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How does urban innovation affect haze pollution? Evidence from 270 cities in China

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Abstract

Urban innovation is not only an important part of achieving high-quality urban development but also an important aspect of the national innovation-based development strategy. The results obtained from using data on the ground-level experience of cities from 2001 to 2016 in the empirical test show that raising the level of urban innovation can reduce haze pollution. Our results are robust to multiple scenarios, such as considering endogeneity problems and controlling interference from external policies. The heterogeneity analysis shows that the innovative haze reduction effect of medium-size, northern towns, and cities with high human capital, high economic development, and an increased infrastructure level is most significant. The transmission mechanism shows that the technological upgrading effect, structural optimization effect, and resource agglomeration effect caused by raising the urban innovation level are important channels for reducing haze pollution. Our expanded analysis indicates that urban innovation has a threshold effect on haze pollution, and the haze reduction effect is only generated after the threshold value is reached. The technology-driven and compact urban development model can strengthen the haze reduction effect of innovation. In contrast, the institutional innovation and sprawling urban development model inhibit the haze reduction effect of innovation.

Keywords Urban innovation · Haze pollution · Resource allocation effect · Structural optimization effect · Technology upgrade effect

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1 Introduction

Since the implementation of the reform and opening-up policy in 1978, China has got some remarkable achievements in its economic development. In 2019, China became the world's second-largest economy, and the gross domestic product (GDP) exceeded USD 14.36 trillion for the first time. However, its long-term, extensive economic growth model has also led to increasingly serious problems with environmental pollution, especially deterioration in air quality and frequent haze pollution. According to the *China Ecological and Environmental Bulletin 2019,* 337 cities in China experienced 2118 days of severe pollution, including 1669 days with PM2.5 as the primary pollutant, accounting for 78.8%. Severe haze pollution induces disease (Schlenker & Walker, 2016), lowers people's happiness, lessens the production efficiency of enterprises, and enlarges the gap in economic development between regions (Schoolman & Ma, 2012). This, in turn, limits sustainable socioeconomic development and is not conducive to the achievement of high-quality development of China's economy (Chang et al., 2016). China is in a new stage of in-depth implementation of its sustainable development strategy. Improving the overall coordination mechanism in ecological civilization and promoting the all-around green transformation of economic development has become the primary goals of China's economic development. Therefore, based on this goal, clarifying the causes of haze pollution and exploring the choice of governance to address haze pollution has great academic significance and policy guidance value.

Existing studies on the causes and treatment of haze pollution mainly focus on environmental regulation, transportation, and foreign direct investment. Few studies focus on urban innovation capacity to explore its impact on reducing the concentration of air pollutants. Generally, haze pollution usually occurs in urban areas where population and economic activities are concentrated. Since 2013, urban haze pollution has demonstrated the characteristics of wide scope, high outbreak frequency, being difficult to control, and normalization (Miao et al., 2020). So, can the cycle of negative externalities of haze pollution in urban development be broken by reforming the urban development model? Since the Chinese government took scientific and technological innovation as a new driving force for high-quality economic development, scientific and technological innovation has achieved a great leap forward in development. Therefore, urban innovation is not only an important driving force for attaining high-quality urban development but also an important link for promoting the formation of a new development pattern. This paper clarifies the mechanism of urban innovation affecting haze pollution. It conducts empirical tests by using the empirical data of Chinese cities from 2001 to 2016 to provide references for the government to design policies for controlling haze pollution.

Different from previous studies, the marginal contributions of this paper are as follows: First, we expand the research horizon of haze pollution control and clarify the internal mechanism in which urban innovation reduces haze pollution. Second, we reveal three mechanisms in reducing haze pollution of urban innovation through technological progress effect, structural upgrading effect and resource agglomeration effect. Third, according to different drivers of urban innovation, we divide cities into technological innovation cities and institutional innovation cities and investigate the moderating effects of innovation-driven modes on urban innovation to reduce haze pollution. Fourth, from the perspective of spatial distribution, we divide the reconstruction mode of urban development into compact and intensive urban development mode and sprawling and expanding urban development mode and examine the impact of urban innovation on haze pollution under different development modes.

2 Literature review

As a public good, the emergence of haze pollution is an example of the tragedy of the commons. At present, the first stream of literature related to the research topic of this paper mainly focuses on the causes of pollution and the measures to control it.

First, scholars have studied the causes of haze pollution from several perspectives. Some scholars believe that the race to the bottom between local governments and free riding in environmental governance aggravates air pollution (Liu et al., 2016). Shi et al. (2020) believe that rapid progress in industrialization and urbanization drives development in the heavy chemical industry real estate, and a continuous increase in population density, which increases haze pollution. Zheng et al. (2020) show that expansion in the economic scale due to transformation in the industrial structure leads to energy consumption growth, exacerbating haze pollution. Zhang et al. (2019) indicate that the rapid increase in motor vehicles and their exhaust emissions caused by urban economic development are the reasons for the rise in the urban haze. Second, many scholars have shown that technological progress effectively controls haze pollution (Zhao et al., 2020). Other studies suggest that public environmental appeals are an important way to urge the government to take corresponding measures to control environmental pollution (Chen et al., 2019). In addition, constructing public transport infrastructure is also an effective way to control haze pollution (Chen & Whalley, 2012). Mandatory environmental regulatory measures (Li et al., 2014), continuous environmental oversight (Zhang et al., 2018), and various energy conservation and emission reduction policies (Zeng et al., 2019) are conducive to the treatment of haze pollution.

Another stream of literature related to the topic of this paper focuses on environmental pollution caused by urbanization but has not yet reached a consensus. One view is that in the urbanization process, the increase in population size expands the energy demand of cities, leading to an increase in total pollutant emissions (Zheng & Kahn, 2013). At the same time, the city's population density brings traffic congestion and aggravates particulate emissions (Luo et al., 2018). In addition, with a rapid expansion of the urban scale and a rapid demand for energy, urbanization leads directly to an increase in pollutant emissions and a worsening of environmental pollution (Sanna et al., 2014). Another perspective is that by employing clean production technology and accumulating human capital, urbanization can not only reduce the generation of pollutants (Chen et al., 2008) but also help to exploit the scale effect of public infrastructure to reduce haze pollution (Aunan & Wang, 2014). The third view is that urbanization may have an inverted-U-shaped relationship with pollutant emissions (Merbitz et al., 2012). The expansion of the industrial scale brought by pre-urbanization greatly increases energy consumption, thus increasing pollutant emissions (Chay & Greenstone, 2005). In the later stage, due to the agglomeration effect caused by urbanization, it not only reduces transportation costs but also encourages technological innovation, thus reducing haze pollution (Kahn & Schwartz, 2008).

A review of the relevant literature shows that considerable advances have been made in researching the causes and controlling factors of haze pollution. A few studies on the impact of haze pollution at the city level are also based on environmental pollution caused by urbanization. Few studies further explore the impact of raising urban innovation on

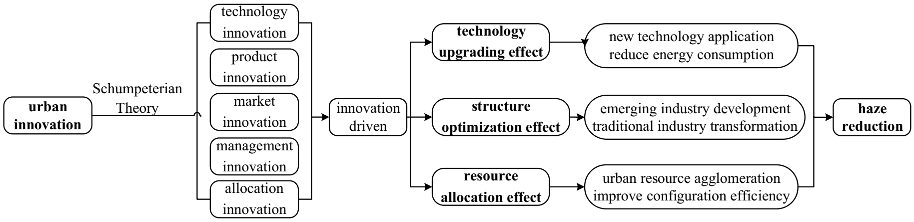

Fig. 1 The theoretical mechanism in which urban innovation affects haze reduction

reducing haze pollution. Increasing urban innovation is conducive to solving the problem of low efficiency and disorderly expansion in urbanization and has a significant impact on urban industrial structure and factor accumulation, accelerating the construction of a new kind of urbanization.

3 Theoretical analysis framework

Urban innovation is a major innovation based on the change in social organization and scientific and technological progress. Therefore, based on the Schumpeterian innovation theory, we analyze the theoretical mechanism in which urban innovation affects haze pollution from five perspectives: technology, products, markets, management, and distribution. Through technological innovation, cities can use intelligent monitoring equipment in production activities to collect the environmental information closely related to enterprise pollutant discharge, raising the efficiency of governance and reducing haze pollution. Product innovation refers to a significant product improvement in input materials, merging software, or other basic functional features, which encourages the application of information technology to enterprise products, the production of environmentally friendly products and improves urban air quality. Market innovation comprises new product concepts, and new market standards, which facilitate the emergence of producer services, expand the development space for tertiary industry, and reduce the emissions of haze pollutants. Management innovation focuses on a set of activities that aim to improve management systems, processes, and other objects, increase enterprise management efficiency (Lin & Su, 2014), drive enterprise transformation to scientific management, reduce resource waste caused by poor management and operations, and reduce haze pollution. Distribution innovation may improve resource utilization efficiency by arranging human, financial, physical, and other resources in the city in a flexible and efficient manner, reducing haze pollution. Based on this, we propose the following hypothesis:

Hypothesis 1: An expansion in urban innovation is conducive to reducing haze pollution; that is, urban innovation has a haze reduction effect.

Driven by urban innovation, the endogenous technology upgrading effect, the structural optimization effect, and the resource distribution effect will help to reduce urban haze pollution by raising the rate of energy utilization, which drives industrial structure optimization and upgrading, as well as a rational distribution of people and goods, respectively. Improving the level of innovation in cities can encourage enterprises to accelerate (Fig. 1).

First, we look at the effect of technology upgrading. Because of the diversification in environmental regulatory measures, raising the level of urban innovation can lead enterprises to accelerate the development and application of energy-saving and environmentally friendly technologies (Ci et al., 2020). The continuous investment in environmental protection products and clean technologies in the production process enables the production mode to be optimized, which effectively drives the transformation of industry as a whole, from extensive development to technology-intensive, lower pollutant emissions and better air quality. Second, we examine the structural optimization effect. A higher urban innovation level is bound to be accompanied by the development of scientific and technological information industry fed by emerging innovation factors. This includes knowledge and technology, which are characterized by low communication cost, deep penetration, returns to scale, and increasing marginal returns (Berliant & Fujita, 2012). By extending the industrial value chain, deepening the division of labor and so on, can greatly reduce pollutant emissions and accelerate the upgrading of the urban industrial structure. In addition, greater urban innovation helps to encourage traditional industries to improve their input structure of production factors, reduce pollution and energy consumption, and significantly improve air quality. Third, we explore the effect of resource distribution. A higher urban innovation level attracts high-quality talents and elements to cities, reducing haze pollution caused by urban sprawl. At the same time, the development of technology-intensive industries with higher urban innovation drives transformation in the urban organization and management form, from traditional inefficient management to intelligent management and network management, to achieve flexible scheduling in urban human and physical resources among industries (Zou & Zhu, 2020), and increase urban pollution control ability. Therefore, we propose the following hypothesis:

Hypothesis 2: The technology upgrading effect, structural optimization effect, and resource distribution effect caused by increasing urban innovation are important transmission channels to reduce haze pollution.

Theoretically, urban innovation increases are driven by city innovation activities (Ma et al., 2015). However, from a practical perspective, urban innovation can have different drivers.[1] We distinguish scientific and technological innovation and industrial innovation in technological innovation cities. Implementing a science and technology-oriented innovation strategy promote the development of advanced scientific and technological productivity. It can optimize and upgrade the industrial structure within a city and give full play to the haze reduction effect of urban innovation. We distinguish open innovation and comprehensive innovation in institutional innovation cities. By integrating various innovation resources, these cities can achieve coordination and interaction in various innovation links and then stimulate economic actors in cities to engage in innovation. Urban institutional innovation can encourage investors to increase investment in urban enterprises (Fu & Mu, 2014), which creates sufficient financial support for enterprise innovation. Due to the continuous injection of foreign direct investment, the accompanying pollution halo effect and pollution haven effect will have an impact on urban haze pollution. Therefore,

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[1] Specifically, it can be divided into scientific and technological innovation, industrial innovation, open innovation, resource-saving and environmentally friendly innovation, institutional innovation, and comprehensive innovation. This classification is based on the different contents and driving forces of urban innovation activities. It is very specific, but it does not have strong generality.

technological innovation and institutional innovation in the urban development model can regulate haze pollution. We propose the third hypothesis as follows:

Hypothesis 3: The haze reduction effect is more significant in technology-driven innovation cities than in institutional-innovation cities.

According to the different urban development promotion modes,[2] we define the reconstruction of old urban areas and the establishment of central business districts as a compact and intensive urban development mode and the establishment of economic development zones, the construction of new cities and new districts, urban expansion, and village and township industrialization as a sprawling and expanding urban development mode. The development mode of a compact and intensive city is not only conducive to the spatial agglomeration effect of knowledge and the economy but also reduces people's dependence on cars and energy consumption (Clark et al., 2011), thus reducing emissions of car exhaust and urban haze pollution. The sprawling urban development model reduces urban economic activities and population density, increasing demand for buildings (Banzhaf & Lavery, 2010), and the emissions of dust pollutants generated in the construction process worsen haze pollution. In addition, it degrades the green space around the city, which is ineffective in improving the air quality. Therefore, we propose the fourth hypothesis as follows:

Hypothesis 4: The haze reduction effect is greater in the compact and intensive urban development model than in the sprawling and expanding urban development model.

4 Model construction and variable selection

4.1 Construction of the econometric model

Based on the theoretical analysis and transmission mechanisms, we study the impact of urban innovation on haze pollution with the following econometric model:

$$lnPM_{2.5it} = \alpha_0 + \alpha_1 lncreative_{it} + \alpha_2 X_{it} + \eta_i + \varphi_t + \varepsilon_{it} \tag{1}$$

where $PM_{2.5it}$ is the degree of haze pollution in city i in year t. $creative_{it}$ is the innovation level of city i in year t. X_{it} represents a collection of control variables, including the urban economic development level, population size, vegetation area, investment in fixed assets, foreign direct investment, and level of government regulation. η_i and φ_t are city-fixed effect and year-fixed effect, used to control for the influence of the inherent characteristics of a city and the macroeconomic trends, respectively. ε_{it} is a random error term.

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[2] China has seven types of urban development: reconstruction of older cities, establishment of central business districts, establishment of economic development zones, construction of new cities and new districts, urban expansion, and village and township industrialization.

4.2 Variable selection and calculation

4.2.1 Dependent variable: haze pollution

The diameter of particulate matter equivalent to ≤ 2.5 μm in aerodynamics (from now on referred to as PM2.5) is the most serious type of haze emissions in China. Therefore, we select the annual average of PM2.5 concentration in cities as the main measurement of the degree of haze pollution. To solve the problem of missing PM2.5 historical data and low accuracy caused by using satellite data and ground monitoring data alone, based on the measurement method of Ma et al. (2016), we incorporate the data obtained from satellite monitoring and ground monitoring into the spatial statistical model for calculation, and then use ArcGIS to match this raster data with the Chinese administrative vector regions to obtain PM2.5 concentration data on 270 cities from 2001 to 2016.

4.2.2 Core explanatory variable: urban innovation index

In current academic research, the number of patents, investment in research and development (R&D), and total factor productivity are usually used to measure urban innovation. These three indicators have their advantages and disadvantages. Considering that it is challenging to obtain R&D investment data in China, it is not only impossible to verify the accuracy of R&D investment data but also possible to double calculate. At the same time, in an imperfectly competitive market, using total factor productivity to measure the level of innovation may produce errors. Although patent data can reflect technological change and innovation to a certain extent, there is no one-to-one correspondence between innovation and the number of patents applied, and patents will not be sought for all innovations. At the same time, the index of patent authorization implies a hypothesis that each patent has a homogeneous effect on innovation, thus ignoring the heterogeneity of patents. Therefore, the index selection is not accurate and reasonable.

Based on this, similar to the research of Ai et al. (2022), this paper selects the urban innovation index in the *China City and Industrial Innovation Report* as the measurement index of the innovation capacity of each city. Considering the lag in the update time of traditional macro statistical data, the index is based on the micro-patent data from the State Industrial and Commercial Administration to ensure the timeliness and foresight of the urban innovation index. The State Intellectual Property Office combines a patent renewal model to calculate the patent value and adds up at the city level to measure the innovation level in each city. Therefore, the urban innovation index in the report includes the heterogeneous patent value as a measurement category, which more accurately reflects the innovation level in each city.

The appropriate calculation methods are as follows: (1) Referring to the patent renewal model of Pakes and Schankerman (1984), estimating the value of all expired invention patents applied from 1987 to 1997, then simulating the distribution of patent value according to the estimated parameters. Further calculating the average value of patents of different ages as the value weighting coefficient of corresponding patents; (2) Taking the end of December 31 as the observation point of each year, selecting the invention patents that are still valid at the observation point (authorized and still in the duration), and finally sum up the patent values of different cities to obtain the stock of patent value. Then, the total value of national patents in 2001 is standardized to 100, and the urban innovation index from

Table 1 Descriptive statistics of the variables

		Obs	Mean	SD	Min	Max
Dependent variable	$lnPM_{2.5}$	4320	3.4702	0.4962	1.5083	4.5104
Independent variable	*lncreative*	4312	– 0.4544	1.9176	– 4.6052	6.9673
	lnpgdp	4320	9.9552	0.8813	7.3852	12.2807
	lninvest	4320	5.9681	1.3387	2.5615	9.7620
Control variables	*fdi*	4142	0.0031	0.0035	0	0.0577
	lnpop	4320	5.8571	0.7040	2.6856	8.1292
	lngreen	4277	7.8296	1.1556	3.1355	12.0319
	govsup	4320	0.1473	0.0838	0.01431	1.0241

2001 to 2016 is calculated. The specific data and calculation steps are detailed in the *China City and Industrial Innovation Report* issued by the Industrial Development Research Center of Fudan University in 2017.

4.2.3 Selection of control variables

The control variables include: the level of urban economic development (*pgdp*), expressed as the logarithm of urban per capita real GDP; investment in fixed assets (*invest*) is expressed by the logarithm of total investment in fixed assets; foreign direct investment (*fdi*) is measured by the proportion of disbursed foreign capital in GDP; population size (*pop*), which is measured by the logarithm of the total population at the end of the year; urban vegetation area (*green*), as the logarithm of the urban vegetation area; and the level of government regulation (*govsup*) is the ratio of government expenditure to GDP. The control variables are derived from the *China City Statistical Yearbook*. The results of descriptive statistics analysis of the variables are listed in Table 1.

5 Analysis of empirical results

5.1 Benchmark regression results

The benchmark regression results of the impact of urban innovation on PM2.5 are shown in Table 2. Column (1) shows the estimated results before all the control variables are introduced, and only the city-fixed and year-fixed effects are controlled for, indicating that the regression coefficient of the urban innovation variable is significantly negative. Columns (2)–(5) are the regression results with all city-fixed and year-fixed effects controlled and the gradual addition of control variables, the results show that the estimated coefficients of urban innovation variables are consistently and significantly negative. In sum, the benchmark empirical results show that urban innovation negatively impacts PM2.5, i.e., higher urban innovation leads to lower PM2.5. Our results confirm Hypothesis 1.

In column (5), the estimated results with the control variables show that the estimated coefficient of the economic development level is significantly negative. With increased economic development, cities have more disposable income for pollution control, thereby mitigating local haze pollution. The impact of urban population size on haze pollution is significantly negative. It might be that, as the total population

Table 2 The benchmark regression

Dependent variable	$PM_{2.5}$				
	(1)	(2)	(3)	(4)	(5)
lncreative	– 0.0304*** (0.0044)	– 0.0383*** (0.0045)	– 0.0341*** (0.0046)	– 0.0358*** (0.0044)	– 0.0349*** (0.0047)
lnpgdp		– 0.0355** (0.0157)	– 0.0446*** (0.0158)	0.0476*** (0.0163)	– 0.0499*** (0.0161)
fdi		2.3172*** (0.8075)	2.0598** (0.8078)	– 1.5744 (1.0068)	2.2053*** (0.8047)
lninvest		– 0.0324*** (0.0082)	– 0.0281*** (0.0082)	0.0731*** (0.0098)	– 0.0219*** (0.0083)
lnpop			– 0.1821*** (0.0416)	– 0.1008* (0.0522)	– 0.1753*** (0.0416)
lngreen				0.0019 (0.0060)	– 0.0119** (0.0048)
govsup				– 0.4164*** (0.0698)	– 0.2238*** (0.0593)
_cons	3.1893*** (0.0119)	3.6374*** (0.1248)	4.7734*** (0.2881)	3.2144*** (0.3356)	4.8595*** (0.2884)
City-fixed effect	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	No	Yes
Sample size	4312	4137	4137	4113	4113
R^2	0.434	0.461	0.464	0.144	0.471

Standard errors are in parentheses. *, **, and *** respectively significant at 10%, 5%, and 1%

grows, people's attention to and concern about the environment gradually increases, which in turn helps to reduce pollution. The urban greening coverage and PM2.5 concentration have a significantly negative relationship. The wider the urban greening coverage, the greater the city's ability to absorb pollution and effectively reduce the concentration of haze pollutants. The regression coefficient of *govsup* is significantly negative. As government investment in pollution control increases, support from government policy plays a more positive role in controlling PM2.5. FDI and urban haze pollution have a significantly positive correlation, further confirming the pollution haven hypothesis. Urban investment in fixed assets has a negative impact on haze pollution. This might be because, with the continuous strengthening of government environmental regulations, investment in fixed assets begins to have environmentally friendly characteristics.

5.2 Robustness test

The results of the benchmark regression show that an increase in the promotion of urban innovation level is conducive to reducing the concentration of haze pollutants. Still, the robustness of the results needs further confirmation. Therefore, this paper conducts empirical tests by considering endogeneity and policy changes, excluding provincial capitals and municipalities samples.

5.2.1 Addressing endogeneity problems

Theoretically, we cannot rule out reverse causality in which haze pollution hinders increases in urban innovation. Therefore, in this paper, the two-stage least square (from now on referred to as 2SLS) method is used for regression estimation, and we select the built-up area (*lnbuiltarea*) of municipal districts in prefecture-level cities as the first instrumental variable for urban innovation. On the one hand, the metropolitan built-up area directly affects the spatial agglomeration of urban economic production factors. The most direct manifestation of their positive externalities is the improvement of urban technological innovation level, which accords with the correlation assumption of effective instrumental variables. On the other hand, the Chinese government's land policy does not directly regard environmental protection as the development goal of a built-up area in a municipality, so it satisfies the exogeneity assumption of effective instrumental variables. The regression results of the instrumental variables are shown in columns (1)–(2) of Table 3, indicating that the estimated coefficients of the urban innovation variables are still significantly negative. At the same time, we also use the one-legged urban innovation variable (*Llncreative*) as the second IV, and the estimated results of the regression using 2SLS are shown in columns (3)–(4). After the endogeneity problem is effectively mitigated, the regression coefficient of *lncreative* is still significantly negative.

5.2.2 Geographic and climatic conditions

Geographic and climatic conditions will influence the haze reduction effect of urban innovation through production and diffusion effects. Columns (5) of Table 3 show that the average annual urban temperature hinders the effect of urban innovation on reducing PM2.5. This might be because a rise in the yearly average temperature in a city will have negative health impacts on the physical and mental well-being of urban residents; these impacts can lead to a decline in the stock of human capital required for urban innovation, thus hindering the improvement of urban innovation level. Column (6) shows that urban annual precipitation has a significantly negative moderating effect. This might be related to the fact that abundant precipitation can significantly reduce PM2.5, which weakens the haze reduction effect of urban innovation. Column (7) shows that urban topographic undulation weakens the haze reduction effect of urban innovation. This might be because when the degree of urban topography is higher, the urban spatial form is more likely to develop toward low density and decentralization, which is not conducive to the spillover of urban innovation, reducing the effect of haze pollution control. Column (8) shows that urban wind speed positively affects the effect of urban innovation on reducing PM2.5. The wind speed and the spread of haze pollutants have a positive relationship, consistent with the subjective perceptions of urban residents, and objectively strengthens the haze reduction effect of urban innovation.

5.2.3 Other robustness tests

Haze pollution is not only an ecological and environmental problem faced by a specific area. To a large extent, it spreads to adjacent areas through natural paths and social and economic mechanisms (Li et al., 2020). Therefore, we further select the spatial panel model to perform the regression estimation again. Column (1) of Table 4 shows that the

Table 3 Robustness test 1

Dependent variable	$PM_{2.5}$							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lncreative		− 0.0747*** (0.0257)		− 0.0394*** (0.0051)	0.1686*** (0.0206)	0.0538** (0.0236)	− 0.0266*** (0.0047)	− 0.0552*** (0.0070)
lnbuiltarea	0.3416*** (0.0311)							
Llncreative			0.9010*** (0.0073)					
*lntemp*lncreative*					− 0.0661*** (0.0064)			
*lnrain*lncreative*						− 0.0121*** (0.0031)		
*high*lncreative*							− 0.0249*** (0.0022)	
*ws*lncreative*								0.0079*** (0.0018)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	4041	4041	3853	3853	2896	2908	4113	4006
R^2	0.960	0.9503	0.993	0.9551	0.293	0.279	0.488	0.488

Standard errors are in parentheses. *, **, and *** respectively significant at 10%, 5%, and 1%. The control variables are the same as in Table 2. The following tables are the same

Table 4 Robustness test 2

Dependent variable	$PM_{2.5}$						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
lncreative	− 0.019*** (0.003)	− 0.031*** (0.005)	− 0.0349*** (0.0047)	− 0.0354*** (0.0048)	− 0.0394*** (0.0049)	− 0.0539*** (0.0072)	− 0.0337*** (0.0048)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	4320	4113	4113	3855	3984	3497	3812
R^2	0.5497	0.471	0.471	0.413	0.469	0.328	0.467

regression coefficient of the urban innovation is still negative, demonstrating the robustness of our results. In 2008, the State Council approved the establishment of six environmental protection centers, which imposed strict regulations to limit environmental pollution. These environmental protection centers were intended to significantly impact haze pollution and might lead to an overestimation of the haze reduction effect of urban innovation. This paper adds a dummy variable for 2008 policy changes to the baseline regression model to identify this impact. Column (2) shows that under the control of policy interference, the reduction effect of urban innovation on haze pollution still exists, and the results are relatively robust.

We also use the growth rate of the innovation index as an alternative index and conduct the empirical test again. The results are listed in column (3), showing that the estimated coefficient of *lncreative* is still significantly negative. To mitigate bias due to reverse causation, we use the urban innovation index with one lag, and the estimated results are shown in column (4), showing that the improvement of urban innovation can still reduce haze pollution. Furthermore, to avoid the influence of extreme outliers in the urban innovation index on the empirical results, column (5) lists the sample estimation results of the urban innovation index in the 1st and 99th percentiles after two-sided censoring processing, indicating that the effect of urban innovation on reducing haze still exists. By changing the measurement method of the explained variables, we take the total number of urban patents as the measurement index of urban innovation to test again. According to the empirical results in column (6), urban innovation is still significantly negative, consistent with the benchmark regression results. In addition, to increase the comparability of the samples, we delete the samples for cities above the prefecture level (municipalities directly under the central government and subprovincial cities)[3] and retain only the samples of prefecture-level cities. As shown in column (7). The estimation coefficient of the variable *lncreative* is significantly negative, and the research conclusion has good robustness.

5.3 Heterogeneity analysis

This section considers the heterogeneous characteristics of urban location conditions and resource endowments to test the effects of urban innovation on haze reduction empirically.

5.3.1 Analysis of heterogeneity in urban location condition

First, to examine the heterogeneity an urban scale, we divide the sample into small and medium-sized cities. The regression results for these subsamples are in columns (1)–(2) of Table 5. The results show that the effect of urban innovation on haze reduction is not significant in small cities but substantial in medium-sized cities. The possible reason is those small cities have poor economic development, and the urban innovation level increases are focused on GDP. However, midsize and larger cities have a stronger economic foundation, which offers a basis for expanding urban innovation.

Central heating in the wintertime is not the fundamental factor causing haze pollution, but it cannot be ignored. The regression results in columns (3)–(4) show that urban

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[3] Municipalities directly under the central government: Beijing, Tianjin, Shanghai, and Chongqing; provincial cities: Harbin, Changchun, Shenyang, Dalian, Jinan, Qingdao, Nanjing, Hangzhou, Ningbo, Xiamen, Wuhan, Guangzhou, Shenzhen, Chengdu, and Xi'an.

Table 5 Heterogeneity test 1

Dependent variable	$PM_{2.5}$					
Heterogeneity	City size		Central heating		Political status	
	(1)	(2)	(3)	(4)	(5)	(6)
lncreative	− 0.0028 (0.0123)	− 0.0426*** (0.0052)	− 0.0292*** (0.0089)	0.0028 (0.0053)	− 0.0061 (0.0205)	− 0.0361*** (0.0049)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	479	3634	1802	2311	531	3582
R^2	0.460	0.493	0.561	0.578	0.462	0.476

innovation has a negative impact on haze pollution in northern cities with central heating but no significant impact on southern cities without heating in the wintertime. Southern cities have relatively high air quality and developed economies. The average air quality in northern cities is relatively poor due to policies such as heating in the winter (Almond et al., 2009). Meanwhile, heavy industries are relatively concentrated in northern China, which has a greater impact on air pollution. Therefore, increasing urban innovation has a greater marginal impact on PM2.5 in the north.

Columns (5)–(6) show the test results of different political statuses. The regression results show that urban innovation only reduces the haze pollution level of non-provincial capital cities, which is not significant in provincial capital cities. The governments of regional capital cities might still be competing economically based on GDP. And the proportion of government expenditure on environmental public goods is relatively low. While in the industrial structure of most non–provincial capital cities, manufacturing still comprises a large proportion, with a high amount of industrial pollution, the marginal haze reduction effect of urban innovation is more significant.

5.3.2 Analysis of heterogeneity in urban resource endowments

The effect of urban innovation in reducing haze is inseparable from the support a city receives in terms of resource endowments. We take the number of college students per 10,000 people in a city as a measurement of human capital; measure urban financial development by the scale of financial development in a city, and measure urban infrastructure by the urban per capita road area. The regression results in columns (1), (3), (5) of Table 6 show that urban innovation in cities that have high human capital, high financial development, and high infrastructure all contribute to decreasing haze pollution. On the contrary, the estimated results in columns (2), (4), (6) show that the haze reduction effect of urban innovation is not significant in cities with low resource endowments. In a city with a high level of human capital, it is easier to carry out technology-oriented production activities. When a city has a complete financial market, more abundant funds can be provided for improving the innovation level, and its haze reduction effect will be more significant. What's more, having good infrastructure is conducive to creating a welcoming environment for innovation, effectively accelerating the flow and diffusion of factors, such as

Table 6 Heterogeneity test 2

Dependent variable	$PM_{2.5}$					
Heterogeneity	Human capital		Financial development		Infrastructure	
	(1)	(2)	(3)	(4)	(5)	(6)
lncreative	− 0.0413*** (0.0058)	− 0.0206* (0.0114)	− 0.042*** (0.0057)	0.0041 (0.0126)	− 0.0363*** (0.0057)	− 0.0187 (0.0116)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	2867	1246	2951	1162	2845	1268
R^2	0.438	0.464	0.511	0.387	0.428	0.503

Table 7 Test of the impact mechanism of urban innovation on PM2.5

Dependent variable	*perelect* (1)	$PM_{2.5}$ (2)	*lnstr* (3)	$PM_{2.5}$ (4)	*lnpopdens* (5)	$PM_{2.5}$ (6)
lncreative	− 0.0006*** (0.0001)		0.0743*** (0.0195)		0.0377*** (0.0073)	
perelect		2.1599*** (0.8328)				
lnstr				− 0.0136*** (0.0042)		
lnpopdens						− 0.0712*** (0.0103)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	3537	3537	3798	3798	4096	4096
R^2	0.595	0.327	0.692	0.417	0.486	0.481

knowledge and labor within and between cities, then giving full play to the haze reduction effect of urban innovation.

5.4 Transmission mechanism test

Next, we use per capita industrial power consumption, value added in tertiary industry, and urban population density as mechanism variables in a stepwise regression model to investigate the channels created by urban innovation on haze pollution.

Columns (1)–(2) of Table 7 are the technology upgrading effect test results. Column (1) shows that industrial energy consumption decreases significantly with an increase in urban innovation. The empirical result in column (2) shows a positive relationship between industrial energy consumption and urban air pollution. Therefore, an increase in urban innovation reduces industrial energy consumption and then reduces haze pollution caused by energy consumption. The structural optimization effect test results are in columns (3)–(4).

Table 8 Threshold effect test results

Threshold variable	Threshold types	F value	P value	Crit10	Crit5	Crit1
lncreative	Single threshold	72.794**	0.043	65.902	72.352	87.771
	Double threshold	5.803	0.333	10.993	13.806	18.708
	Triple threshold	0.000	0.125	0.000	0.000	0.000

Crit10, Crit5, and Crit1 are the critical values at the significance levels of 10%, 5%, and 1%, respectively, which are obtained with 300 bootstrap samples

Table 9 Threshold effect analysis

Dependent variable	$PM_{2.5}$		
	(1)	(2)	(3)
lncreative		– 0.0041 (– 0.19)	– 0.0421*** (– 8.07)
lncreative ≤ – 2.592	0.0127 (1.58)		
lncreative > – 2.592	– 0.0218*** (– 3.41)		
Control variables	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
Sample size	4113	433	3680
R^2	0.310	0.412	0.456

According to the empirical results in column (3), an increase in urban innovation significantly increases the value added in tertiary industry and drives optimization of the urban industrial structure. The empirical results in column (4) mean that industrial upgrading also plays an essential role in reducing PM2.5. The regression results of the resource allocation effect in column (5) show that urban innovation drives growth in the urban human capital agglomeration and reduces urban sprawl. Column (6) shows that the spatial overflow reduces haze pollution, that is, urban innovation reduces haze pollution by increasing urban population density. Our results confirm Hypothesis 2.

6 Expansibility analysis

6.1 The threshold effect of haze reduction

Does the level of urban innovation exceed a certain threshold before haze pollution is reduced? To explore this question, we perform a threshold effect test, and the results are listed in Table 8, showing that the result of the single threshold model is significant. That is, the haze reduction effect of urban innovation has a threshold effect.

Based on this, we construct Eq. (2):

Table 10 Moderating effect test

Dependent variable	$PM_{2.5}$			
	(1)	(2)	(3)	(4)
lncreative	– 0.0222*** (0.0068)	– 0.0381*** (0.0050)	– 0.0292*** (0.0050)	– 0.0513*** (0.0103)
*technology*lncreative*	– 0.0566** (0.0227)			
*system*lncreative*		0.6473* (0.3348)		
*intensity*lncreative*			– 0.0004*** (0.0001)	
*sprawl*lncreative*				0.0368* (0.0188)
Control variables	Yes	Yes	Yes	Yes
City-fixed effect	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes
Sample size	4110	4113	4090	4041
R^2	0.471	0.471	0.478	0.324

$$lnPM_{2.5it} = \delta_0 + \delta_1 lncreative_{it} P(lncreative \leq r) + \delta_2 lncreative_{it} P(lncreative > r) + \delta_3 X_{it} + \eta_i + \varphi_t + \varepsilon_{it} \tag{2}$$

where $P(.)$ is the indicative function, and r is the estimated threshold of the city's innovation level. The results show that the threshold estimated endogenously determined by the sample data is – 2.592.

In column (1) of Table 9, when the urban innovation level is lower than – 2.592, urban innovation does not reduce haze pollution. Still, when the urban innovation level is higher than the threshold, urban innovation plays a significant role in haze pollution reduction. To confirm this conclusion, we use – 2.592 as the threshold and divide the research sample into subsamples for regression. The empirical results in columns (2)–(3) show that it has a negative impact on PM2.5 only when the city's innovation level exceeds the threshold. In general, a low level of urban innovation, to a certain extent, means that the level of urban economic development is also low. These cities might pay more attention to maximizing urban economic output value, but not the application and promotion of green environmental protection technology, which is not conducive to improving urban air quality. When the urban innovation level exceeds the threshold value, it reflects good development in the city, which creates higher requirements in the living environment. At the same time, the government has good financial operations, so it can provide sufficient financial support for addressing haze pollution. Thus the haze reduction effect of urban innovation is significant.

6.2 The moderating effect

To verify the moderating effect of different driving forces on the haze reduction effect of urban innovation, we divide cities into two types: technological innovation (*technology*) and institutional innovation (*system*). Then, for each type, we measure the proportion of total education and science and technology expenditure and the proportion of FDI in GDP.

At the same time, based on the urban spatial form, the sample cities are divided into two types: compact (*intensity*) and sprawl (*sprawl*). To determine which cities are compact, we measure the output intensity per area unit. We identify the sprawling cities, following Fallah et al. (2011).

The test results of the moderating effect are listed in Table 10. The results in columns (1)–(2) show that a technological innovation-driven model can strengthen the haze reduction effect of urban innovation. In contrast, an institutional innovation-driven model inhibits the haze reduction effect of urban innovation. This might be because technological innovation usually occurs in urban manufacturing, directly improving the clean production technology of enterprises in cities and reducing corporate pollutant emissions. Policy-oriented institutional innovation can attract a large amount of FDI. However, although FDI inflows bring advanced production technology, they can also produce a pollution haven effect, which intensifies urban haze pollution and reduces the haze reduction effect of urban innovation. Our results confirm Hypothesis 3. The results in columns (3)–(4) show that the compact and intensive development model is conducive to strengthening the haze reduction effect, whereas the sprawling and expansive development model inhibits it. The possible reason is that the compact and intensive urban development model can encourage urban public facilities to be closer to spatial equilibrium in supply and demand, thereby enabling pollution control to play the scale effect. The sprawling and expanding development model tends to disperse the internal spatial structure of cities. Inhabitants tend to rely on driving their cars to travel the longer commuting distances, and the increase in vehicle exhaust emissions increases severe air pollution. Our results confirm Hypothesis 4.

7 Conclusions and implications

This paper focuses on the impact of urban innovation on haze pollution and its channels at a theoretical and empirical level, which offers support for China's economy to achieve high-quality development. Our results show that the increase in China's urban innovation level was conducive to reducing haze pollution between 2001 and 2016—that is, urban innovation had a significant effect on haze reduction. The results remained robust to multiple models that consider endogeneity problems, policy changes and variable replacement. In addition, the results on heterogeneity show that this effect is more significant in medium-size cities, northern cities, cities that are not provincial capitals, cities with high human capital, high financial development, and high level of infrastructure. The most important channels for decreasing haze pollution are the effects of technological upgrading, structural optimization, and resource allocation caused by urban innovation. Moreover, the effect is strengthened by technology-driven and compact-intensive urban development models but inhibited by the institutional innovation and sprawling urban development models.

The results of our theoretical and empirical analyses lead to some important implications for the continuous increases in urban innovation ultimately achieving sustainable development. First, the government should continue improving the specific haze pollution systems to encourage cities to increase their green technology innovation. In addition, cities should strengthen collaborative governance and establish a unified mechanism of joint prevention and control to improve urban air quality more efficiently. Second, the government should promote establishing and improving market-oriented mechanisms focused on energy conservation and reducing consumption, especially by enterprises. While formulating and perfecting various systems and policies related to energy conservation and emissions reduction, the government should also actively drive enterprises' use of energy-saving and innovative technologies. Third, the government can increase financial support for high-tech industries, and encourage traditional industries to upgrade production technologies. While ensuring the rapid development of beneficial industries, cities can actively cultivate new areas for economic growth and develop resource-saving and environmental-friendly services based on local conditions aimed at mitigating haze pollution.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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