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Heterogeneous industrial agglomeration, technological innovation and haze pollution

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ABSTRACT

Haze pollution is becoming more and more prominent in recent years with the development of China's economy. This article studies how different types of industrial agglomeration contribute to haze pollution. Based on a panel data of 264 Chinese cities from 2003 to 2016, a spatial econometric model was adopted to analyze the related variety and unrelated variety impact on haze pollution and further investigate the moderating effect of technological innovation. The results show that: (1) There is an inverted U-shaped relationship between related variety and haze pollution, however, the overall variety aggravates haze pollution. (2) Technological innovation can significantly alleviate haze pollution, and the level of technological innovation can strengthen the inverted U-shaped relationship between variety and haze pollution.

1. Introduction

Haze pollution has been a serious environmental issue with China's economic development in the past four decades (Sun et al, 2016). In 2013, the average number of haze days in China was 30 days. The frequent haze weather involved more than 100 large and medium-sized cities in 25 provinces. The 2016 Global Urban Pollution Database (from the World Health Organization) displays that 30 of the world's top 100 cities with the worst air quality ($PM_{2.5}$ caliber) are in China. In addition, the "2016 China Environmental Status Bulletin" reports that 254 of China's 338 prefecture-level and above cities have failed to meet air quality standards. The compliance rate of ambient air quality in 338 prefecture-level cities was only 35.8% in 2018. This serious haze pollution has had a major impact on people's lives and further regional economic development (Sueyoshi & Yuan, 2015).

Although the existing literature has drawn the conclusion that adjusting the industrial structure is an effective way to reduce pollution on the premise of ensuring a certain amount of economic growth (Chen, Xu, Cui, Huang & Song, 2019; Shi, Zhang, Zhou & Wang, 2020), there is little research on the emission reduction effects of industry spatial structure. As Chen, Zhu and Cheng (2022) pointed out, most of the studies only consider adjusting the inter-industrial structure while ignoring the spatial structure of industry. Given that industrial agglomeration is an important identification method of industrial spatial structure (Brenner, 2006), this paper studies the direct relationship between industrial agglomeration and haze pollution.

Further, the existing literature shows ambiguous results regarding the impact of industrial agglomeration on pollution. Some scholars believe that industrial agglomeration aggravates environmental pollution (Ahmad, Khan, Anser and Jabeen, 2021; Cheng, 2016; Effiong, 2018). Others find that industrial agglomeration can alleviate air pollution (Hosoe & Naito, 2006; Karkalakos, 2010;

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Zeng & Zhao, 2009). Moreover, some studies have shown that the relationship between agglomeration and pollution is nonlinear (Grossman & Krueger, 1995; Zhu & Xia, 2019; Wang & Wang, 2019; He, Huang & Ye, 2014; and Shen & Peng, 2021). A closely related paper Chen et al. (2022) further finds that there is an inverted U-shaped relationship between agglomeration and haze pollution. The possible reason for these inconclusive results is that existing studies have not considered the heterogeneity of industrial agglomeration.

Thus, this paper tries to fill in this gap by discussing the relationship between different types of industrial agglomeration and haze. Different types of industrial agglomeration bring different external effects, which is essential to understand in order to reduce pollution. When enterprises are located in areas with strong inter-industry correlation (related variety), they can make full use of positive externalities due to agglomeration, such as technology spillover and pollution treatment infrastructure (Chen et al., 2022). In contrast to this, enterprises in areas with less inter-industry correlation (unrelated variety) do not have such advantages (Naldi, Criaco & Patel, 2020). Therefore, ignoring the heterogeneity of industrial agglomeration will make its impact on pollution unclear.

This paper decomposes the internal structure of industrial agglomeration into related and unrelated varieties, and examines their impact on haze pollution. Following Frenken, Van Oort & Verburg (2007), related variety is the agglomeration of enterprises with strong correlation in a specific geographical location, while unrelated variety is defined as the agglomeration of weakly related enterprises (The overall variety is simply the sum of related variety and unrelated variety). Using Chinese city level panel data from 2003 to 2016, our spatial econometric model finds that the overall variety aggravates haze pollution. However, there is a nonlinear relationship between related variety and haze pollution in the sense that related variety will increase haze pollution first and then decrease haze pollution. This paper also analyzes the influencing mechanism of related agglomeration on haze, and finds that the level of technological innovation will strengthen the inverted U-shaped relationship between related variety and haze pollution.

Therefore, the main contribution can be summarized in the following three aspects. First, it decomposes the industrial agglomeration into related and unrelated types, and finds different patterns of haze pollution between these two types of agglomeration. Specifically, the related type of industrial agglomeration shows an inverted U-shaped relationship between related variety and haze pollution. This is not the case for the unrelated type. This helps us understand the ambiguous results found in previous studies: the externalities produced by different types of agglomeration are different (Andersson, Larsson & Wernberg, 2019), and thus the impact on the environment will also be different (Li, Xu & Yao, 2021; Zhu & Xia, 2019). Second, this paper takes the level of technological innovation as an exogenous factor, and analyzes how the related effects of agglomeration and technological innovation affect air pollution. Literature indicates that technological innovation is one of the important mechanisms affecting production efficiency and air quality, and that technological innovation has an important impact on the relationship between industrial agglomeration and air quality (Liu & Zhang, 2021; Zheng et al., 2019). Compared with other research (Li et al., 2021; Shi et al., 2020), this paper finds that the level of technological innovation plays a moderating role in the relationship between related variety and air pollution. Finally, although previous studies have explored the relationship between agglomeration and air pollution, air pollution indicators usually chosen include SO_2, CO_2, and nitrogen oxides (Sun & Yan, 2015; Wu, Xu & Tang, 2021). When these harmful gases are discharged into the air, they will further undergo chemical reactions and eventually form haze pollution. Therefore, the study of the relationship between industrial agglomeration and haze pollution adds a more comprehensive study to the existing literature (Li et al.,2021; Chen et al., 2022).

The remainder of this paper proceeds according to the following structure. Section 2 discusses the impact mechanism of industrial agglomeration on haze pollution. The empirical spatial econometric model and data issues will be introduced in Section 3. Section 4 introduces the current situation of industrial agglomeration and haze pollution, respectively. The analysis of the empirical results is in Section 5. Section 6 concludes.

2. Theoretical mechanism

The main research objective is to explore how different types of industrial agglomeration affect haze pollution. To do so, this paper first decomposes industrial agglomeration into related and unrelated varieties based on Frenken et al. (2007), and then calculates the degree of two types of agglomeration using Chinese industrial data. The key difference between them is whether enterprises can take advantage of the positive externalities brought by agglomeration, which is the main reason for the different effects on haze pollution.

First, no matter what types of industrial agglomeration, the haze pollution will be gradually aggravated in the initial stage of aggregation occurrence. In the initial stage of industrial agglomeration, positive externalities caused by agglomeration may be limited. Since environmental protection is not prominent in this stage, the demand for development and expansion is greater than the demand for pollution control. Enterprises usually focus on expanding production and there are no close connections among enterprises regardless of types of agglomeration. Expanding production means that businesses have more demand for energy-related products, which results in increased pollution and environmental degradation (called scale effect following Yi, Wang, Sheng, Sharpb & Zhang, 2020). The scale effect is prominent in this stage, which leads to intensified haze pollution. Therefore, as the degree of industrial agglomeration increases, haze pollution will become more and more serious. Meanwhile, at the beginning of industrial agglomeration, investment in technological innovation is relatively small and thus the level of technology spillover is limited, which also limits the technology spillover effect in terms of pollution emissions. Due to the limitations of related technologies, energy efficiency is relatively low (Han, Xie & Fang, 2018). The technology spillover effect cannot play a role in emission reduction. At the same time, since there are few connections among enterprises in the industrial agglomeration area, there is no competition effect to reduce pollution. Besides, there is limited infrastructure such as the public emission reduction and pollution treatment facilities due to diseconomies of scale. All of these lead to more and more pollution emissions with the increase of industrial agglomeration at this stage. Therefore, there will be a trend of increasing haze pollution in both related variety and unrelated variety. As shown in part AB in Fig. 1.

As the degree of industrial agglomeration further increases, the relationship between industrial agglomeration and haze pollution will be affected by types of industrial agglomeration. The scale effect exists for both related diversity and unrelated diversity that the increase in the degree of industrial agglomeration will lead to more pollution. However, the technology spillover effect and competition effect will have different effects on the two types of agglomeration. When enterprises are located in areas with related variety, the connection among enterprises is relatively close. The technology spillover effect will play an important role (Grabner & Modica, 2022). There may be mutual spillover effects among the technologies of relevant enterprises, and it will gradually form a material recycling system among related enterprises (Boschma & Frenken, 2011). The material recycling system has advantages in resource utilization and in the pollution treatment rate. For resource utilization, similarity in production is conducive to promoting companies with a strong correlation to make full use of raw materials (Aarstad, Kvitastein & Jakobsen, 2016; Boschma & Iammarino, 2009). For pollution treatment, the waste of a certain enterprise will be used by other enterprises through the material recycling system. The utilization rate of resources is thus improved, and it also consumes part of the pollutants brought by enterprises. The formation of the material recycling system will attract more enterprises to join the system as it allows them to reduce production costs to be more competitive. In this case, the amount of haze pollution produced by enterprises located in areas with related variety will decrease due to the technology spillover effect and competition effect. When enterprises are located in areas with strong inter-industry correlated companies, there exists the pollution treatment technology spillover effect. In addition, it is possible to share production infrastructure and pollution treatment infrastructure (Krugman, 1998). This is conducive to the centralized treatment of pollutants, which reduces haze pollution to a certain extent. To sum up, as the degree of related variety further increases, it will help alleviate haze pollution, as shown in part BC in Fig. 1. Hypothesis 1 below summarizes this net effect (the effect when the spillover effects and the competition effects are greater than the scale effect) when the agglomeration type is related variety:

Hypothesis 1. When the agglomeration type of enterprises is related variety, there is an inverted U-shaped curve between industrial agglomeration and haze pollution.

On the other hand, when the type of industrial agglomeration is unrelated variety, there is limited technology spillover and competition effect in the production process and in the treatment of pollution because of the poor relevance of enterprises. Besides, it's also difficult to realize the sharing of infrastructure. In this case, haze will continue to intensify as the degree of unrelated variety increases, as show in part BD in Fig. 1. Hypothesis 2 summarizes this based on the above analysis:

Hypothesis 2. When the agglomeration type of enterprises is unrelated variety, haze pollution will be further aggravated with the increase of agglomeration.

The overall variety consists of related variety and unrelated variety. As discussed above, the pollution at the early stage of production gets worse for the overall variety due to the scale effect. When the degree of agglomeration gets higher, the related variety will have the effect of reducing pollution due to technology spillovers and competition effects; however, the unrelated variety will increase pollution. Combining related variety and unrelated variety together, the technology spillover effect and competition effect on pollution reduction will be greatly weakened. The increase of haze pollution caused by the scale effect may be greater than the decrease of haze pollution caused by technology spillover and competition effect. Based on the above analysis, Hypothesis 3 is proposed as follows.

Hypothesis 3. The overall variety may increase haze pollution if the increase of haze pollution caused by scale effect is greater than the decrease of haze pollution due to technology spillover and competition effects.

Through the above analysis, the positive externalities are mainly reflected in resource utilization and in pollution treatment rate. According to the “Porter Hypothesis”, the “innovation compensation” that stimulates enterprises through technological innovation is an important way to decrease energy usage and alleviate pollution. Therefore, technological innovation and application will affect the efficiency of resource utilization and pollution treatment.

When the type of agglomeration is related variety, it has a positive driving force for enterprise innovation (Aarstad et al., 2016). There are two reasons that enterprises promote technological innovation to improve the overall technical level of resource utilization and pollution treatment. First, the competition among enterprises in the same industry gives enterprises the motivation to make technological improvements and innovations in industrial agglomeration areas. When the technology of one enterprise in the industrial chain improves, the technological innovation of enterprises in complementary industries has a knock-on effect. In this way, the

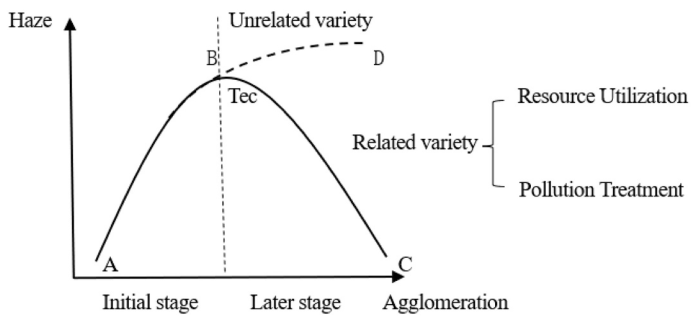

Fig. 1. Mechanism of influence.

technological innovation of a certain enterprise will prompt enterprises in related industries to make technological improvements. Second, the technological innovation risk of a single enterprise can be reduced under the effect of knowledge spillover effects, which will encourage enterprises to carry out R&D activities and increase R&D investment (Hu, 2021). Enterprises with strong connections can realize the complementarity of knowledge and technology, which is conducive to technological innovation. Competition among enterprises will prompt enterprises to improve their production processes and upgrade their technological level to gain a competitive advantage. As a result, the technical level of the entire agglomeration area can be improved. Since the relevance among unrelated industries is limited, the exchanges among enterprises in terms of technology and input/output are small. The effect of technological innovation among these industries is greatly restricted. In addition, the competitive pressure among relatively independent enterprises is low, which lowers their motivation for technological innovation.

As the number of enterprises in the agglomeration areas continues to increase, the technology spillover effects will gradually appear in production technologies and pollution reduction technologies (Fujita, Krugman & Venables, 2001; Lai, Hsu, Lin, Chen & Lin, 2014; Ma, Murshed & Khan, 2021). When the production technology or pollution reduction technology of one enterprise in the agglomeration area is innovated, other enterprises with a strong correlation can imitate and learn the new technology. In this way, the overall production technology level and pollution treatment technology level in the agglomeration area will be improved. Besides, the competitive pressure brought by a certain enterprise's technological innovation will stimulate other enterprises to strengthen self-learning and innovation to enhance their own competitiveness. This promotes the dissemination of knowledge and technology in agglomeration areas. The result of the technology spillover effect, will be to promote the technological innovation and upgrading of the entire agglomeration area to improve the overall technological level.

Nevertheless, when the type of agglomeration is unrelated variety, the technological innovation of a certain enterprise cannot be widely used due to the large differences in production between enterprises. Meanwhile, the technology spillover effect cannot play a corresponding role.

In summary, compared with unrelated variety, related variety based on industrial association is more conducive to promoting technological innovation and thus improving the overall technical level of the agglomeration area. The average technology level in the region is important for industrial agglomeration to affect haze pollution. When the agglomeration level of a region reaches a certain level, the relationship between the degree of industrial agglomeration and haze pollution depends on the type of industrial agglomeration. Different types of agglomeration differ in promoting the average technical level of an agglomeration area. Related variety is stronger than unrelated variety in promoting technological innovation and technology spillover effects, and it is more conducive to alleviating haze pollution. Based on the above analysis, Hypothesis 4 is proposed as follows.

Hypothesis 4. Technological innovation can help reduce haze pollution and strengthen the relationship between related variety and haze pollution.

3. Industrial agglomeration level and haze pollution

3.1. Calculation of industrial agglomeration indicators

This paper follows Frenken et al. (2007) in the classification of industrial agglomeration. Frenken et al. (2007) described the level of variety v with entropy index as:

$$v = \sum_{j=1}^{n} p_j ln\left(\frac{1}{p_j}\right) \tag{1}$$

Where p_j is the employment share of industry j ($j = 1, 2, \ldots, n$) in one area. If there is only one sector in a region ($p_j = 1$), the entropy value is 0, when the level of industry variety is the lowest. If $p_1 = p_2 = \ldots = p_n = 1/n$, the entropy value is the maximum, indicating that the industry has the highest degree of variety.

It is assumed that there are M major sectors in the economic system, and the M major sectors are subdivided into n sub-sectors ($n \geq m$). For each major sector m ($m = 1, 2, \ldots, M$), the proportion of employed persons is the sum of the proportions of employed persons in sub-sectors:

$$P_m = \sum_{t \in m} p_t \tag{2}$$

And the level of industry variety is:

$$v_m = \sum_{t \in m} \left(\frac{p_t}{P_m}\right) ln\left(\frac{P_m}{p_t}\right) \tag{3}$$

In the economic system, the product of the internal variety entropy index of a major sector and the sector's share P_m is used to measure related variety, indicating the level of variety among sub-industries with strong correlations in industry, namely:

$$Related\ \ variety = \sum_{m=1}^{M} P_m v_m \tag{4}$$

The variety entropy index among M sectors is used to measure unrelated variety, indicating the level of industry variety with a low level of industrial relevance, namely:

$$Unrelated\ \ variety = \sum_{m=1}^{M} P_m ln\left(\frac{1}{P_m}\right) \tag{5}$$

According to the characteristics of the entropy index, the overall variety level can be decomposed into the sum of related variety and unrelated variety (Frenken et al., 2007):

$$Overall\ \ variety = Related\ \ variety + Unrelated\ \ variety \tag{6}$$

In terms of industry classification, this paper mainly follows Sun & Chai (2012) to take 19 sectors in the statistical yearbook as sub-sectors in industry classification. Based on 19 sub-sectors, six major sectors have been identified including the primary industry, the secondary industry, the producer service industry, the consumer service industry, the circulation service industry and the social service industry.

3.2. Industrial agglomeration level

This paper uses the number of employees of each industry at the end of the year to calculate the index of industrial agglomeration according to the above formula. The top 30 cities with the average value of agglomeration index are listed in Table 1. Beijing has the highest overall variety index and unrelated variety level, but its related variety ranks low. As the center of politics, economics and culture in China, Beijing has shown vigorous development vitality in a variety of industries while the relevance of the industries is loose. Similarly, Suzhou has a low level of related variety as the employment in the secondary industry accounts for more than 60% of the employment, and the manufacturing industry accounts for more than 90% of the employment in the secondary industry. Correspondingly, Wuhai ranks first in the related variety index. The possible reason for this is that the variety level of industry segmentation within the secondary industry is high. Extractive industries, manufacturing, electricity, gas and water production, and construction all occupy a certain proportion of employment in Wuhai. It is worth noting that most of the top 30 cities in the related variety index are located in the mid-west region while the related variety degree of the eastern coastal cities is relatively low. The possible reason for this lies in the mature economic development in eastern China, which no longer blindly pursues the variety development of industries. Based on their resource endowment and comparative advantages, regions give priority to the development of advantageous industries, so industrial agglomeration is more inclined to specialization.

3.3. Haze pollution

The haze concentration in China has been much higher than the safe range in recent years. Based on the *Air Quality Guidelines* issued by the World Health Organization (WHO) in 2005, the annual average $PM_{2.5}$ value needs to be less than 10 μg/m^3, as a safe range. The average $PM_{2.5}$ concentration had fluctuated around 31–41 μg/m^3 from 2003 to 2016 (Fig. 2). China has adopted the standard of Transitional Objective 1 in the WHO Air Quality Guidelines as China's air quality standards. According to the "Ambient Air Quality Standards" promulgated by the *Ministry of Environmental Protection of China* in 2012, the annual average $PM_{2.5}$ value of less than 35 micrograms/cubic meter is a safe value. Deviations from the overall trend include a slight rise before 2007 while there is an overall declining trend after 2007. Although there has been a downward trend in recent years, the annual average concentration of $PM_{2.5}$ exceeded the safe standard in most years.The maximum concentration of $PM_{2.5}$ in China is 77.73 μg/m^3 between 2003 and 2016 on average. In 2006, it reached 90.86 μg/m^3, which is the highest value of this period. The cities with the largest distribution are mainly in Hebei and Shandong, including Hengshui, Cangzhou, Dezhou, and Langfang. This is mainly due to the industrial structure of the two provinces. They are dominated by industry, and most of them are labor-intensive and resource-intensive industries. To sum up, whether from the average or from the maximum concentration of $PM_{2.5}$, China's air quality is still not great.

Figs. 3-5 captures China's spatial distribution of $PM_{2.5}$ concentration in the years 2003, 2006, and 2016. $PM_{2.5}$ concentration is divided into five levels, and the five colors from light to dark in the figure represent the first to fifth levels of $PM_{2.5}$ concentration.[1] Overall, the $PM_{2.5}$ concentration showed an increasing trend; meanwhile, some provinces showed an increasing and then decreasing trend. In 2003, the $PM_{2.5}$ concentration in the first-tier provinces was 2.44–20.3 μg/m^3, and the $PM_{2.5}$ concentration in the fifth-tier provinces was 47.17–64.85 μg/m^3 (Fig. 3). In 2016, the $PM_{2.5}$ concentration in the first-tier provinces was 3.20–19.31 micrograms/m^3, and the $PM_{2.5}$ concentration in the regional-level provinces was 50.85–70.79 micrograms/m^3 (Fig. 5). Interestingly, Anhui, Sichuan, Hubei, and Chongqing show a trend of increasing first and then decreasing. For example, the $PM_{2.5}$ concentration in Sichuan Province was 34.25 μg/m^3 in 2003 (Fig. 3), and it increased to 39.19 μg/m3 in 2010 (Fig. 4); however, by 2016, the $PM^{2.5}$ concentration was 25.67 μg/m^3 (Fig. 5).

Geographically, most of the provinces with the lowest $PM_{2.5}$ concentration belong to the western region, and the provinces with the highest $PM_{2.5}$ concentration are the eastern and central regions. The provinces with the lowest $PM_{2.5}$ concentrations are Xinjiang, Inner Mongolia, Qinghai and Tibet, while the provinces with the highest $PM_{2.5}$ concentrations are Shandong, Jiangsu, Henan, Hebei, Tianjin, Shanghai and Anhui. The economic development level in the eastern and central regions is high, and thus the pollution situation is

[1] The map haze data is based on the provincial level, using 285 cities, and the provincial data is replaced by the average haze concentration of the cities. Areas with missing data are rendered blank in the map, including Taiwan Province and Tibet.

Table 1
Top 30 cities' overall variety, related variety and unrelated variety index.

Rank	City	Overall variety index	City	Related variety index	City	Unrelated variety index
1	Beijing	2.67	Wuhai	1.22	Beijing	1.60
2	Haikou	2.60	Daqing	1.21	Sanya	1.59
3	Jiuquan	2.59	Chenzhou	1.21	Haikou	1.59
4	Urumqi	2.59	Dazhou	1.19	Jiamusi	1.55
5	Hohhot	2.59	Fushun	1.19	Mudanjiang	1.53
6	Yinchuan	2.58	Handan	1.19	Hulunbuir	1.53
7	Nanning	2.52	Guangyuan	1.18	Qiqihar	1.50
8	Xining	2.51	Yinchuan	1.18	Fangchenggang	1.49
9	Jinzhou	2.49	Weinan	1.17	Urumqi	1.48
10	Tieling	2.49	Fuxin	1.17	Nanning	1.46
11	Lijiang	2.49	Hechi	1.16	Harbin	1.46
12	Kunming	2.48	Taiyuan	1.16	Jiuquan	1.45
13	Zhangye	2.48	Huaihua	1.16	Shanghai	1.45
14	Guilin	2.48	Tieling	1.16	Guangzhou	1.44
15	Shenyang	2.47	Hohhot	1.16	Huhehot	1.43
16	Dandong	2.47	Leshan	1.15	Jixi	1.43
17	Harbin	2.47	Yulin	1.15	Jinzhou	1.43
18	Beihai	2.45	Puyang	1.15	Baicheng	1.42
19	Taiyuan	2.45	Dandong	1.15	Bayannur	1.42
20	Zhangjiajie	2.45	Zhengzhou	1.14	Zhoushan	1.41
21	Bayannur	2.45	Zhangjiajie	1.14	Baishan	1.41
22	Hangshan	2.45	Ya'an	1.14	Heihe	1.41
23	Sanya	2.45	Xingtai	1.14	Zhanjiang	1.41
24	Daqing	2.44	Lanzhou	1.14	Kunming	1.41
25	Chifeng	2.44	Xining	1.14	Yinchuan	1.41
26	Cangzhou	2.44	Jiuquan	1.13	Beihai	1.40
27	Baishan	2.44	Pingdingshan	1.13	Hegang	1.40
28	Zhangjiakou	2.44	Zhangjiakou	1.13	Tongliao	1.40
29	Weinan	2.44	Zaozhuang	1.13	Zhangye	1.39
30	Changchun	2.43	Taian	1.13	Shenyang	1.39

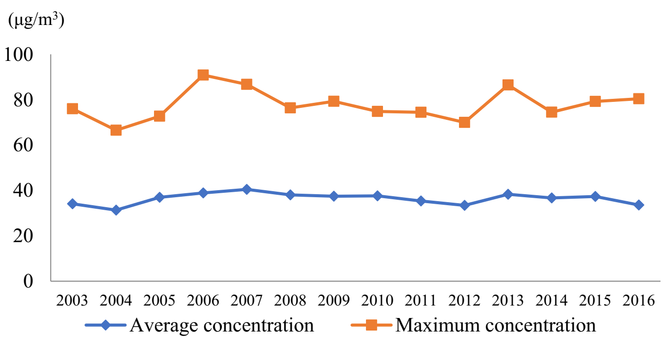

Fig. 2. Annual changes of haze pollution.

serious. Besides, it can also be seen from the figures that these heavily polluted areas are adjacent in spatial distribution and air pollution which has obvious mutual dependence.

Fig. 6 shows the spatial distribution of the related variety in the year 2016.[2] Combined with the spatial distribution of $PM_{2.5}$ concentration, it can be found that the related variety levels in the western regions are high, while haze pollution is light. Compared with the central and western regions, the related variety level in the eastern region is lower, while the haze pollution situation is more serious. Whether haze pollution can be further reduced by enhancing the related variety remains to be tested empirically.

4. Model and data source

4.1. Econometric models and variables

Following the existing literature (Marbuah & Amuakwa-Mensah, 2017; Yuan, Feng, Lee & Cen, 2020), a spatial econometric

[2] The data in the Tibet is missing, so the related variety index cannot be obtained.

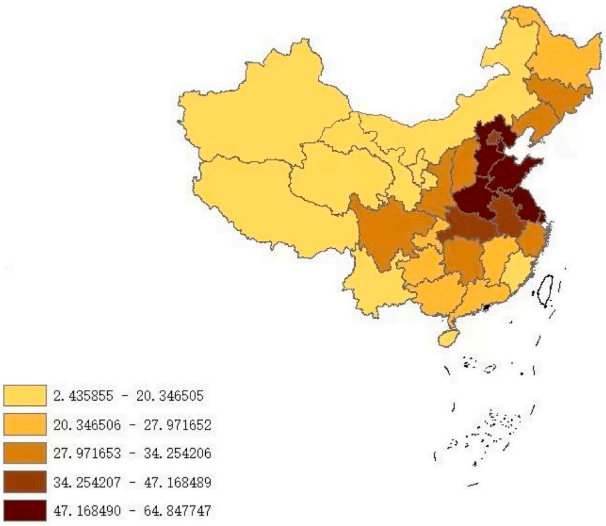

Fig. 3. Spatial distribution map of haze concentration in 2003.

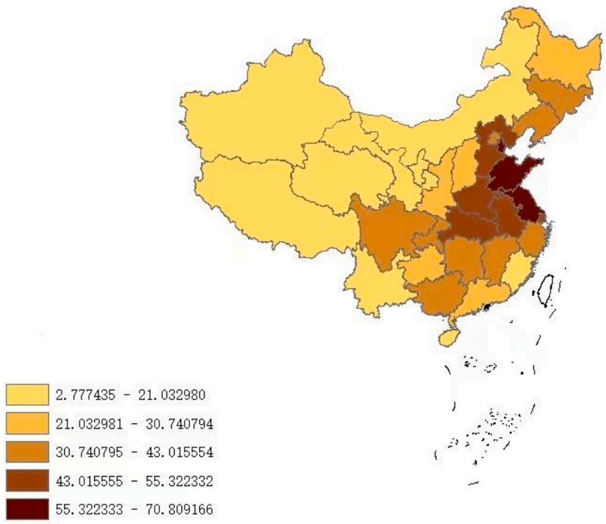

Fig. 4. Spatial distribution map of haze concentration in 2010.

method will be used to test the impact of industrial agglomeration on haze pollution. Since the static spatial panel model may ignore some important factors, such as resident behavior, construction and traffic pressure, the first-order lag term of $PM_{2.5}$ is used as an explanatory variable to capture the impact of those missing variables on haze pollution. Thus, it is necessary to establish a dynamic spatial econometric model. The commonly used spatial analysis methods are the spatial lag model (SLM), spatial error model (SEM), and spatial Durbin model (SDM).

The selection of the spatial model needs to be determined by tests. The general approach is to perform three tests: Lagrange Multiplier (LM) test (Robust), Likelihood Ratio (LR) test, and the Wald test. The significant results of LM-lag, LM-error, and Robust LM test indicate that there is a significant spatial dependence in the model. Both the LR test and the Wald test reject the null hypothesis, indicating that the spatial Durbin model is more suitable at this time. In addition, between a fixed effect and a random effect model, the Hausman test indicates that a fixed effect is preferred. Therefore, the double fixed space Durbin model is adopted for the following analysis.

According to the theoretical analysis of the relationship between different agglomeration types and haze pollution, this paper takes the annual average haze concentration as the explained variable, and the agglomeration (including overall variety, related variety, unrelated variety) and technology as the core explanatory variables. The square term of agglomeration is added to the model to test the potential nonlinear relationship as follows:

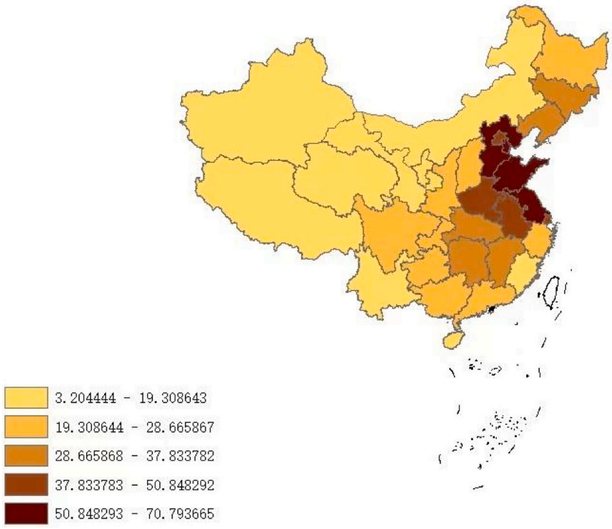

Fig. 5. Spatial distribution map of haze concentration in 2016.

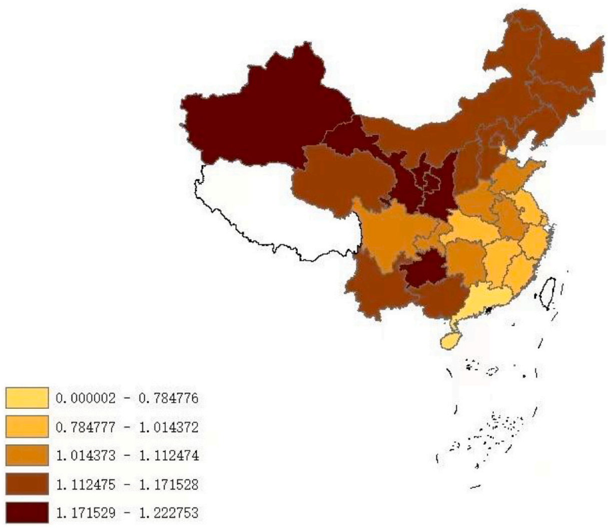

Fig. 6. Spatial distribution map of Related variety in 2016.

$$\begin{aligned} lnPM_{it} = {} & \alpha_0 + \alpha_1 lnPM_{i(t-1)} + \alpha_2 A_{it} + \alpha_3 A_{it}^2 + \alpha_4 Tech_{it} + \boldsymbol{\theta}\mathbf{X} + \eta_1 \mathbf{W} lnPM_{it} \\ & + \eta_2 \mathbf{W} lnPM_{i(t-1)} + \eta_3 \mathbf{W} A_{it} + \eta_4 \mathbf{W} A_{it}^2 + \eta_5 \mathbf{W} Tech_{it} + \boldsymbol{\lambda}\mathbf{W}\mathbf{X} + \varepsilon_{it} \end{aligned} \tag{7}$$

In addition, the model below tests whether the technological innovation is the moderator between agglomeration and haze pollution:

$$\begin{aligned} lnPM_{it} = {} & \beta_0 + \beta_1 lnPM_{i(t-1)} + \beta_2 A_{it} + \beta_3 A_{it}^2 + \beta_4 Tech_{it} + \boldsymbol{\gamma}\mathbf{C} + \rho A_{it} {}^* Tech_{it} \\ & + \omega_1 \boldsymbol{W} lnPM_{it} + \omega_2 \boldsymbol{W} lnPM_{i(t-1)} + \omega_3 \boldsymbol{W} An_{it} \\ & + \omega_4 \boldsymbol{W} A_{it}^2 + \omega_5 \boldsymbol{W} A_{it} {}^* Tech_{it} + \boldsymbol{\delta}\mathbf{W}\mathrm{C} + \mu_{it} \end{aligned} \tag{8}$$

Where *i*, *t* refers to city *i* in year *t*. PM_{it} represents the average annual $PM_{2.5}$ concentration; $PM_{i(t-1)}$ denotes the lagging one-period of $PM_{2.5}$ concentration. A_{it} represents industrial agglomeration. Based on the classification of industrial agglomeration, the main indicators of industrial agglomeration are as follows: $Overall_{it}$ represents the overall variety; $Related_{it}$ is the related variety; $Unrelated_{it}$ is the unrelated variety. $Tech_{it}$ represents technological innovation. **X** and **C** include all control variables. α_0, α_1, α_2, α_3, α_4, $\boldsymbol{\theta}$, η_1, η_2, η_3, η_4, η_5, λ, β_1, β_2, β_3, β_4, $\boldsymbol{\gamma}$, ρ, ω_1, ω_2, ω_3, ω_4, ω_5, $\boldsymbol{\delta}$ represents the regression coefficient, and ε_{it}, μ_{it} represents the error term. **W** is the spatial weight matrix. Considering the influence of geographic distance and economic distance, this paper establishes an economic spatial weight matrix. The specific form is as follows:

$$W = w^{*} diag\left(\frac{\overline{y}_1}{\overline{y}}, \frac{\overline{y}_2}{\overline{y}}, \quad \ldots, \frac{\overline{y}_n}{\overline{y}}\right), \overline{y}_i = \frac{1}{t_1 - t_0 + 1}\sum_{t_0}^{t_1} y_{it}, \overline{y} = \frac{1}{n(t_1 - t_0 + 1)}\sum_{i=1}^{n}\sum_{t_0}^{t_1} y_{it} \quad (9)$$

Where w is the inverse distance space matrix. The matrix element $w_{ij} = 1/d_i \ (i \neq j)$, if $i = j$, it is 0, where d_{ij} represents the spatial distance between the two places, and y is the regional GDP.

The annual average $PM_{2.5}$ concentration of each city is used as the explained variable to measure haze, which is the concentrated manifestation of the pollution caused by agglomeration and more representative of air pollution than other air pollution emissions, such as SO_2, CO_2, and nitrogen oxides. It is measured as the specific value of the annual average $PM_{2.5}$ concentration in Chinese cities from 2003 to 2016. The overall variety index , the related variety and unrelated variety index and technology are used as core explanatory variables to explore the impact of agglomeration on haze pollution. Since patents are closely related to technological innovation, and patent standards are relatively objective, this paper uses the total number of patents granted in each city each year to measure the level of technological innovation.

Control variables in the model include GDP per capita, Education level , Openness level, Economic structure, Urban Greening Level, Population size, Environmental regulations (Fang & Yu, 2021; Yuan et al., 2020), and other control variables as shown in Table 2. Existing research shows that the impact of regional economic development on the level of environmental pollution cannot be ignored (Liu, Sadiq, Ali & Kumailc, 2022). The level of education will affect the level of production technology. The more educated resident has stronger awareness of environmental protection, and they will pay more attention to environmental quality. They are also willing to purchase more environment-friendly products (Cordier, Uehara, Baztan, Jorgensen & Yan, 2021). The construction of urban infrastructure will not only promote local economic development, but will also affect energy and production utilization rates (Krugman, 1991). The construction of pollution disposal infrastructure will also have an impact on the ecological environment (Chen et al., 2022). The expansion of the regional industry can bring economies of scale, improve energy efficiency, and reduce environmental pollution. With industrial expansion, it appears that an increase in input may increase environmental pollution. The adjustment of the industrial structure means a change in the mode of production, which affects the situation of environmental pollution (Chen et al., 2019; Shi et al., 2020). The degree of regional openness and government environmental regulations are also important factors. Table 3 summarizes descriptive statistics of variables used in this paper.

4.2. Data source

This paper uses the panel data of 264 prefecture-level cities in China from 2003 to 2016. The data of haze pollution comes from the raster data of the annual average $PM_{2.5}$ concentration of the world based on satellite monitoring published by the Social Economic Data and Application Center of Columbia University. The data indicators are obtained by transforming satellite data with high credibility. The data used for the calculation of the industrial agglomeration level comes from the employment statistics of 19 sub-industries in the China City Statistical Yearbook. The patent data for measuring technological innovation comes from the China Research Data Service Platform. The remaining data of main variables and control variables come from China City Statistical Yearbook. Meanwhile, all currency quantities are adjusted according to the related price index to a comparable price based on 2003.

5. Empirical results

5.1. Spatial correlation test

In order to comprehensively investigate the spatial effects of industrial agglomeration and haze pollution, Global Moran's I and Local Moran's I on spatial data analysis are used to analyze the spatial autocorrelation. As shown in Table 4, there exists a significant positive relationship between the Global Moran's I of haze pollution and industrial agglomeration.[3] It means that both industrial agglomeration and haze pollution have strong spatial dependence, and the impact of haze across regions is very significant.

In order to further illustrate the spatial correlation of China's haze pollution, the three-year data of 2003, 2010, and 2016 was selected for local spatial correlation tests (Fig. 7). The scatter plot of Local Moran's I shows that the haze pollution in most cities is located in the first and third quadrants of the scatter plot, indicating that the spatial agglomeration characteristics of haze are high-high and low-low agglomeration dominant. There are fewer cities with high-low and low-high agglomeration types. This result is similar to the result of the Global Moran value test; the haze pollution presents an obvious positive correlation in space.

5.2. Analysis of the impact of industrial agglomeration on haze pollution

The empirical models test the relationship between different types of agglomeration and haze pollution respectively, using a potential quadratic function of the agglomeration index to examine the potential nonlinear relationship between agglomeration and haze pollution. Further, the interaction term of agglomeration and technological innovation is added to the model to examine the moderating impact of the technological level on haze pollution.

[3] The Moran's I is generally used to test whether a variable is spatially correlated. Moran's I is divided into Global Moran's I and Local Moran's I. The Global Moran's I only indicates whether there is agglomeration in space, and the Local Moran's I can indicate where and what kind of agglomeration occurs.

Table 2
Definition of variables.

	Variable	Definition
Explained variable	*$PM_{2.5}$*	Haze pollution ($PM_{2.5}$ concentration)
Core explanatory variables	*Overall*	The overall variety
	Related	The related variety
	Unrelated	The unrelated variety
	Percent	The related variety/ The overall variety
	Tech	Technique level (number of patents granted)
Control variables	*$PM_{2.5\ (-1)}$*	Lagging item of haze pollution
	Edu	Education level (Education expenditure / government fiscal expenditure)
	GDP	GDP per capita
	Open	Openness level (expenditure of direct foreign investment/GDP)
	Scale	Industrial scale (fixed asset investment)
	Structure	Economic structure (The proportion of the output value of the primary industry * 1 + the proportion of the output value of the secondary industry * 2 + the proportion of the output value of the tertiary industry * 3)
	Green	Urban Greening Level (Per capita green area in municipal districts)
	Population	Population size (Total population at the end of the year)
	Investment	• Investment in pollution control (Investment in pollution control/GDP)

Table 3
Descriptive statistics.

Variable	N	Mean	Sd.	Min	Max
$PM_{2.5}$	3696	36.26	15.71	4.517	90.86
$PM_{2.5\ (-1)}$	3696	35.95	15.60	4.517	90.86
Overall	3696	2.237	0.225	0.961	2.706
Related	3696	1.001	0.146	0.22	1.273
Unrelated	3696	1.236	0.148	0.609	1.714
Percent	*3696*	0.447	0.045	0.209	0.562
Tech	3696	2427	7143	3	102,205
Edu	3696	0.187	0.046	0.0177	0.494
GDP	3696	22,256	17,510	73.96	289,356
Open	3696	0.0213	0.0236	1.00E-05	0.376
Scale	3696	7.41E+06	9.78E+06	122,170	1.30E+08
Structure	3696	222.6	14.09	182.2	279.7
Green	3696	39.29	55.61	0.571	1179
Population	3696	438.5	307.2	41.6	3392
Investment	3696	1.223	0.574	0.3	4.24

Table 4
Global Moran's I of haze pollution and industrial agglomeration.

Year	*P*	*v*	*Related*	*Unrelated*
2003	0.207***	0.031***	0.059***	0.023***
2004	0.154***	0.056***	0.09***	0.027***
2005	0.162***	0.063***	0.097***	0.023***
2006	0.173***	0.076***	0.108***	0.031***
2007	0.183***	0.091***	0.122***	0.038***
2008	0.167***	0.085***	0.12***	0.034***
2009	0.173***	0.071***	0.117***	0.025***
2010	0.183***	0.088***	0.126***	0.041***
2011	0.167***	0.09***	0.127***	0.039***
2012	0.161***	0.100***	0.131***	0.036***
2013	0.192***	0.128***	0.164***	0.036***
2014	0.159***	0.119***	0.154***	0.043***
2015	0.227***	0.109***	0.131***	0.038***
2016	0.222***	0.103***	0.132***	0.037***

The results are presented in Table 5. In the overall variety model (model 1), the significant positive regression coefficient of overall variety shows that the current increase in variety will aggravate haze pollution. The coefficient of technological innovation is significantly negative, indicating that improvement of the technological innovation level is beneficial in alleviating haze pollution. After adding the square term (model 2), the coefficient of the quadratic term is not significant, which shows that there is no non-linear relationship between the overall variety and haze pollution. Therefore, the empirical results show that with the increase of overall

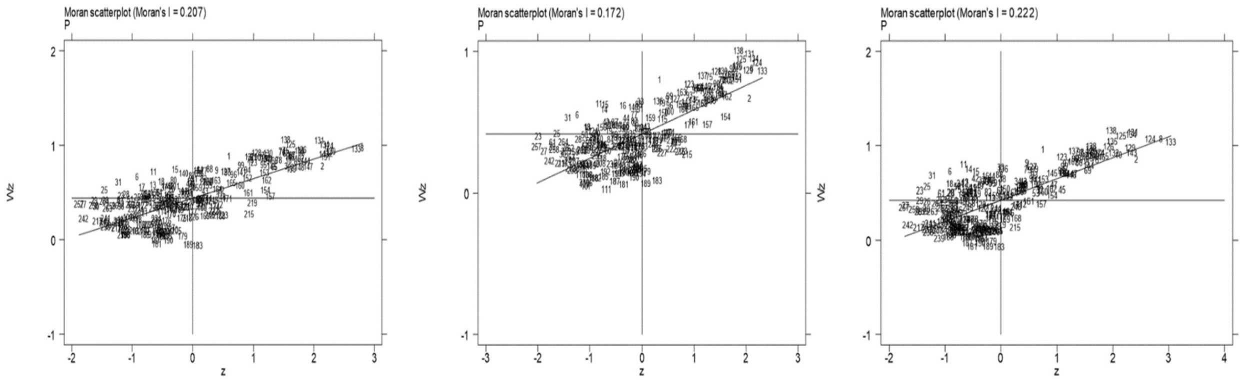

Fig. 7. Local Moran's I scatter plots of haze pollution in 2003 (left), 2010 (middle), and 2016 (right).

variety, haze pollution will continue to increase, which is consistent with Hypothesis 3.

In order to show the impact of different types of agglomeration on haze pollution, Table 5 further reports the impact of related variety and unrelated variety on haze pollution separately. The coefficient of related variety is significantly positive at the 1% level (model 3), indicating that the current increase in the related variety level will aggravate haze pollution. Model 4 further shows that there is an inverted U-shape relationship between related variety and haze pollution. As discussed in Hypothesis 1, related enterprises can realize the sharing of production infrastructure and pollution treatment infrastructure, effectively increasing the pollution treatment rate. For example, many industrial parks in Henan Province transformed the traditional linear economy model "resources-products-waste" into a circular economy model of "resources-products-renewable resources" by establishing waste treatment facilities. This greatly enhances the pollution treatment capacity in the park. The premise of the operation of the circular economy model is that

Table 5
Spatial Dubin Model of the Overall Variety, Related Variety and Unrelated Variety.

	Haze pollution						
	(1)	(2)		(3)	(4)	(5)	(6)
Overall	0.096***	0.116					
	(3.401)	(1.157)					
Overall²		−0.016					
		(−0.664)					
Related				0.118***	0.509***		
				(4.879)	(4.396)		
Related ²					−0.220***		
					(−3.446)		
Unrelated						0.013	0.158
						(0.598)	(1.053)
Unrelated ²							−0.061
							(−0.975)
	ln(Tech)	−0.011**	−0.012***	−0.010**	−0.011***	−0.010**	−0.011***
		(−2.614)	(−2.912)	(−2.471)	(−2.601)	(−2.584)	(−2.559)
	W Overall*	0.020	3.168***				
		(0.204)	(5.748)				
	W Overall²*		−0.823***				
			(−5.787)				
	W Related*			0.594***	2.971***		
				(3.504)	(4.089)		
	W Related²*				−1.339***		
					(−3.285)		
	W Unrelated*					−0.426***	5.227***
						(−2.705)	(4.794)
	W Unrelated²*						−2.407***
							(−5.239)
	W ln(Tech)*	−0.167***	−0.198***	−0.147***	−0.165***	−0.192***	−0.173***
		(−5.420)	(−6.371)	(−4.818)	(−5.338)	(−6.325)	(−5.338)
Controls	Yes	Yes		Yes	Yes	Yes	Yes
City FE	Yes	Yes		Yes	Yes	Yes	Yes
Year FE	Yes	Yes		Yes	Yes	Yes	Yes
Observations	3696	3696		3696	3696	3696	3696
R^2	0.973	0.974		0.974	0.974	0.973	0.974

Note: t statistics in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, applies to all tables below.

there is a certain correlation between industries.

In comparison, there is no significant inverted U-relationship between unrelated variety and haze pollution, as shown in model 6. This may be due to the fact that unrelated variety cannot share the positive externalities that decrease pollution. At the same time, there is a positive relationship between unrelated variety and haze pollution (model 5). This shows that with the increase of irrelevant diversity, haze pollution will be further aggravated. This is consistent with the expectations mentioned above. However, the coefficient is not significant as it is difficult to distinguish between 'within the industry' and 'between industries' in unrelated variety. For example, the increase in unrelated variety could be from within the manufacturing industries, which is likely to increases haze pollution. It could also come through different industries such as service industries, which are likely to decreases haze pollution. This is worth exploring in future research.

Note that the turning point in the related variety quadratic relationship is 1.15. This value is larger than most cities' related variety value in China (the mean value is 1.001 in China). That means that the level of related variety has not yet reached the peak point for most Chinese cities. Together with insignificant results of unrelated variety, this may lead to a positive relationship between overall diversity and haze pollution (model 1 and 2). In addition, from the above empirical regression results (from model 1 to model 6), it can be found that technology has a significant negative impact on haze pollution.

5.3. *Robustness test*

According to the agglomeration index calculation formula (1), the overall variety is the sum of related variety and unrelated variety. Section 4 has verified the inverted U-shaped relationship between related variety and haze pollution in absolute terms. In order to further check the robustness of the results, the proportion of related variety in the overall variety (*Percent*) is selected as an explanatory variable.

The estimation results in Table 6 show that there is an inverted U-shaped curve relationship between the proportion of related variety and haze pollution. The inflection point of the inverted U-shaped curve is about 0.47. It shows that when the proportion of related variety is low, the variety agglomeration aggravates haze pollution; when regional variety agglomerations tend to be more related, agglomeration alleviates haze pollution, which is consistent with the previous results.

5.4. *The moderating effect of technological innovation*

In order to verify the key role of technological innovation in influencing the relationship between agglomeration and haze pollution, the interaction term of agglomeration and technology was added to the model. It can be seen from Table 7 that the regression coefficient of the interaction term between the overall variety level and technological innovation is significantly negative (model 9), and the interaction term of related variety and technological innovation is also negative (model 10). It shows that technological innovation plays an important role in regulating the relationship between variety and haze pollution. The improvement of the level of technological innovation can slow down the aggravating effect of agglomeration on haze pollution. The interaction term of related variety and technological innovation is significantly negative. When the level of technological innovation increases, the inflection point of the inverted U-shaped curve will become smaller. The main reason lies in two aspects: first, the improvement of technological innovation level itself can alleviate haze pollution; second, the sharing of knowledge and technology between related enterprises can significantly improve the level of technological innovation in the agglomeration area, thereby alleviating haze pollution. The synergy between agglomeration and technological innovation can significantly improve production efficiency and achieve full utilization of resources. Therefore, in the mechanism of related variety's impact on haze pollution, technological innovation has played a key role in strengthening the inverted U-shape relationship between the two, which is consistent with Hypothesis 4. As expected, the regression coefficient of the interaction term between the unrelated variety level and technological innovation is not significant (model 11).

6. Conclusion and policy implications

This paper examines the impact of different types of agglomeration on haze pollution. An index is generated to separate related variety from the overall variety. This decomposition helps us understand the ambiguous findings of previous studies on the relationship between industrial agglomeration and air pollution. Based on the panel data of 264 prefecture-level cities in China from 2003 to 2016, the proposed hypotheses are tested using the spatial Dubin model. The main conclusions are as follows:

First, there is an inverted U-shaped relationship between related variety and haze pollution. Related variety aggravates the pollution and then alleviates it. At present, the level of related variety in most Chinese cities is still before the inflection point (1.15) of the inverted U-shape, and the increase in the agglomeration level at this time will increase haze pollution.

Second, technological innovation can alleviate the aggravating effect of agglomeration on haze pollution, and the level of technological innovation can strengthen the inverted U-shaped relationship between related variety and haze pollution. When the level of technological innovation is low, the increase in the agglomeration level will aggravate the haze pollution. When the level of technological innovation rises, the related variety will cross the inflection point of the inverted U-shaped curve, thereby alleviating haze pollution.

Finally, there is a positive relationship between overall variety and haze pollution. Although the related variety to a certain extent can inhibit the haze pollution, unrelated variety dilutes the emission reduction effect caused by the technology spillover effect and competition effect. Since the overall variety consists of related variety and unrelated variety, the final relationship depends on the trade-off between the two types of agglomeration. In the empirical study, the effect of pollution reduction is small due to the low level

Table 6
The Relationship between the Proportion of Related Variety and Haze Pollution.

	Haze pollution		
	(7)		(8)
Percent	0.319***		2.653***
	(4.339)		(4.728)
Percent^2			−2.776***
			(−4.182)
	ln(Tech)	−0.01**	−0.009**
		(−2.422)	(−2.249)
Controls	Yes		Yes
City FE	Yes		Yes
Year FE	Yes		Yes
Observations	3696		3696
R^2	0.974		0.974

Note: t statistics in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, same for all tables below.

Table 7
The Moderating Effect of Technological innovation on haze.

	Haze pollution			
	(9)		(10)	(11)
Overall	0.372***			
	(2.738)			
Overall ^{2}	−0.057**			
	(−1.987)			
Related			0.716***	
			(2.993)	
Related^2			−0.282***	
			(−4.018)	
Unrelated				0.212
				(0.950)
Unrelated^2				−0.072
				(−0.914)
ln(Tech)	0.007		−0.011***	−0.010**
	(0.867)		(−2.599)	(−2.371)
*Overall * ln(Tech)*	−0.024**			
	(−2.732)			
Related ln(Tech)*			−0.013**	
			(−2.225)	
Unrelated ln(Tech)*				−0.002
				(−0.296)
	W Overall*	1.707		
		(1.507)		
	W Related*		2.656	
			(1.583)	
	W Unrelated*			−2.265
				(−1.162)
	W Overall * ln(Tech)*	0.123		
		(1.551)		
	W Related** ln*(Tech)*		0.010	
			(0.193)	
	W Unrelated* ln(Tech)*			0.382***
				(4.643)
Control		Yes	Yes	Yes
City FE		Yes	Yes	Yes
Year FE		Yes	Yes	Yes
Observations		3696	3696	3696
R^2		0.974	0.974	0.974

Note: t statistics in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, same for all tables below.

of related variety in most cities in China. The overall variety will further contribute to the increase of haze pollution.

The findings of this paper provide important policy implications on mitigating haze pollution by rationally arranging industrial agglomeration. First, while considering increasing the variety of local industries, local governments should try their best to appropriately introduce relevant enterprises that have a high degree of association with local enterprises, so that agglomeration is more inclined to related variety. More importantly, in order to enable related variety to cross the inflection point as soon as possible, it's necessary to increase investment in technological innovation and promote technology spillover in the agglomeration areas. Second, governments should strengthen interregional cooperation to promote more related variety agglomeration. This adjustment of the industrial spatial structure will help alleviate regional haze pollution in the long term.

Data availability

Data will be made available on request.

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