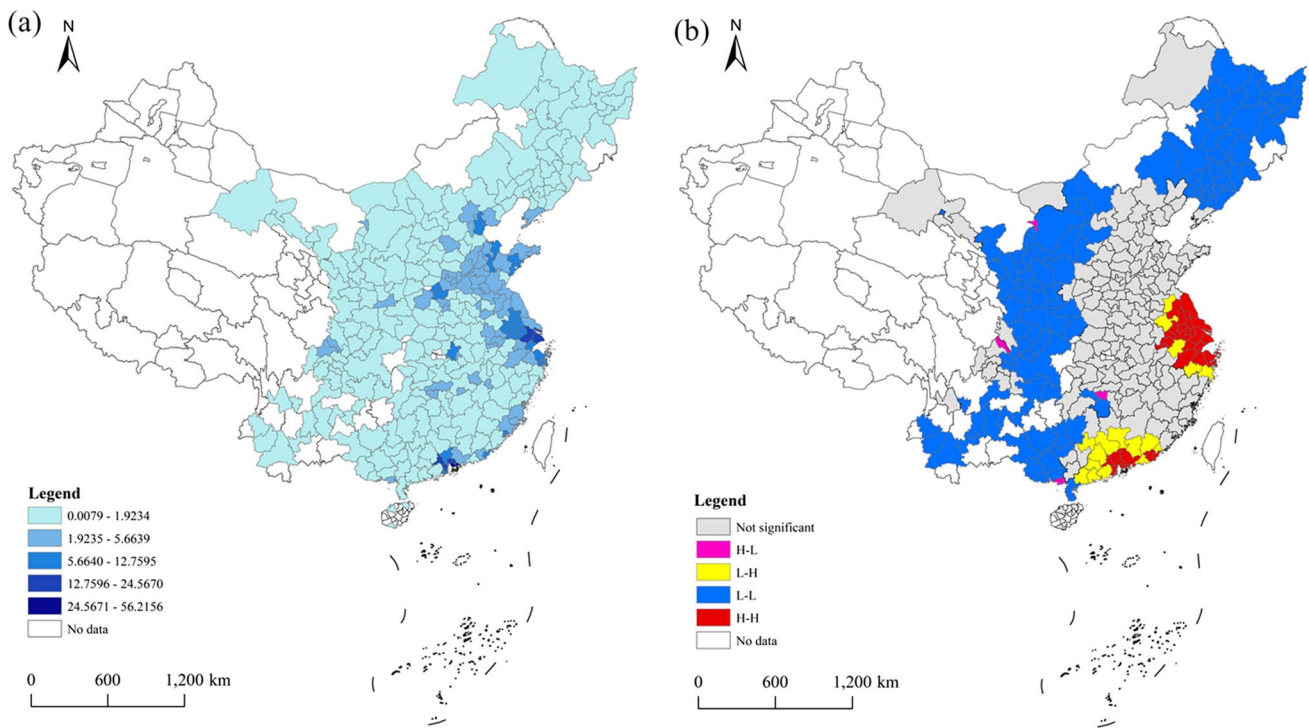


Fig. 2 Industrial agglomeration level and LISA distribution in China

the central and western inland regions was relatively low. Specifically, cities with high industrial agglomeration level were mainly distributed in the Yangtze River Delta and Pearl River Delta, followed by Beijing-Tianjin-Hebei, Shandong Peninsula, Liaozhong Peninsula, and Fujian coastal regions, and the industrial agglomeration level of other regions was relatively low. It can be seen that the regions with high level of industrial agglomeration were mainly concentrated in the economically developed eastern coastal regions, which may be attributed to the early start of industrial development and the relatively perfect industrial system, which made many enterprises highly concentrated here.

In order to further explore the spatial agglomeration characteristics of China's industrial agglomeration, the spatial autocorrelation analysis method was introduced to analyze the spatial correlation. The global Moran's I of industrial agglomeration calculated by the GeoDa software was 0.1961, $P=0.002$. First, the global Moran's I of industrial agglomeration was 0.1961, which passed the significance test at the 1% level, indicating that there was a significant and positive spatial autocorrelation of industrial agglomeration in China. Second, the following results can be obtained from LISA cluster of industrial agglomeration, there was a significant local spatial autocorrelation of industrial agglomeration in China, and the main types of spatial agglomeration were High-high, Low-low, and Low-high. Specifically, High-high agglomeration type cities were mainly distributed in the Yangtze River Delta and the Pearl River Delta, which indicated that the industrial agglomeration in this region and surrounding regions was high. Low-low agglomeration type cities were most widely distributed; northeast, northwest, and southwest of China were the main distribution regions, which showed that the industrial agglomeration level of the region and surrounding regions was low. Low-high agglomeration type cities were mainly distributed in the periphery of the Yangtze River Delta and the Pearl River Delta, which may be attributed to the fact that the region has been affected by the agglomeration effect of the Yangtze River Delta and the Pearl River Delta for a long time, and its own industrial agglomeration level was relatively low, forming the "Matthew Effect" in space.

Spatial distribution characteristics of industrial pollution discharge

Industrial wastewater

In terms of the total industrial wastewater discharge, the total industrial wastewater discharge in China showed a spatial distribution pattern of "high in the east and low in the west" (Fig. 3). The total industrial wastewater discharge in the eastern coastal regions was relatively high, while the total industrial wastewater discharge in the central and western

regions was relatively low. Among them, the Yangtze River Delta, the Pearl River Delta, the Bohai Sea Rim, the coast of Southern Fujian and Chongqing had the highest industrial wastewater discharge, followed by North China, Northeast China, and Southwest China, and the industrial wastewater discharge in other regions was relatively low, which was basically consistent with China's "π" shaped regional development strategy. In terms of the total industrial wastewater discharge intensity, the wastewater discharge intensity in northeast, northwest, and southwest China was the highest, while the wastewater discharge intensity in eastern coastal and central inland regions was relatively low. There was an obvious spatial non-corresponding relationship between the total and intensity of industrial wastewater discharge in China, which could be attributed to the fact that developed regions had more advanced industrial production technology than underdeveloped regions, resulting in lower wastewater discharge per unit of industrial output value.

Industrial SO₂

In terms of the total industrial SO₂ discharge, the total industrial SO₂ discharge in China showed a spatial pattern of "high in the north and low in the south" (Fig. 3). Among them, the industrial SO₂ discharge in North China, Southwest China, and Yangtze River Delta were the highest, while the industrial SO₂ discharge in Central China and South China were relatively low. On the whole, the industrial SO₂ discharge intensity showed a similar spatial pattern to the total industrial SO₂ discharge. Among them, the industrial SO₂ discharge intensity in Northeast China, Northwest China, and Southwest China was higher, while the industrial SO₂ discharge intensity in Central China, South China, and the eastern coastal regions was relatively lower. The industrial SO₂ discharge intensity formed obvious regional differences along both sides of the Hu Huanyong line. It showed that the regional difference accords with the trend of Heihe-Tengchong line.

Industrial smoke and dust

The total and intensity of industrial smoke and dust discharge in China showed a spatial distribution pattern of "high in the north and low in the south" (Fig. 3), indicating that smoke and dust pollution was more serious in northern China than in southern China, which may be attributed to the fact that the northern region has more heavily polluting enterprises with large smoke and dust discharges than the southern region. Specifically, cities with high total industrial smoke and dust discharge were mainly concentrated in the Yellow River Basin, the Yangtze River Basin, and the Bohai Rim region, which may be attributed to the relatively concentrated distribution of heavy chemical enterprises in

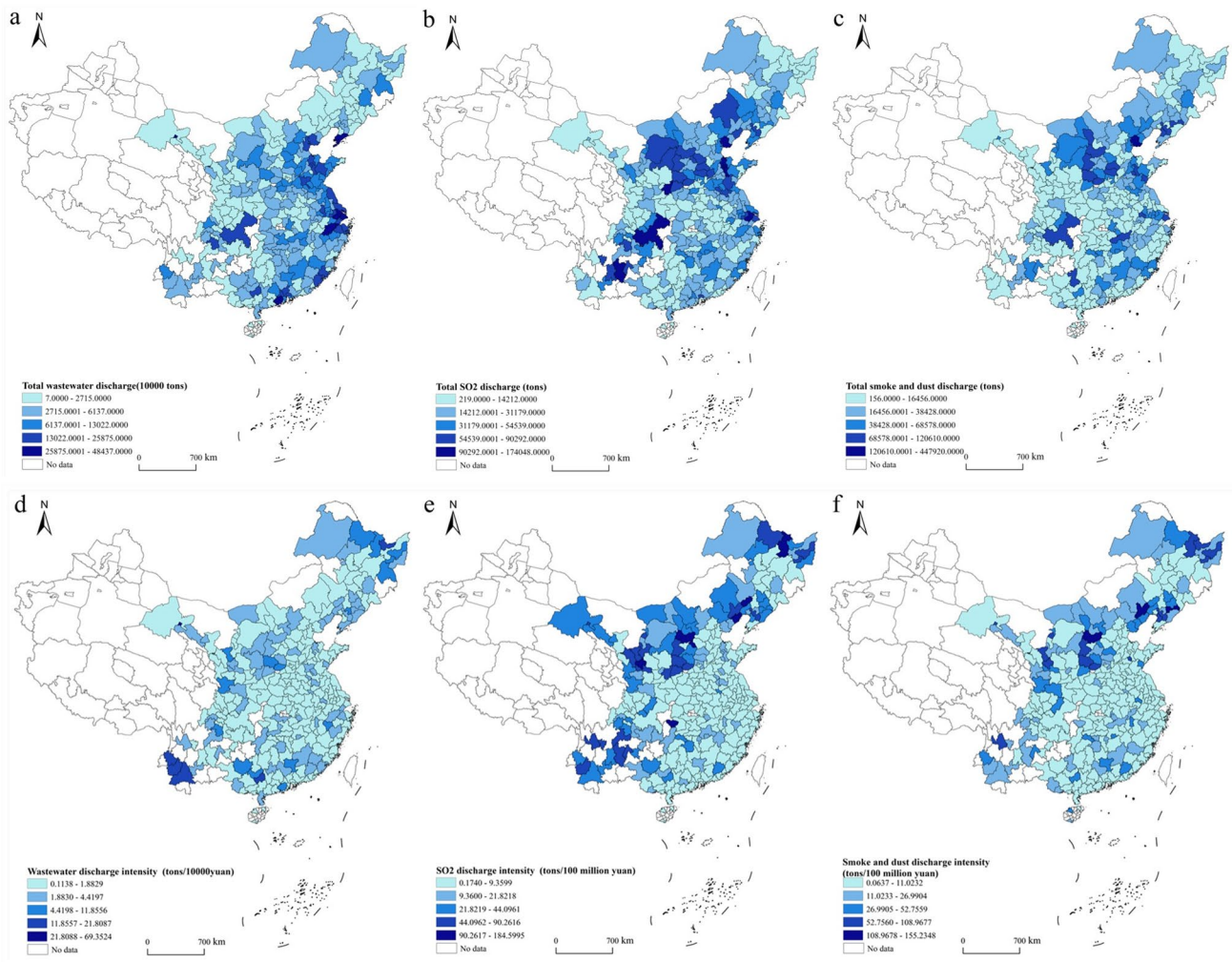


Fig. 3 Spatial distribution of industrial pollution discharges

these regions, resulting in more industrial smoke and dust discharges. Cities with high industrial smoke and dust discharge intensity were mainly distributed in Shanxi Province, Shaanxi Province, Liaoning Province, and Heilongjiang Province. Compared with the eastern coastal regions, the level of industrial technology in these regions lagged behind, resulting in more smoke and dust discharges per unit of industrial output value.

Spatial correlation between industrial agglomeration and pollution discharge

Global bivariate spatial autocorrelation analysis

The global Moran’s *I* of total industrial wastewater discharge was 0.1657 (Table 3), which passed the significance test at the level of 1%, indicating that there was a significant positive spatial correlation between industrial agglomeration and the total industrial wastewater discharge. The global Moran’s

Table 3 Bivariate global Moran’ *I*

Variables	Moran’s <i>I</i>	<i>P</i> -value	<i>Z</i> -score
Twater	0.1657	0.0020	8.9334
Tso ₂	−0.0011	0.4960	−0.0210
Tsoot	0.0013	0.4040	0.1628
Rwater	−0.0693	0.0020	−4.0340
Rso ₂	−0.1516	0.0020	−9.3193
Rsoot	−0.1293	0.0020	−8.1602

I of total industrial SO₂ and industrial smoke and dust discharges were negative, which failed to pass the significance test, indicating that the spatial dependence effect of industrial agglomeration and total industrial SO₂ and industrial smoke and dust discharges was not significant at the national level. Moreover, the global Moran’s *I* of the three industrial pollution discharge intensities were negative, and all passed the significance test at the level of 1%. It showed that

there was a significant spatial negative correlation between industrial agglomeration and industrial pollution discharge intensity, which reflected that industrial agglomeration was conducive to reducing industrial pollution discharge intensity at the national level. To a certain extent, this could be attributed to the fact that industrial agglomeration not only improved industrial production efficiency through technological scale effect but also reduced industrial pollution discharge through pollution control scale effect.

Local bivariate spatial autocorrelation analysis

Industrial agglomeration and industrial wastewater discharge (Fig. 4). The spatial correlation between industrial agglomeration and total industrial wastewater discharge included three types: high agglomeration-high pollution, low agglomeration-low pollution, and low agglomeration-high pollution. Among them, cities with high agglomeration-high pollution

were mainly distributed in the Yangtze River Delta, Pearl River Delta, and Shandong Peninsula, indicating that the level of industrial agglomeration in these regions and the total of industrial wastewater discharge in their adjacent regions were high. Cities with low agglomeration-low pollution were mainly distributed in Northeast and Northwest China, indicating that the level of industrial agglomeration in these regions and the total of industrial wastewater discharge in their adjacent regions were low. Cities with low agglomeration-high pollution type were mainly distributed in the adjacent regions of high agglomeration-high pollution type regions and Jiuquan City, Gansu Province, indicating that the level of industrial agglomeration in these areas was low, while the total of industrial wastewater discharge in their adjacent regions was high. Moreover, the spatial correlation types between industrial agglomeration and industrial wastewater discharge intensity included three types: low agglomeration-low pollution, low agglomeration-high

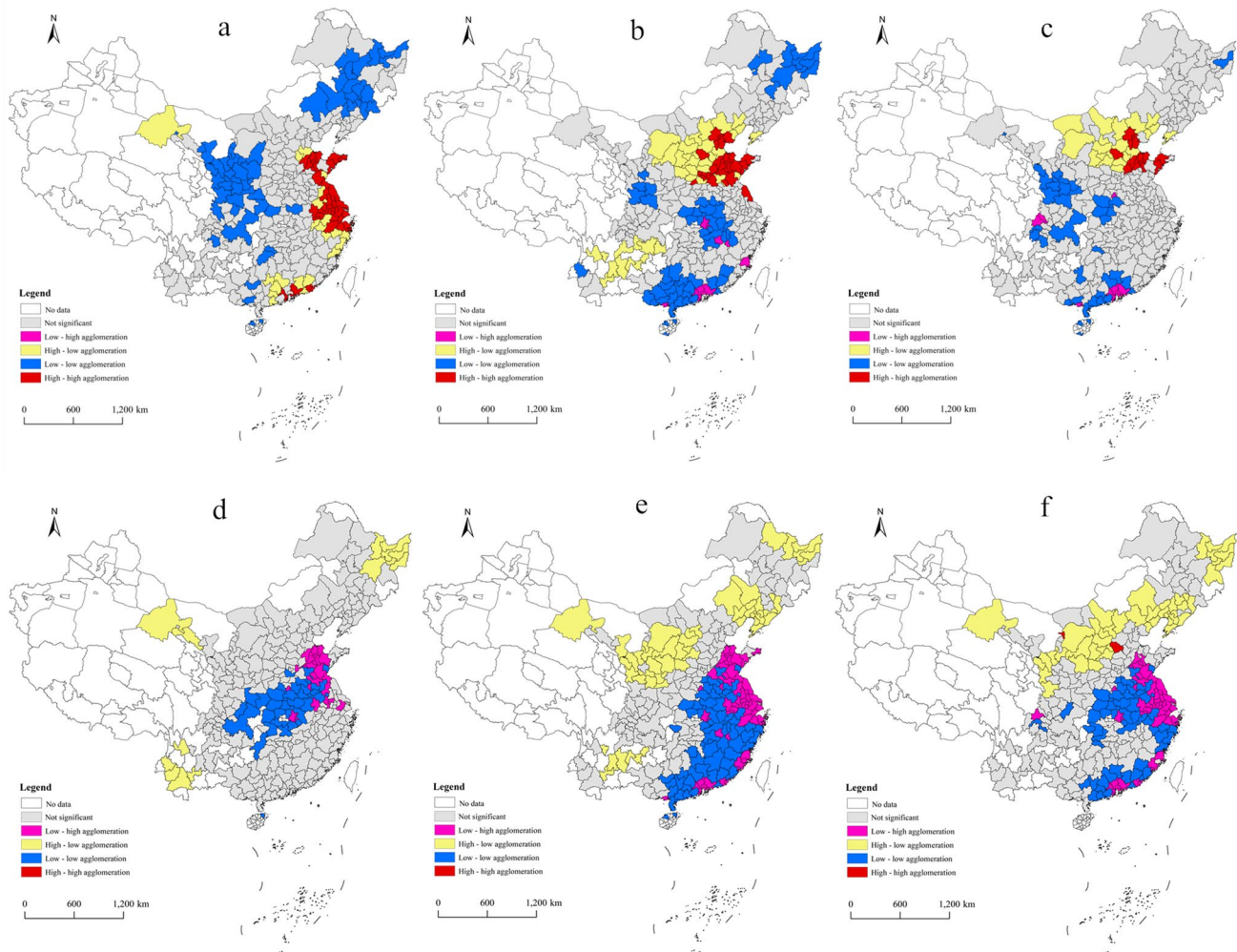


Fig. 4 LISA agglomeration of industrial agglomeration and industrial pollution

pollution, and high agglomeration-low pollution. Among them, cities with low agglomeration-low pollution were mainly distributed in Central China, indicating that the industrial agglomeration level in this region and the industrial wastewater discharge intensity in its adjacent regions were low. Cities with low agglomeration-high pollution types were mainly distributed in the northeast of Northeast China, the northwest of Gansu Province, and the southwest of Yunnan Province, indicating that the level of industrial agglomeration in these regions was low, while the industrial wastewater discharge intensity in their adjacent regions was high. Cities with high agglomeration-low pollution were mainly distributed in Shandong Province, indicating that the level of industrial agglomeration in this region was high, while the industrial wastewater discharge intensity in its adjacent regions was low.

Industrial agglomeration and industrial SO₂ discharge (Fig. 4). The spatial correlation types between industrial agglomeration and total industrial SO₂ discharge mainly included high agglomeration-high pollution, low agglomeration-low pollution, and low agglomeration-high pollution. Among them, cities with high agglomeration-high pollution were mainly distributed in Shandong Peninsula, Beijing, and Tianjin. Cities with low agglomeration-low pollution were mainly distributed in Central China, South China, and Heilongjiang Province. Cities with low agglomeration-high pollution were mainly distributed in North China and southwest China. Moreover, the spatial correlation types between industrial agglomeration and industrial SO₂ discharge intensity mainly included low agglomeration-low pollution, low agglomeration-high pollution, and high agglomeration-low pollution. Among them, cities with low agglomeration-low pollution were mainly distributed in the southeast coastal regions and Central China. Cities with high agglomeration-low pollution were mainly distributed in the eastern coastal regions and the Pearl River Delta. Cities with low agglomeration-high pollution were mainly distributed in Northwest China, Southwest China, and the two wings of Northeast China.

Industrial agglomeration and industrial smoke and dust discharge (Fig. 4). The spatial correlation types between industrial agglomeration and total industrial smoke and dust discharge mainly included high agglomeration-high pollution, low agglomeration-low pollution, and low

agglomeration-high pollution. Among them, cities with high agglomeration-high pollution mainly distributed in North China. Cities with low agglomeration-low pollution were mainly distributed in the border regions of Northwest China, Southwest China, and central China, as well as Guangdong Province. Cities with low agglomeration-high pollution were mainly distributed in North China. Moreover, the spatial correlation types between industrial agglomeration and industrial smoke and dust discharge intensity mainly included high agglomeration-low pollution, low agglomeration-low pollution, and low agglomeration-high pollution. Among them, cities with high agglomeration-low pollution were mainly distributed in the eastern coastal regions. Cities with low agglomeration-low pollution type were mainly distributed in the adjacent regions of the high agglomeration-low pollution type regions. Cities with low agglomeration-high pollution were mainly distributed in North China, the north and south wings of Northeast China, and the northwest of Gansu Province.

Influencing factors of industrial pollution discharge

Model selection

In order to avoid the influence of multicollinearity between variables on the results, it is necessary to test the multicollinearity of variables. The test results showed that VIF < 7.5, indicating that there was no multicollinearity between variables, so the next step of regression analysis could be carried out. According to the criterion proposed by Anselin: when Lagrange multiplier (LM) (lag) is more significant than LM (error) in the spatial correlation test, and when R-LM (lag) passes the significance test but R-LM (error) fails, Spatial Lag Model (SLM) should be selected. On the contrary, when LM (error) is more significant than LM (lag), and R-LM (error) passes the significance test while R-LM (lag) fails, spatial error model (SEM) should be selected.

The spatial dependence test results of industrial pollution discharge were shown in Table 4. LM (error) and LM (lag) of total industrial wastewater discharge were significant, RLM (error) was significant, and RLM (lag) was not significant. LM (lag) and LM (error) of industrial SO₂ discharge intensity and total industrial smoke and dust discharge were significant, RLM (lag) was significant, and RLM (error) was

Table 4 Test results of spatial dependence of total and intensity industrial pollution discharge

Test	Twater	Rwater	Tso ₂	Rso ₂	Tsoot	Rsoot
LM(lag)	15.5285***	11.9588***	69.1556***	19.8676***	31.7646***	5.6020**
RLM(lag)	0.2374	0.2632	17.6963***	1.6168	12.9974***	0.3699
LM(error)	25.0400***	18.6019***	51.6192***	31.2535***	19.3510***	7.7439***
RLM(error)	9.7488***	6.9062***	0.1598	13.0028***	0.5839	2.5118

***, **, and * refer to the 1%, 5%, and 10% significance levels, respectively.

not significant. LM (error) and LM (lag) of industrial wastewater discharge intensity and industrial SO₂ discharge intensity were significant, RLM (error) was significant, and RLM (lag) was not significant. LM (error) of industrial smoke and dust discharge intensity was more significant than LM (lag). According to the test results, total industrial wastewater discharge, industrial wastewater discharge intensity, industrial SO₂ discharge intensity, and industrial smoke and dust discharge intensity were suitable to select SEM to analyze the influencing factors, while total industrial SO₂ discharge and total industrial smoke and dust discharge were suitable to select SLM to analyze the influencing factors.

In order to further diagnose the validity of regression results of the model, multiple coefficient of determination (R^2), Log-likelihood (LogL), Akaike information criterion (AIC), and Schwarz criterion (SC) were selected for further test. When the logL value is larger, AIC value and SC value

are smaller; the explanatory power of the spatial econometric model is better. According to the regression results in Table 5 and Table 6, SEM and SLM were better than ordinary least squares (OLS) in R^2 , LogL, AIC, and SC, indicating that SEM and SLM considering spatial elements had stronger explanatory power than OLS. Therefore, the calculation results of SEM and SLM were selected to analyze the influencing factors of industrial pollution discharge.

Analysis on the influencing factors of the total industrial pollution discharge

Analysis of core explanatory variables.

The influence coefficient of industrial agglomeration on the total amount of industrial wastewater discharge was 0.2194, and it passed the significance test at the level of 1%. Every 1% increase in the level of industrial agglomeration

Table 5 Regression results of total industrial pollution discharges

	Twater		Tso ₂		Tsoot	
	OLS	SEM	OLS	SLM	OLS	SLM
<i>constant</i>	6.7076***	7.7471***	-0.9260	-3.6395**	-1.5043	-3.9100*
<i>agg</i>	0.1972***	0.2194***	-0.1065*	-0.0846	-0.2466***	-0.2295***
<i>ind</i>	0.7844***	0.6229**	1.1744***	0.8914***	1.2726***	1.0946***
<i>eci</i>	0.2774***	0.2780***	0.4085***	0.3472***	0.5032***	0.4640***
<i>tec</i>	-0.0127	-0.0427	-0.1507**	-0.1374**	-0.0916	-0.0664
<i>fdi</i>	0.0003	-0.0468	-0.0141	-0.0251	0.0876**	0.0533
<i>nat</i>	-1.1374***	-1.3114***	0.0967	-0.1743	-0.0828	-0.2304
<i>env</i>	-0.0138	0.0585	0.1448*	0.0869	0.0419	-0.0139
R^2	0.4477	0.5098	0.2822	0.4257	0.2741	0.3571
<i>LogL</i>	-365.8270	-355.9360	-346.5660	-323.4330	-381.7330	-370.6590
<i>AIC</i>	747.6530	727.8720	709.1330	664.8670	779.4670	759.3190
<i>SC</i>	776.8450	757.0640	738.3250	697.7080	808.6580	792.1600

***, **, and * refer to the 1%, 5%, and 10% significance levels, respectively.

Table 6 Regression results of industrial pollution discharge intensity

	Rwater		Rso ₂		Rsoot	
	OLS	SEM	OLS	SEM	OLS	SEM
<i>constant</i>	1.8932	1.2943	-5.7404***	-2.8302	-6.3186***	-4.8437**
<i>agg</i>	-0.2331***	-0.1908***	-0.5369***	-0.4660***	-0.6769***	-0.6368***
<i>ind</i>	0.0706	0.0337	0.4606*	0.2598	0.5588*	0.4806
<i>eci</i>	0.1398***	0.1483***	0.2709***	0.2154***	0.3655***	0.3413***
<i>tec</i>	-0.1148*	-0.1901***	-0.2528***	-0.3303***	-0.1937**	-0.2303**
<i>fdi</i>	-0.0692**	-0.0816**	-0.0836**	-0.0693*	0.0181	-0.0038
<i>nat</i>	-0.7805**	-0.6874*	0.4536	0.1582	0.2741	0.1034
<i>env</i>	-0.0444	0.0045	0.1142	0.0845	0.0114	-0.0150
R^2	0.1750	0.2393	0.5353	0.5980	0.4396	0.4714
<i>LogL</i>	-324.7820	-318.6667	-343.3620	-330.6652	-401.4670	-398.0692
<i>AIC</i>	665.5640	653.3330	702.7230	677.3300	818.9340	812.1380
<i>SC</i>	694.7560	682.5250	731.9150	706.5220	848.1260	841.3300

***, **, and * refer to the 1%, 5%, and 10% significance levels, respectively.

will increase the total amount of industrial wastewater discharge by 0.2194%, indicating that industrial agglomeration may increase the total amount of industrial wastewater discharge, which may be attributed to the fact that China's current centralized wastewater treatment technology needs to be further improved, and the negative environmental externalities caused by industrial agglomeration lead to the intensification of industrial wastewater discharge. The influence coefficient of industrial agglomeration on the total industrial SO₂ discharge was -0.0846 , but it failed to pass the significance test, indicating that industrial agglomeration may reduce the total industrial SO₂ discharge, which may be attributed to the fact that industrial agglomeration promotes the centralized treatment of industrial waste gas to some extent. However, China's centralized waste gas treatment technology is still in the stage of continuous improvement and upgrading, resulting in no obvious discharge reduction effect. The influence coefficient of industrial agglomeration on industrial smoke and dust was -0.2295 , and it passed the significance test at the level of 1%. Every 1% increase in the level of industrial agglomeration will reduce the total amount of industrial smoke and dust discharge by 0.2295%, indicating that industrial agglomeration can effectively inhibit industrial smoke and dust discharge, which may be attributed to the relatively advanced industrial smoke and dust treatment technology in China, which brings the scale effect of industrial smoke and dust pollution control into play.

Control variable analysis.

The influence coefficients of industrial structure and energy intensity on total industrial wastewater discharge, total SO₂ discharge, and total smoke and dust discharge were 0.6229, 0.8914, 1.0946, 0.2780, 0.3472, and 0.4640 respectively, which had passed the significance test, indicating that industrial structure can increase industrial pollution discharge. This may be attributed to the fact that the secondary industry is dominated by heavy chemical enterprises, and industrial power consumption indirectly reflects energy consumption. The impact coefficient of technology investment on total industrial SO₂ discharge was -0.1374 , and passed the significance test at the level of 5%, while the impact on total industrial wastewater and smoke and dust discharge was not significant. The impact of openness to the outside on the total of industrial wastewater discharge, SO₂ discharge, and smoke and dust discharge was not significant, which may be attributed to the combined effect of positive and negative environmental externalities caused by FDI. The influence coefficient of nationalization degree on total industrial wastewater discharge was -1.3114 , which had passed the significance test at the level of 1%, but had no significant effect on total industrial SO₂ and smoke and dust discharge, which may be due to stricter control standards for industrial wastewater discharge by state-owned enterprises. The impact

of environmental regulation on the total discharge of the three pollutants was not significant, which may be attributed to the fact that the sulfur dioxide treatment rate cannot fully characterize the environmental regulation.

Analysis on the influencing factors of industrial pollution discharge intensity

Analysis of core explanatory variables.

The influence coefficient of industrial agglomeration on industrial wastewater discharge was -0.1908 , and it passed the test at the significance level of 1%, indicating that every 1% increase in industrial agglomeration degree will promote the reduction of industrial wastewater discharge intensity by 0.1908%, which is mainly due to the positive externality of the environment of industrial agglomeration. The influence coefficient of industrial agglomeration on industrial SO₂ discharge intensity was -0.4660 , which passed the test at the significance level of 1%, indicating that every 1% increase in the degree of industrial agglomeration will promote the reduction of industrial SO₂ discharge intensity by 0.4660%. The influence coefficient of industrial agglomeration on industrial smoke and dust discharge intensity was -0.6368 , which passed the test at the significance level of 1%, indicating that every 1% increase in the degree of industrial agglomeration will promote the reduction of industrial smoke discharge intensity by 0.6368%, which is conducive to improving industrial production efficiency and reducing industrial smoke and dust discharges. In conclusion, industrial agglomeration had a significant negative effect on the discharge intensity of industrial wastewater, SO₂, and smoke and dust, indicating that industrial agglomeration is conducive to reducing the discharge intensity of industrial pollution, which was consistent with the research results of Glaeser and Kahn (2010). This may be attributed to the positive environmental externalities and agglomeration economic effects of industrial agglomeration by promoting the increase of economic scale, the upgrading of industrial structure, and the upgrading of technological level, which is conducive to increasing industrial output value and reducing industrial pollution discharges, thereby reducing the intensity of industrial pollution discharges.

Control variable analysis.

The industrial structure had no significant effect on the discharge intensity of the three major industrial pollutants, which may be attributed to the joint increase of industrial pollution discharge and industrial output value promoted by the secondary industry. The influence coefficients of energy consumption intensity on industrial wastewater discharge intensity, industrial SO₂ discharge intensity, and industrial smoke and dust discharge intensity were 0.1483, 0.2154, and 0.3413 respectively, and all passed the significance test at the level of 1%, indicating that energy consumption

intensity is conducive to the improvement of industrial pollution discharge intensity. The influence coefficients of technology investment on the discharge intensity of industrial wastewater, industrial SO₂, and industrial smoke and dust were -0.1901 , -0.3303 , and -0.2303 respectively, which had passed the significance test, indicating that scientific and technological investment is conducive to reducing the discharge intensity of industrial pollution, which may be attributed to the fact that science and technology investment can not only increase industrial output value by improving enterprise production efficiency but also reduce industrial pollution discharge through technological upgrading. The influence coefficients of openness to the outside on the discharge intensity of industrial wastewater and industrial SO₂ were -0.0816 and -0.0693 respectively, and both had passed the significance test, indicating that opening to the outside world is conducive to reducing the discharge intensity of industrial wastewater and industrial SO₂, but had no significant effect on the discharge intensity of industrial smoke and dust. The influence coefficient of the degree of nationalization on the discharge intensity of industrial wastewater was -0.6874 , which had passed the significance test at the level of 10%, indicating that nationalization degree is conducive to reducing the discharge intensity of industrial wastewater, while the effect on the discharge intensity of industrial SO₂ and industrial smoke and dust was not significant, which may be attributed to the greater control of industrial wastewater discharge by local governments. The impact of environmental regulation on the discharge intensity of the three major industrial pollutants was not significant, which may be attributed to the use of sulfur dioxide treatment rate to characterize the environmental regulation index, which cannot fully reflect its impact on industrial pollution discharge intensity.

Discussion

Industrial agglomeration and pollution discharge

There were obvious differences between the East and the West in the level of industrial agglomeration in China. The level of industrial agglomeration in the eastern coastal regions was relatively high, while that in the central and western inland regions was relatively low, which was consistent with the results of some previous studies (Dong et al. 2019b). As the frontier area of China's opening to the outside world, the eastern coastal regions had an early start in industrial development and a high level of economic development and industrial technology. Moreover, the region had a broad overseas market, which was conducive to attracting foreign-funded enterprises to layout here. Compared with the eastern coastal region, the central and western inland

regions had a low degree of opening to the outside world due to the late start of industrial development and the lagging level of industrial technology. In addition, local governments had more strict control over enterprises, resulting in the region's lack of attraction to foreign-funded enterprises.

Among the spatial correlation types between industrial agglomeration and total industrial pollution discharges, high agglomeration-high pollution and low agglomeration-low pollution were the most widely distributed. Industrial agglomeration was conducive to the increase of total regional pollution discharges, which was consistent with the research conclusions of Dong et al. (2019a). It showed that there was a positive correlation between industrial agglomeration and total pollution discharge, which may be attributed to the fact that excessive industrial agglomeration may lead to extensive expansion of enterprises, disorderly competition, and increased energy consumption, resulting in the intensification of regional industrial pollution discharge, which was consistent with the research conclusions of Liu et al. (2022a).

Among the spatial correlation types of industrial agglomeration and industrial pollution discharge intensity, low agglomeration-high pollution and high agglomeration-low pollution were the most widely distributed. Industrial agglomeration was conducive to reducing regional industrial pollution discharge intensity, which was consistent with the research results of Ke and Yu (2014). It showed that there was a negative correlation between industrial agglomeration and pollution discharge intensity, which may be attributed to the fact that industrial agglomeration not only realized the agglomeration economy by promoting the increase of enterprise scale and the upgrading of industrial structure but also promoted the centralized treatment of enterprise pollution discharge and effectively reduced the regional industrial pollution discharge by strengthening the exchange and cooperation among enterprises, which was consistent with the research conclusions of Fang et al. (2021).

Influencing factors of industrial pollution discharge

Industrial structure had a positive effect on the total discharge of the three major industrial pollutants, indicating that the secondary industry is conducive to the increase of industrial pollution discharge, which was consistent with the results of some previous studies (Yang et al. 2016). The impact of industrial structure on the discharge intensity of three industrial pollutants was not significant, which may be attributed to the fact that the discharge intensity is measured by the proportion of the total discharge of pollutants to the industrial output value. The secondary industry not only produced pollution discharges, but also brought high industrial output value.

Energy intensity had a significant positive promoting effect on the total and intensity of the three major industrial pollutants, indicating that energy intensity is conducive to increasing industrial pollution discharge, which was consistent with the results of some previous studies (Li et al. 2020). This may be attributed to the fact that the current energy consumption generated by Chinese enterprises in the production process is mainly burning fossil fuels such as coal; it not only promotes the increase of industrial output value but also leads to the increase of pollution discharges.

Technology investment had a significant negative effect on the discharge intensity of the three major industrial pollutants and the total industrial SO₂ discharge, indicating that technology investment is conducive to reducing industrial pollution discharge, which was consistent with the results of some previous studies (Chen et al. 2016). This may be attributed to the fact that technology investment is conducive to promoting the upgrading of industrial structure and the improvement of production technology, improving industrial production efficiency, and then reducing energy consumption and pollution discharges. Openness to the outside had a significant negative effect on the discharge intensity of industrial wastewater and SO₂, which was contrary to the previous research conclusion (He 2007). This may be due to the fact that in the early foreign-funded enterprises introduced by China, the backward production capacity eliminated by western developed countries was the main, and the local government had less control over the pollution discharge of foreign-funded enterprises, which led to the increase of industrial pollution discharge promoted by foreign investment. With the rapid development of China's economy, the Chinese government pays more attention to the introduction of high-tech industries with low energy consumption, low discharge, and high yield when introducing foreign-funded enterprises, so that foreign investment can help reduce industrial pollution discharges.

The degree of nationalization had a significant negative effect on the total and intensity of industrial wastewater discharge, indicating that the degree of nationalization helps to reduce industrial wastewater discharge, which was consistent with the results of some previous studies (Zhang et al. 2020). This may be attributed to the fact that China's state-owned enterprises are enterprises under the key supervision of the environmental protection department and are subject to stricter supervision in pollution control and discharge reduction, resulting in less pollution to the ecological environment. In China's market economy system, the government has been playing an important role in macro-control (Yin et al. 2018), and the government plays a role in supervision and control of enterprise pollution discharges. However, the effect of environmental regulation on the total amount and intensity of industrial pollution discharge was not significant, which may be attributed to the use of sulfur dioxide

treatment rate to characterize environmental regulation indicators, which cannot fully reflect its impact on the intensity of industrial pollution discharge.

Conclusion and policy suggestions

Conclusion

Taking 284 cities in China as the research object, this study explored the spatial correlation and influencing factors between industrial agglomeration and pollution discharge, which is of great significance to clarify the spatial relationship between industrial agglomeration and pollution discharge, identify the main factors affecting industrial pollution discharge, and promote regional sustainable development. The main results were as follows:

- China's industrial agglomeration level presented the spatial distribution characteristics of "high in the east and low in the west". The regions with the highest industrial agglomeration level were mainly concentrated in the Yangtze River Delta and Pearl River Delta, followed by Beijing-Tianjin-Hebei, central and southern Liaoning, Shandong Peninsula and Fujian coastal regions. The industrial agglomeration level in inland regions was the lowest, and industrial agglomeration and economic development had spatial convergence. China's industrial pollution discharges showed North-South differences and East-West differences. The total discharge of industrial wastewater presented a spatial distribution pattern of "high in the east and low in the west". The discharge intensity of industrial wastewater in Northeast, Northwest, and Southwest China was high, while that in eastern coastal regions and central inland regions was low. Industrial SO₂ discharge presented a spatial differentiation pattern of "high in the west, low in the east, high in the north, and low in the south". Industrial SO₂ discharge intensity presented a spatial distribution pattern of "high in the north and low in the south". The total and intensity of industrial smoke and dust discharge showed the spatial distribution characteristics of "high in the north and low in the south".
- From the whole country, there was a significant spatial negative correlation between industrial agglomeration and pollution discharge. The local spatial correlation between industrial agglomeration and industrial wastewater, industrial SO₂ and industrial smoke and dust was strong, and the main types were high agglomeration-low pollution, low agglomeration-high pollution and low agglomeration-low pollution. High agglomeration-low pollution type cities were mainly distributed in the eastern coastal regions, low agglomeration-high pollution

type cities were mainly distributed in the Northeast and Northwest China, and low agglomeration-low pollution type cities were mainly distributed in the central inland regions.

- In terms of influencing factors, industrial agglomeration had a positive effect on the total of industrial wastewater discharge, a negative effect on the total of industrial smoke and dust discharge, and had no significant effect on the total of industrial SO₂ discharge. Industrial agglomeration had a significant negative effect on the discharge intensity of industrial wastewater, industrial SO₂, and industrial smoke and dust. Industrial agglomeration was conducive to reducing the discharge intensity of industrial pollution. Industrial structure had a positive effect on the total discharge of three industrial pollutants. Energy consumption intensity had a significant positive effect on the total discharge and discharge intensity of the three industrial pollutants. Technological investment played a significant negative role in promoting the discharge intensity of three major industrial pollutants and the total of industrial SO₂ discharge. Opening to the outside world had a significant negative effect on the discharge intensity of industrial wastewater and industrial SO₂. The degree of nationalization had a significant negative effect on the total and intensity of industrial wastewater discharge.

Policy suggestions

According to the distribution characteristics of industrial agglomeration and pollution discharge in China and the influencing factors of industrial pollution discharge, the following suggestions were put forward:

For local governments, first of all, they should guide local enterprises to gather reasonably, give full play to the scale benefits and positive environmental externalities of industrial agglomeration, strengthen cooperation and exchanges among enterprises, and improve the production efficiency and pollution treatment efficiency of enterprises. Secondly, a regional joint prevention and control mechanism should be established to strengthen the control of high polluting enterprises and reduce regional industrial pollution discharges.

For local enterprises, first of all, they should adjust the industrial structure, increase investment in science and technology, strengthen technical exchanges among enterprises and promote industrial technology upgrading. Secondly, they should take the initiative to improve pollution discharge standards, strengthen exchanges and cooperation with advanced enterprises, and form a centralized treatment mode of industrial pollution discharge among enterprises.

Finally, developed and underdeveloped regions should form their own unique industrial development model. Developed regions should strictly control industrial pollution

discharge standards, give full play to their own radiation driving role, and promote the spillover of technical elements to the surrounding regions. Underdeveloped regions should learn advanced production technology and management concepts from developed regions, and selectively undertake enterprises from developed regions. Furthermore, they should not ignore the protection of the ecological environment due to the blind pursuit of economic interests.

Owing to this study only examined the spatial correlation and influencing factors between China's industrial agglomeration and pollution discharge in 2017, it cannot reflect the temporal and spatial evolution characteristics of the research object. In addition, the selection of influencing indicators of industrial pollution discharge was not comprehensive enough, so the analysis of influencing factors may not be comprehensive enough. In the future, we will try to collect multi-year data to analyze the temporal and spatial evolution of China's industrial agglomeration and pollution discharge, and select more comprehensive impact indicators to deeply analyze the impact mechanism of industrial pollution discharge.

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Author contribution All authors contributed to the study conception and design. Methodology, software, and writing/original draft preparation were performed by Chengzhen Song. Conceptualization, methodology, writing/review and editing, and funding acquisition were performed by Guanwen Yin. Data curation and software were performed by Yiming Hou. Conceptualization, writing/review and editing, methodology, supervision, and funding acquisition were performed by Yanbin Chen. All authors read and approved the final manuscript.

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References

- Anselin L (1988) *Spatial Econometrics: Methods and Models*. Springer, Netherlands
- Anselin L (2010) Local Indicators of Spatial Association—LISA. *Geogr Anal* 27:93–115

- Chen D, Chen S, Jin H (2018) Industrial agglomeration and CO₂ discharges: evidence from 187 Chinese prefecture-level cities over 2005–2013. *J Clean Prod* 172:993–1003. <https://doi.org/10.1016/j.jclepro.2017.10.068>
- Chen Y, Yin G, Liu K (2021) Regional differences in the industrial water use efficiency of China: the spatial spillover effect and relevant factors. *Resour Conserv Recycl* 167:105239. <https://doi.org/10.1016/j.resconrec.2020.105239>
- Chen Y, Han B, Liu W (2016). Green technology innovation and energy intensity in China. *Natural Hazards* <https://doi.org/10.1007/s11069-016-2158-7>
- Cheng Z (2016) The spatial correlation and interaction between manufacturing agglomeration and environmental pollution. *Ecol Ind* 61:1024–1032. <https://doi.org/10.1016/j.ecolind.2015.10.060>
- Dong F, Li J, Zhang S, Wang Y, Sun Z (2019) Sensitivity analysis and spatial-temporal heterogeneity of CO₂ discharge intensity: evidence from China. *Resour Conserv Recycl* 150:104398. <https://doi.org/10.1016/j.resconrec.2019.06.032>
- Dong F, Wang Y, Zheng L, Li J, Xie S (2019) Can industrial agglomeration promote pollution agglomeration? Evidence from China. *J Clean Prod* 246:118960. <https://doi.org/10.1016/j.jclepro.2019.118960>
- Fang C, Liu H, Wang S (2021) The coupling curve between urbanization and the eco-environment: China's urban agglomeration as a case study. *Ecol Ind* 130:108107. <https://doi.org/10.1016/j.ecolind.2021.108107>
- Glaeser EL, Kahn ME (2010) The greenness of cities: carbon dioxide discharges and urban development. *J Urban Econ* 67:404–418. <https://doi.org/10.1016/j.jue.2009.11.006>
- Guan W, Xu S (2016) Study of spatial patterns and spatial effects of energy eco-efficiency in China. *J Geog Sci* 26:1362–1376. <https://doi.org/10.1007/s11442-016-1332-x>
- Ha L, Tu J, Yang J, Xu C, Pang J (2020) Regional eco-efficiency evaluation and spatial pattern analysis of the Yangtze River Economic Zone. *J Geog Sci* 30:78–100. <https://doi.org/10.1007/s11442-020-1773-0>
- He J (2007). Environmental impacts of international trade: the case of industrial discharge of sulfur dioxide (SO₂) in Chinese provinces. *Cahiers de recherche*.
- He C, Huang Z, Ye X (2014) Spatial heterogeneity of economic development and industrial pollution in urban China. *Stoch Env Res Risk Assess* 28:767–781. <https://doi.org/10.1007/s00477-013-0736-8>
- Hong Y, Lyu X, Chen Y, Li W (2020). Industrial agglomeration externalities, local governments' competition and environmental pollution: evidence from Chinese prefecture-level cities. *Journal of Cleaner Production*, 123455 <https://doi.org/10.1016/j.jclepro.2020.123455>
- Ke S, Yu Y (2014) The pathways from industrial agglomeration to TFP growth – the experience of Chinese cities for 2001–2010. *Journal of the Asia Pacific Economy* 19:310–332. <https://doi.org/10.1080/13547860.2014.880286>
- Krugman P (1991) Increasing Return and Economic Geography. *J Polit Econ* 99:483–499
- Li Y, Wu H, Shen K, Hao Y, Zhang P (2020) Is environmental pressure distributed equally in China? Empirical evidence from provincial and industrial panel data analysis. *Sci Total Environ* 718:137363. <https://doi.org/10.1016/j.scitotenv.2020.137363>
- Liu Q, Wang Q (2017) How China achieved its 11th Five-Year Plan discharges reduction target: a structural decomposition analysis of industrial SO₂ and chemical oxygen demand. *Sci Total Environ* 574:1104–1116. <https://doi.org/10.1016/j.scitotenv.2016.08.176>
- Liu C, Hong T, Li H, Wang L (2018) From club convergence of per capita industrial pollutant emissions to industrial transfer effects: an empirical study across 285 cities in China. *Energy Policy* 121:300–313. <https://doi.org/10.1016/j.enpol.2018.06.039>
- Liu Q, Wang S, Zhang W, Zhan D, Li J (2018) Does foreign direct investment affect environmental pollution in China's cities? A spatial econometric perspective. *Sci Total Environ* 613–614:521–529. <https://doi.org/10.1016/j.scitotenv.2017.09.110>
- Liu H, Cui W, Zhang M (2022) Exploring the causal relationship between urbanization and air pollution: evidence from China. *Sustain Cities Soc* 80:103783. <https://doi.org/10.1016/j.scs.2022.103783>
- Liu H, Liu J, Li M et al (2022) Assessing the evolution of PM_{2.5} and related health impacts resulting from air quality policies in China. *Environmental Impact Assessment Review* 93:106727. <https://doi.org/10.1016/j.eiar.2021.106727>
- Moran PAP (1948) The interpretation of statistical maps. *J r Stat Soc Ser B-Stat Methodol* 10:243–251
- Ning L, Wang F, Li J (2016) Urban innovation, regional externalities of foreign direct investment and industrial agglomeration: Evidence from Chinese cities. *Res Policy* 45:830–843. <https://doi.org/10.1016/j.respol.2016.01.014>
- Otsuka, Akihiro, Goto M, Sueyoshi T (2014). Energy efficiency and agglomeration economies: the case of Japanese manufacturing industries. *Regional ence Policy & Practice* 6.
- Shen J, Wei YD, Yang Z (2017) The impact of environmental regulations on the location of pollution-intensive industries in China. *J Clean Prod* 148:785–794. <https://doi.org/10.1016/j.jclepro.2017.02.050>
- Shen N, Peng H (2020). Can industrial agglomeration achieve the discharge-reduction effect? *Socio-Economic Planning Sciences*, 100867 <https://doi.org/10.1016/j.seps.2020.100867>
- Song C, Yin G, Lu Z, Chen Y (2022) Industrial ecological efficiency of cities in the Yellow River Basin in the background of China's economic transformation: spatial-temporal characteristics and influencing factors. *Environ Sci Pollut Res* 29:4334–4349. <https://doi.org/10.1007/s11356-021-15964-2>
- Tian X, Gao W, Liu Y, Xu M (2020) Secondary resource curse's formation and transmission mechanism based on environmental externality theory. *Resour Conserv Recycl* 161:104958. <https://doi.org/10.1016/j.resconrec.2020.104958>
- Wang B, Nie X (2016) Industrial agglomeration and environmental governance: the power or resistance. *China Industrial Economics* 12:75–89
- Wang S, Fang C, Wang Y, Huang Y, Ma H (2015) Quantifying the relationship between urban development intensity and carbon dioxide discharges using a panel data analysis. *Ecol Ind* 49:121–131. <https://doi.org/10.1016/j.ecolind.2014.10.004>
- Wang Y, Yan W, Ma D, Zhang C (2018) Carbon discharges and optimal scale of China's manufacturing agglomeration under heterogeneous environmental regulation. *J Clean Prod* 176:140–150. <https://doi.org/10.1016/j.jclepro.2017.12.118>
- Wu Y, Mo Z, Peng Y, Martin S (2018) Market-driven land nationalization in China: a new system for the capitalization of rural homesteads. *Land Use Policy* 70:559–569. <https://doi.org/10.1016/j.landusepol.2017.10.003>
- Xiao Z, Shen Z (2019). The temporal and spatial evolution of population & industrial agglomeration and environmental pollution and the relevance analysis. *Journal of Arid Land Resources and Environment*.
- Yang X, Wang SJ, Zhang WZ, Li JM, Zou YF (2016) Impacts of energy consumption, energy structure, and treatment technology on SO₂ discharges: a multi-scale LMDI decomposition analysis in China. *Appl Energy* 184:714–726. <https://doi.org/10.1016/j.apenergy.2016.11.013>

- Yin G, Liu Y, Wang F (2018) Emerging Chinese new towns: local government-directed capital switching in inland China. *Cities* 79:102–112. <https://doi.org/10.1016/j.cities.2018.02.026>
- Zhang P, Yang D, Zhang Y, Li Y, Shao J (2020). Re-examining the drive forces of China's industrial wastewater pollution based on GWR model at provincial level. *Journal of Cleaner Production*, 121488 <https://doi.org/10.1016/j.jclepro.2020.121309>
- Zhao Y, Zhang J, Nielsen CP (2012) The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO₂ in China. *Atmos Chem Phys* 12:24985–25036. <https://doi.org/10.5194/acpd-12-24985-2012>
- Zheng S, Wang J, Sun C, Zhang X, Matthew E (2019) Air pollution lowers Chinese urbanites' expressed happiness on social media. *Nature Human Behaviour* 3:237–243. <https://doi.org/10.1038/s41562-018-0521-2>
- Zheng S, Kahn M (2013). Understanding China's urban pollution dynamics. *Journal of Economic Literature* <https://doi.org/10.1257/jel.51.3.731>
- Zheng Q, Lin B (2018). Impact of industrial agglomeration on energy efficiency in China's paper industry. *J Clean Prod* <https://doi.org/10.1016/j.jclepro.2018.03.016>

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