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Urban innovation, heterogeneous environmental regulations and haze reduction effects–evidence from pilot policies of innovative cities

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Innovation-driven development strategies have injected new momentum into haze management. In addition to its core innovation-driven role, innovative city pilot policy is significant for environmental enhancement and should not be overlooked. To assess the performance of the pilot policy in decreasing haze, a multiperiod double difference model was employed, and a spatial econometric model was used to empirically examine the potential spatial spillover effect of haze management as a regional synergistic concept between 2006 and 2020. Panel data from 282 prefecture-level cities were selected. To investigate and empirically examine the territorial spillover effect of haze reduction as a regional synergistic notion, a spatial econometric model was applied. Based on the study, the pilot construction significantly reduced haze pollution. In China's eastern and central regions, small cities, and newer industrial bases, the inhibitory effect of pilot policies on haze pollution was more pronounced, according to heterogeneity analysis. Moreover, analysis of the heterogeneous environmental regulations revealed that the enforcement of policies would increase the sense of urgency of local governments, strengthen the concern and responsibility of the government for the environment, and further awaken the public's concern for the environment, in addition to forcing enterprises to practice clean and sustainable production, thus achieving the effect of accelerated haze reduction. From the spatial perspective, innovative pilot cities have certain spatial spillover effects and thus can increase the effects of policy for neighboring regions, similar economic regions and local transportation regions.

KEYWORDS

innovative city pilot construction, heterogeneous environmental regulation, haze reduction effect, multiperiod double difference model, spatial econometric model, heterogeneous environmental regulation

1 Introduction

Over the past four decades of reform and opening up, with the rapid development of industrialization and urbanization, China's economy has always maintained a high growth rate (Lu and Cai, 2016). In 2013, the ambient air quality in more than 70% of Chinese cities did not meet the standards set by the World Health Organization (Wang, 2022). As an important environmental issue that has attracted social attention in recent years, haze has undergone a series of treatments, but its effects have not yet been completely eliminated.

The Ministry of Ecology and Environment (MOE) released the "2020 China's Ecological and Environmental Status Bulletin" in 2021, which showed that in 2020, there were still 40.1% of cities above prefecture level with air quality exceeding the standard across the country. Severe haze weather limits the development of countries and cities while reducing people's quality of life and health (Cheng, 2022), the problem of urban haze pollution has triggered widespread concern in the society, and controlling the total amount of haze within the city limits has become crucial. Therefore, it has become imperative to find and apply new urban development models.

Cities are the gathering place of innovation factors and the spatial carrier of innovation activities, and they have rich resources, diverse talents and advanced technologies to provide favorable conditions for innovation (Xu and Cui, 2020; Zhang and Feng, 2021). Urban innovation can improve the development capacity of cities and further promote economic growth and social progress. At the same time, urban innovation can not only improve its economic and social development capacity, but also provide a strong support for finding and implementing effective haze reduction measures, so as to realize the sustainable development of cities. Therefore, to promote the management of urban haze and improve the quality of the atmospheric environment, the resources and advantages brought by cities should be fully utilized, and the research and development and promotion of advanced technologies related to haze reduction should be continuously promoted. However, due to the externalities of the technology market, technological innovation activities to improve the environment have lacked some effective market incentives, so policy intervention is crucial (Wang, 2022). Since 2008, the Chinese government has conducted six rounds of pilot city approvals and established several national innovative pilot cities. Based on the policy establishment principle of "pilot first, promote gradually", the Ministry of Science and Technology and the National Development and Reform Commission (NDRC) promoted the pilot innovative city policy to some cities batch by batch, and then the scope of the pilot cities has been expanded continuously, so that by the end of 2018, 78 cities (districts) in 31 provinces have become national innovative pilot cities.

Environmental regulation plays a bridging role in the haze reduction effect of the innovative city pilot policy. Specifically, after the implementation of the pilot policy, local governments tend to adopt forward-looking strategies, such as strengthening financial support for environmental technology innovations, optimizing green infrastructure, and enhancing environmental regulation, which in turn promotes the continuous improvement of the urban environment (Ding et al., 2021). At the same time, innovative city pilot policies can awaken the public's environmental awareness and form a bottom-up governance model (Bian et al., 2022). The increase in public environmental awareness and environmental participation promotes green technological innovation and strengthens the regulation of corporate pollution emissions, thus creating a positive impact in air pollution management.

Nowadays, environmental regulation has become increasingly mature as an important tool to address environmental pollution. For example, in 2017, the Chinese government launched the "Defense of the Blue Sky" action plan to address severe haze pollution, which focuses on adjusting industrial structure, promoting clean energy, and strengthening monitoring of pollution sources. After several years of implementation of the Action Plan for the Defense of the Blue Sky, concentrations in several Chinese prefecture-level cities have dropped by more than 20%. In addition, environmental regulation is not only focused on formal government-led environmental regulation. As the information age continues to evolve, informal environmental regulation dominated by public scrutiny is also synergizing environmental governance (Zhao and Ni, 2022). For example, with the popularity of electric cars and shared bicycles, public groups and NGOs in some cities have launched green travel initiatives to encourage citizens to reduce the use of gasoline-powered vehicles, thereby reducing tailpipe emissions and mitigating air pollution. At the same time, environmental organizations and public figures have launched social media campaigns such as "Refuse single-use plastics", which has prompted many businesses and enterprises to reduce the use of single-use plastics, thereby reducing land pollution and harmful gas emissions. To summarize, formal environmental regulation and informal environmental regulation has become a new direction of environmental governance by the government (Wu et al., 2022).

Apart from the economic and innovation benefits brought by the innovative pilot policy that relies on innovation to drive the economy and has the main objective of realizing internal economic growth, is the policy conducive to the management of haze pollution? What is its mechanism of action for haze management? What is the role of formal and informal environmental regulation in the process of innovative pilot policies for haze reduction? The above questions will be the focus of this paper. Despite the fact that the implementation of innovative city pilot policies has been effective in environmental pollution control and the green effect it leads to, there is a lack of theoretical analysis and empirical research that can accurately assess the impact of innovative city pilot policies on urban haze reduction. On the one hand, the existing studies mostly select the traditional double-difference model for policy evaluation, and lack of analyzing and evaluating the pilot cities at different points in time through the multi-period double-difference model; on the other hand, the existing studies lack of attention to environmental regulation, and do not consider the possible impact of environmental concern from both the government and the public. In addition, as a regional synergy concept, the existing literature lacks to consider and explore the existence of spatial effects of haze management. In view of this, this paper aims to analyze the pilot policies of innovative cities empirically and analyze the policy effects from different dimensions in depth, so as to provide reference for clarifying the direction of further development of the pilot policies of innovative cities.

The main innovations of this paper include: 1) By incorporating urban innovation, environmental regulation and haze governance into the same analytical framework, it provides new theoretical support for the link between urban innovation and environmental governance, further enriches the related research on innovative cities, and provides a strong empirical basis for an in-depth understanding of the actual role of urban innovation on haze governance. 2) This study explores the specific mechanism of the role of innovative city pilot policies on haze regulation, conducts an in-depth study on the possible spatial spillover effect of haze governance as a regional synergistic concept, and carries out an empirical analysis by means of a spatial econometric model, which provides new perspectives for the cross-study of spatial economics and environmental economics. 3) Panel data of prefecture-level cities are used and combined with the scale size of the cities and whether they are old industrial bases or not, to systematically explore the differential effects of the pilot policies of innovative cities in different geographic regions, city sizes and industrial backgrounds, and to provide policymakers with more detailed policy recommendations.

2 Literature review

The literature that is more closely related to the research content of this paper can be summarized in the following three categories.

The first category is related research on the effects of innovative city pilot policies. Some scholars have pointed out that the innovative city pilot policy has improved the innovation level of the city, and the policy effect has shown an inverted "V" characteristic over time (Li and Yang, 2019). From a regional perspective, some scholars believe that the policy effect is more obvious in cities on the east coast with higher administrative levels (Bai et al., 2022). From the perspective of urban economy, some scholars believe that the pilot policies of innovative cities have enhanced the economic resilience of cities by facilitating the gathering of talents and increasing the results of innovation (Wang et al., 2022; Chang et al., 2023). From the perspective of firms, some scholars find that pilot policies can sustainably promote firms' innovation (Cao et al., 2022). However, some scholars further point out that firms of different natures respond differently to this policy, with SOEs showing a stronger willingness to innovate under the stimulus of the policy, especially when the government is under the pressure of promotion appraisal, and this difference becomes even more obvious (Wang et al., 2022).

The second category is related studies on urban innovation and environmental pollution. Some scholars have shown that as the process of urbanization continues to advance, a large number of rural populations enter large cities, and the scale of cities gradually expands, which leads to an increase in consumption as well as industrialization, and a large increase in the emission of pollutants such as haze (Ala-Mantila et al., 2014; Liu et al., 2015; Wang, 2016). However, some scholars believe that the increase in the level of urban innovation has an obvious inhibitory effect on environmental pollution (Yang T. et al., 2020), and the technological upgrading within the city as well as the large accumulation of resources and manpower will lead to a subsequent reduction in the production of pollutants (Liang et al., 2017; Wen and Wang, 2017; Deng and Zhang, 2018). At the same time, some scholars believe that there is no significant correlation or simple linear relationship between the two (Gao and Guo, 2018; Liang et al., 2019; Shao et al., 2019).

The third category is the research related to environmental regulation and environmental pollution. Environmental regulation has a wider application in mitigating environmental pollution, but there is an intricate relationship between environmental regulation and environmental pollution due to different research perspectives and research objects. When considering the management of environmental pollution, a balance should be struck between formal environmental regulation led by the government and informal environmental regulation led by the public and the media (Hui and Duman, 2021). Some studies have shown that the coercive nature of formal environmental regulation increases hidden economic activities, thus exacerbating haze pollution, while the normative pressure of informal environmental regulation is an effective tool for managing haze pollution (He et al., 2022). However, some scholars argue that formal environmental regulation promotes environmental performance, but informal environmental regulation has a dampening effect (Lu, 2021).

3 Mechanism analysis

With the continuous improvement of the pilot construction of innovative cities, the design concept of the policy also focuses more on the high-quality development of the city, and more attention has been paid to the issue of pollution emission and the concept of green development. Among them, assessment indicators such as the city's air quality index have been incorporated into the testing and evaluation system attached to the policy. Therefore, in addition to its core innovation-driven role, the effect of the innovative city pilot policy on environmental improvement should not be overlooked. In the process of promoting this new model of urban innovation and development, enterprises, as the main body of innovation, continue to enhance their sense of responsibility, standardize corporate behavior, and promote green production technology and low-carbon environmentally friendly intelligent technology for continuous upgrading, so that the production of products in line with the purification of the environment (Ran et al., 2022), which effectively inhibit pollution emissions. In addition, the public goods attribute of the environment makes its existence externalities, so in addition to giving full play to the role of the market in environmental improvement, should also pay attention to the external intervention of the government for environmental pollution management (Berman and Linda, 2001; Yang S. D. et al., 2020). The government can make full use of the special funds for innovation, increase green innovation investment and green infrastructure construction, and promote the enhancement of China's green technology production efficiency by increasing the amount of corporate innovation and technical equipment research and development tax credits, so as to realize the purpose of urban haze pollution reduction. Therefore, this paper proposes the first hypothesis:

Hypothesis 1: The construction of innovative city pilots significantly promotes the haze reduction effect.

Goals play an important role in performance improvement through guidance, incentive and action plan functions (Zhang, 2021). After the establishment of the innovative city pilot policy, urban innovation has been increasing in governmental decision-making, and local leaders have greater incentives to accept higher demands for urban innovation because governments or organizations set the level of goal expectations and the priority of goals based on the preferences of their superiors (Nielsen, 2014). Since a high concentration of talent has a positive contribution to the growth of urban innovation capacity (Gao and Chen, 2023) and environmental quality is important for attracting high-quality talent

(Liu et al., 2021). Therefore, in order to fulfill their performance objectives, localities increase the level of attention to the local environment and take more active governance measures (Wang et al., 2023a), thus improving the sustainability of the local environment. In addition, urban innovation has led to the development and innovation of technologies such as green technology, clean energy and pollution control (Guo et al., 2023), and technological innovations and breakthroughs have provided local governments with more means and capabilities to improve the environment. As a result, local governments are more inclined to incorporate environmental protection into their core considerations when making decisions (Wang et al., 2023b), and their concern and emphasis on the environment has been enhanced. Based on the above analysis, this paper proposes the following hypotheses:

Hypothesis 2: Innovative city pilot construction triggers a sense of urgency in local governments and strengthens the government's concern for the environment.

The implementation of innovative city pilot policies requires public participation and cooperation, and most pilot cities include content and initiatives to improve the environmental quality of residents' lives and promote green development in the program and process of implementing innovative work, so the construction of innovative city pilots stimulates the public's concern for the environment and pollution control. In addition, consumers' concern for the environment drives firms to adopt green production strategies (Waheed A et al., 2020). Specifically, as the implementation of the pilot policy promotes the public to pay more attention to environmental issues, the public prefers to choose green production enterprises (Tjahjadi et al., 2020), so enterprises will be guided by the public's demand for environmental preferences to strengthen their own awareness of environmental responsibility, to increase the investment in green technology, to carry out the innovation, production, and application of green technology, so as to improve the efficiency of pollutant management (Waheed A et al., 2020). Thus, the efficiency of pollutant management will be improved (Bian et al., 2022). Based on the above analysis, this paper proposes the following research hypotheses:

Hypothesis 3: The pilot construction of innovative cities further awakens people's concern for the environment and forces enterprises to carry out cleaner and greener production, thus realizing the effect of accelerated haze reduction.

Figure 1 shows the research framework of this paper.

4 Research design

4.1 Model setting

The difference-in-differences (DID) model is one of the most popular nonexperimental approaches used in policy evaluation. If the presumption of parallel trends in the treatment and control groups is satisfied, the approach can detect differences before and after the introduction of the policy in the treatment group while accurately measuring the average treatment effect in the treatment group before and after policy implementation (Xue and Zhou, 2022). The enforcement of pilot policies in national innovative cities will not only produce differences before and after the pilot cities' approval but also make haze pollution in national innovative pilot cities different from that in nonpilot cities during the sample period. Meanwhile, the traditional double-difference model is only valid for a single fixed pilot

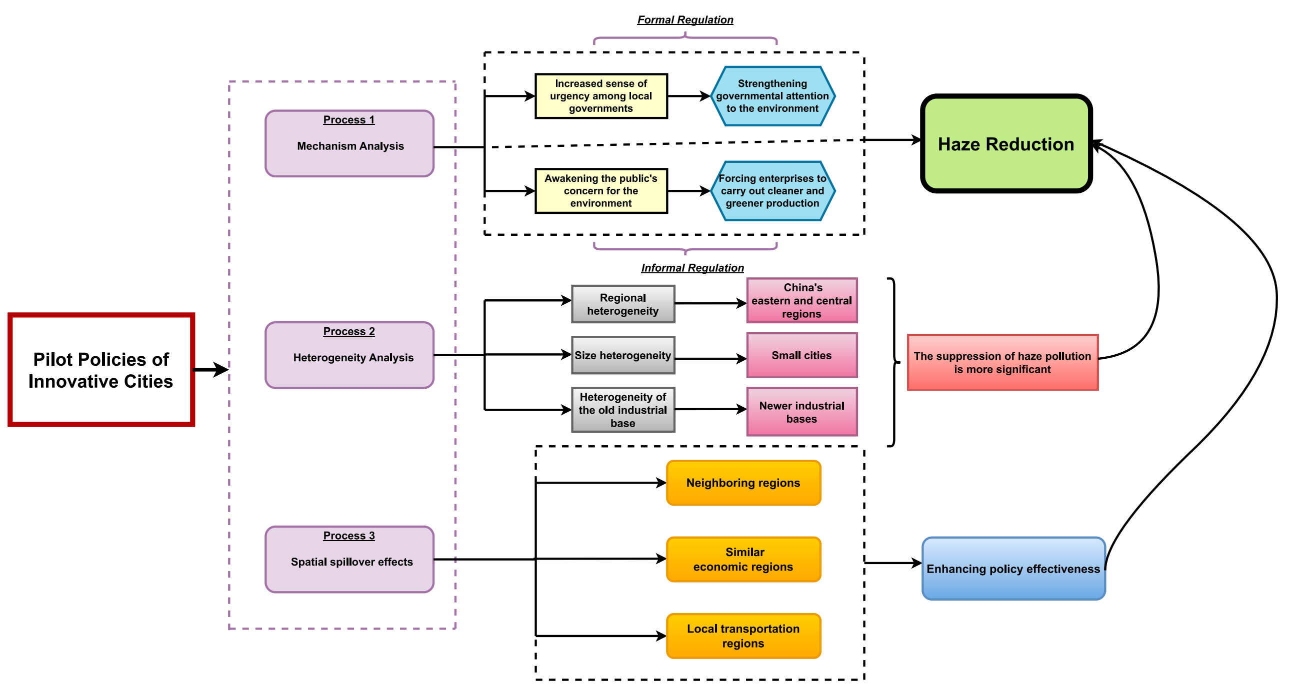

FIGURE 1
Theoretical framework for the effect of PPIC policy on Haze Redction.

policy but lacks an effective evaluation of incremental policies. Taking this into account, to compare haze pollution in pilot and nonpilot cities before and after the implementation of the innovative pilot city policy, this paper views the policy's implementation as a quasinatural experiment and draws on Bertrand et al. (2004) and Wolff (2014). The specific model setup is described as follows:

$$pol_{it} = \beta_0 + \beta_1 policy_{it} + \delta X_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (1)$$

where i is the city and t is the year; pol_{it} is the explanatory variable, i.e., haze pollution in city i in year; $policy_{it}$ is a dummy variable used to represent the national innovative pilot cities, where $policy_{it}$ takes 1 in the year of approval and subsequent years and takes 0 for the nonselected cities, and β_1 is the core coefficient to measure the effect of the implementation of the innovative pilot city policy on haze reduction. Additionally, a series of control variables X_{it} are controlled for; the individual effect of μ_i and the point-in-time effect of η_t are considered; and ε_{it} is a term for erratic disturbance.

4.2 Variable selection

4.2.1 Explained variables

$PM_{2.5}$ is an important "raw material" of haze. Therefore, this paper makes reference to the study by Ma et al. (2016) and utilizes the annual average $PM_{2.5}$ data of Chinese prefecture-level cities published by Columbia University to represent haze pollution.

4.2.2 Core explanatory variables

Dummy variables for national innovation pilot cities ($policy$). More specifically, based on the roster of authorized national innovative city pilots and their respective approval years, the 76 innovative cities adopted in 2008, 2010, 2011, 2012, 2013 and 2018 were used as the experimental group and were calculated as 1 in the year it was approved as well as the years that followed, and calculated as 0 for cities that were not chosen.

4.2.3 Mechanism variables

Referring to the way (Dong and Wang, 2021) defined government environmental concern and public environmental concern, formal environmental regulation (er) is defined in terms of government environmental concern, i.e., using textual crawling. Specifically, the number of words related to pollution in each region's annual government work reports is counted using the textual analysis method to show to what extent the government is concerned about the environment., i.e., formal environmental regulation. Informal environmental regulation ($aware$), i.e., public environmental concern, was used to extract the Baidu search index from 2011 to 2020 by using "environmental pollution" as a search keyword to obtain the average daily number of searches for "environmental pollution" in each city, and this was used to represent the public environmental concern of the city (Dong and Wang, 2021).

4.2.4 Other control variables

To mitigate the influence of other factors on the model, the following control variables are incorporated in this paper:

Green technology innovation ($green\_create$): Referring to Yan et al. (2023), green technology innovation is characterized by the number of green patent applications in the city during the present year. Fiscal science and education bias ($fiance$): According to Wang et al. (2022), in order to characterize fiscal science and education, the ratio of fiscal science and education expenditures to total fiscal expenditures was used. Human capital level (hum): Referring to Feng and Xiao (2023), it is expressed as the number of students enrolled in general higher education in each city as a share of the total city population. The level of foreign direct investment (fdi_pop): Referring to Yang (2023), using the amount of foreign investment actually utilized by each city in the current year to express the foreign capital use. Industrial agglomeration level (co): references are made to Chen et al. (2016) and Yang (2023) to measure the level of industrial synergistic agglomeration in 282 cities above the prefecture level nationwide by summing the number of mining and manufacturing employment and the number of employments in productive services.

4.3 Data sources

This study utilized a balanced panel dataset comprising 282 Chinese prefecture-level cities from 2006 to 2020 as the sample. The aim was to evaluate the influence of experimental

TABLE 1 Statistical characteristics of table attributes of the main variables.

Type	Symbols	Sample size	Average value	Standard deviation	Minimum value	Maximum value
Explained variables	$PM_{2.5}$	4,230	44.342	15.518	11.614	108.526
Explanatory variables	$policy$	4,230	0.127	0.333	0	1
Mechanism Variables	er	4,230	0.003	0.001	0	0.012
	$aware$	2,810	45.49852	68.31957	0	1118.208
Control variables	fdi_pop	4,230	372,000	23,800,000	0.2	1.55E+09
	$green\_create$	4,230	0.081	0.076	0.003	2.255
	co	4,230	0.367	0.071	0.094	1.116
	hum	4,230	0.047	0.043	0.042	0.448
	$fiance$	4,230	0.183	0.056	0.011	1.688

TABLE 2 Baseline regression results.

Variables	[1]	[2]	[3]	[4]	[5]	[6]
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
policy	−6.668***	−6.492***	−6.312***	−3.448***	−3.449***	−3.447***
	[0.606]	[0.615]	[0.618]	(0.764)	(0.764)	(0.768)
fiance		−9.102**	−10.319***	−7.450**	−7.451**	−6.961**
		[3.573]	[3.564]	(3.265)	(3.265)	(3.284)
hum			−33.068**	−32.007**	−31.979**	−29.850**
			[16.170]	(15.364)	(15.368)	(15.031)
green_create				−14.496***	−14.496***	−0.001***
				(2.707)	(2.707)	(0.000)
fdi_pop					−0.000***	−0.000***
					(0.000)	(0.000)
co						−6.378*
						(3.333)
Obs	4,230	4,230	4,230	4,230	4,230	4,230
R-squared	0.799	0.799	0.801	0.812	0.812	0.812

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively. Parentheses surround robust standard deviations.

city policies on the reduction of haze. The main sources of the relevant data include the "China City Statistical Yearbook," the "China Science and Technology Statistical Yearbook," the "City Construction Statistical Yearbook," as well as statistical yearbooks from various provinces and prefecture-level cities. In this paper, the missing data are added by linear interpolation and trend extrapolation methods. To offset confounding factors such as inflation, this paper deflates all monetary indicators to fixed prices with the base period of 2006 according to Guo and Wang (2022), as shown in Table 1.

5 Empirical results and analysis

5.1 Baseline regression

In this study, the effect of a new urban pilot policy on haze reduction is empirically examined using an econometric tool. This study chooses a fixed-effects model that passes the Hausman test for regression analysis. The benchmark regression is conducted using the stepwise regression method, and Table 2 displays a summary of the findings. The change in R^2 from column [1] to column [6] shows that the value of R^2 increases with the gradual inclusion of control variables, making the model's fit more ideal as a result. perhaps suggesting that this paper's choice of control variables was more logical. As seen from column [1] of Table 2, the coefficient of the core explanatory variable $PM_{2.5}$ indicator is significantly negative at the 1% level, indicating that the pilot construction of innovative cities reduces the content of $PM_{2.5}$. Columns [2] to [6] are the outcomes of the model regressions with the sequential inclusion of variables such as fiscal science and education bias, human capital level, green technology innovation, foreign capital usage, and industrial agglomeration level. This result remains true after the inclusion of control variables. The coefficients of $PM_{2.5}$ indicators are all considerably negative at the 1% level with the incremental addition of control factors. This confirms that the implementation of the national innovation city pilot policy effectively suppresses the atmospheric content of $PM_{2.5}$ and promotes the haze reduction effect, as was mentioned in the above section.

5.2 Robustness test

5.2.1 Parallel trend test

The assumption of parallelism must be satisfied in order for the DID approach to policy evaluation of the national innovation city pilot to work. Therefore, before the pilot policy was put into place, the mean $PM_{2.5}$ concentrations of the treatment and control groups were compared to see if there was a significant difference. Drawing from the study of Beck et al. (2010), to investigate the dynamic impact of being designated an innovation pilot city, this paper employs the event study approach to conduct a parallel trend test. The specific model construction is outlined as follows:

$$pol_{it} = \beta_0 + \sum_{\eta=-2}^{\eta=12} \beta_\eta policy_{it} + \delta X_{it} + \mu_i + \eta_t + \varepsilon_{it} \tag{2}$$

in Eq. 2, η is the specific year when the city was approved as a national innovation city pilot. Specifically, when $\eta = -2$, it indicates the first 2 years of the approved pilot city; when $\eta = 12$, it indicates

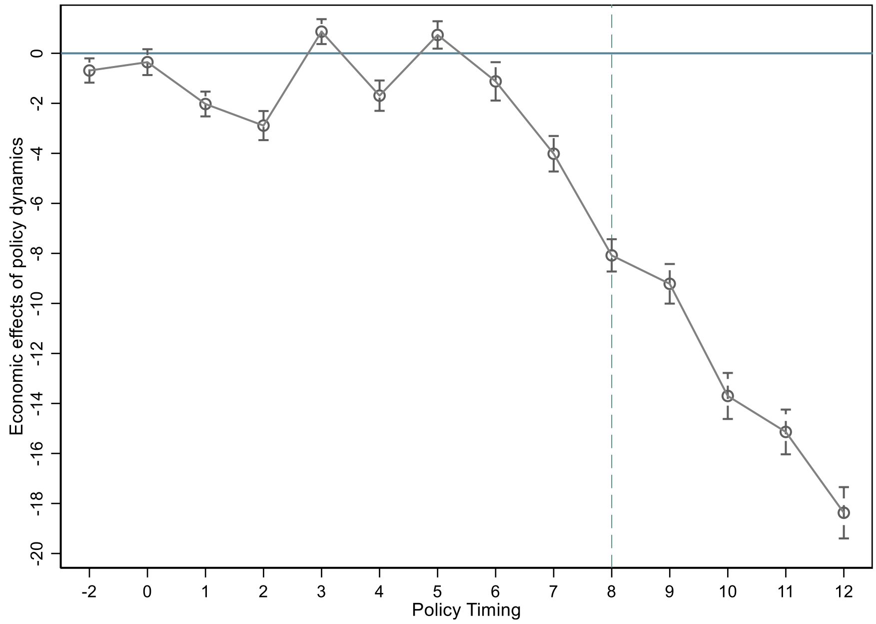

FIGURE 2
Parallel trend test results.

the 12th year after the approval of the pilot city. The remaining variables are explained in an identical way to Equation 1. As can be seen from Figure 2, there may be a leakage of the policy effect before the approval of the pilot city, i.e., there is a forward spillover effect of the haze reduction effect (Fang et al., 2023; Wang, 2023). With this conclusion in mind, there is no significant difference between the treatment and control groups before the official implementation of the policy, satisfying the parallel trend assumption. Additionally, the quantity of pilot cities implementing the innovative city pilot policy in different years is expected to exert a substantial influence on the extent of the policy's impact at different stages. The process of implementing policy can be broken down into corresponding time stages based on differences between the selection of cities in various years and the interannual trends of the average concentration of cities. Figure 2 illustrates that in the 2 years since the policy was launched, i.e., between 2008 and 2010, the average concentration of $PM_{2.5}$ showed a decreasing trend, and the haze reduction effect of the policy had a preliminary appearance. However, since the pilot cities selected in 2010 were mostly heavy industrial cities, whose development was in a state of high emissions, high energy use, and high pollution, the innovation of these pilot cities was limited by their original industrial structure, and the environmental problems were not fundamentally alleviated; therefore, between 2010 and 2013, the average concentration of $PM_{2.5}$ showed a floating increase again. After 2013, the average concentration of $PM_{2.5}$ showed a significant decrease. This is probably because after the 18th Party Congress, the goal of "green water and green mountains are golden mountains" in the new socialist ecological era with Chinese characteristics has promoted the importance of pollution reduction in China. Ma (2019), a time period in which the green and low-carbon development approach has become the mainstream concept of society, and under the constraints of such a strong policy and concept, the selected pilot cities have gradually shifted from the original focus on the innovation of the city's original industries to green technological innovation. This change in development and the improvement of factor allocation efficiency are the inherent requirements and key mechanisms for practicing sustainable development theory and realizing the green transformation of cities (Zhu and Li, 2023). As a result, the haze concentration and environmental quality have improved significantly, and the development of an ecological civilization has deteriorated (Ma, 2019).

5.2.2 Placebo test

Although this paper has controlled for the corresponding control variables in the baseline regressions and provided some treatment for possible biased estimates, the estimation findings of the model are still subject to some unobservable elements that vary with time and space and have corresponding impacts (Chen et al., 2016). Therefore, referring to Topalova (2010), the method of implementing the innovative city pilot policy 2 years in advance was used to examine whether it has a significant contribution to haze reduction. Meanwhile, the selected cities in 2008, 2010, 2011, 2012, 2013, and 2018 were randomly replaced to construct dummy innovative pilot cities, and then dummy variables were created for regression. From the results, it is clear that the estimated coefficients of the baseline regression significantly differ from the test coefficients when advancing the policy by 2 years and randomly replacing the list of pilot cities, so the baseline regression results are not systematically biased, and the omitted variables can be excluded.

5.2.3 Stability analysis results

Since there are many similar region-based policies running at the same time or at crossover, there are cases where some cities are selected for different pilot policy lists simultaneously while the innovative city pilot policy is being implemented. This study

TABLE 3 Placebo test.

	The policy is 2 years ahead of schedule	Selected cities replaced in 2008	Selected cities replaced in 2010	Selected cities replaced in 2011	Selected cities replaced in 2012	Selected cities replaced in 2013	Selected cities replaced in 2018
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
policy	−0.492	−0.242	−0.435	−0.508	−0.408	0.221	0.338
	[0.508]	[0.511]	[0.478]	[0.310]	[0.475]	[0.470]	[1.679]
Obs	4,230	4,230	4,230	4,230	4,230	4,230	4,205
R-squared	0.72	0.724	0.725	0.926	0.725	0.724	0.586

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively. Parentheses surround robust standard deviations.

controls for low-carbon city pilot policies, carbon emission trading city pilot policies, and smart city pilot policies to exclude the impact of other policies on the evaluation of innovation city pilot policies. The regression model used in this study, which is based on the baseline regression, specifically includes the three policy dummy variables mentioned above. Based on the regression results presented in Table 3, incorporating the low-carbon city pilot policy, carbon emission trading city pilot policy, and smart city pilot policy did not yield any discernible impact on the reduction of haze concentration attributed to the innovative city pilot policy. The estimated coefficients of the key explanatory variables remained consistent in both direction and significant when compared to the baseline regression results, and all variables passed the 1% significance test. These findings suggest that the introduction of other policies did not impede the effectiveness of the innovative city pilot policies in reducing haze. Furthermore, although the three types of policies mentioned above have excess suppressive effects on haze pollution, the robustness of the baseline regression results in this paper is further supported by the greater efficacy of the innovative city pilot policy in reducing haze, surpassing the impact of other policies.

The aforementioned experiments and analyses support hypothesis 1, as the hypothesis states that the effect of haze reduction will be considerably enhanced by the pilot construction of innovative cities.

To address the potential issue of non-random selection in the approval of innovative pilot cities, which can introduce sample bias and compromise the accuracy and reliability of the baseline regression results, this study employed the propensity score matching method to match samples from the treatment and control groups. This approach enhances the comparability between the samples of pilot cities and non-pilot cities, further strengthening the validity of the analysis. Following a K-nearest neighbor matching procedure, the samples are matched, and the final matched results are re-estimated, as shown in Table 4. According to the outcomes in the table, the estimated coefficients of still show a significance level of 1% in K-nearest neighbor matching, and its coefficient is negative, agreeing with the outcomes of the baseline regression results. The significant impact of innovative city pilot policies on haze reduction further attests to the robustness of the study's findings.

5.3 Heterogeneity analysis

5.3.1 Regional heterogeneity

Due to China's vast geography and pronounced regional differences in city size, resources, and economic development levels (Ren et al., 2023), the impact of innovative city pilot policies on haze reduction has significant regional heterogeneity. It is clear from Table 5 regional heterogeneity that the eastern and central haze pollution in China has been significantly reduced thanks to the innovative city pilot policy. However, the policy has a reverse effect on haze reduction in western China and does not achieve the expected effect. This is because the eastern region, being the focal point of the nation's economic development, has experienced rapid economic growth since China's reform and opening-up, and it relies on its geographical advantage of being near the sea, has more foreign trade opportunities and foreign frontier technology, and has a higher level of innovative technology and science and technology, improving its capacity for innovation in transforming traditional industries, and its level of cutting-edge technology related to haze reduction can be effectively raised. Although the central region's effect is slightly less significant than in the eastern region, the pilot policy's inhibitory impact on urban haze pollution is still significant, likely because the central region received a new burst of dynamic energy from the central rising strategy that began in 2004; moreover, the industrial structure of the central region began to be gradually optimized and upgraded, and its innovation capacity was improved, helping to lower the pollution level that causes haze. Western cities' effectiveness at reducing haze is unsatisfactory, most likely as a result of the fact that they have absorbed some polluting businesses and industries from the eastern and central regions that are known for their high pollution rates and excessive energy usage; in addition, there is a certain inertia in their production and development patterns, their energy utilization methods and industrial structures need to be improved, and the above characteristics restrict the promotion of innovation in western cities, thus seriously inhibiting their haze reduction effect.

5.3.2 Size heterogeneity

The effectiveness of innovative city pilot policies and their ability to reduce haze pollution are influenced by the size of the cities. Therefore, under various city sizes, this paper verifies the heterogeneous effects of innovative city pilot policies on haze reduction. In this study, the sample cities are split into two subsample groups–large and medium-sized cities and small

TABLE 4 Stability analysis results of the haze reduction effects of innovative city pilots.

	Low carbon city pilot	Carbon emission trading city pilot	Smart city pilot	PSM nearest neighbor matching
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
DT	−3.070***			
	[0.422]			
TPF		−3.388***		
		[0.618]		
ZH			−7.254***	
			[0.441]	
policy	−3.659***	−4.184***	−1.475*	−3.434***
	[0.787]	[0.754]	[0.778]	[0.769]
Obs	4,205	4,205	4,205	4,205
R-squared	0.809	0.808	0.831	0.812

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively.

TABLE 5 Heterogeneity analysis.

	Regional heterogeneity			Size heterogeneity		Heterogeneity of old industrial bases	
	Eastern region	Central region	Western region	Large and medium-sized cities	Small cities	Old industrial base	Non-old industrial base
	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
policy	−4.527***	−3.112*	2.858**	−2.980***	−4.575***	−2.708**	−4.272***
	[0.878]	[1.815]	[1.197]	[0.903]	[1.389]	[1.166]	[0.902]
Obs	1290	1199	1221	1035	3,170	1749	2,456
R-squared	0.864	0.723	0.902	0.815	0.822	0.795	0.819

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively. Parentheses surround robust standard deviations.

cities–and are regressed separately in accordance with the State Council's Notice on Modifying the City Size Classification Criteria. This is done by considering the resident population size of each prefecture-level city and applying the classification criteria developed by Liu and Guo (2022). Both large and medium-sized cities experience a significant reduction in haze pollution because of the innovative city pilot policy, but small cities experience a greater reduction in haze. This is because small cities have more potential for industrial transformation and available space, making their ability to control haze pollution more effective than that of large and medium-sized cities. Large and medium-sized cities, on the other hand, have better infrastructure and a higher base of green development, limiting the space and magnitude of haze pollution reduction in such cities.

5.3.3 Heterogeneity of old industrial bases

In its National Plan for the Adjustment and Transformation of Old Industrial Bases (2013–2022), the National Development and Reform Commission identified 120 cities of old industrial bases, including 27 provinces (Yan et al., 2022). This paper explores the similarities and differences in the effects of innovative city pilot policies for reducing haze in old industrial bases and nonold industrial bases based on different approaches to city functional positioning. From the results of the heterogeneity analysis of old industrial bases in Table 5, it is obvious that nonold industrial bases have a greater impact on haze reduction than old industrial bases. This is perhaps due to the fact that the majority of old industrial bases are known for their high levels of energy use and pollution (Shi and Li, 2020), and the production methods of their bases are relatively difficult to transform, and thus to some extent such methods prevent the innovation process of the old industrial bases and thus inhibits the haze reduction effect. In contrast, nonold industrial bases have more diversified and creative industrial structures, and the higher level of information disclosure leads the policy to have a powerful "warning effect" for enterprises as it is implemented, thus requiring them to develop eco-friendly technology (Deng and Zhao, 2018). Therefore, the innovative city pilot policy's impact on haze reduction is more significant for nonold industrial bases.

5.4 Mechanism testing

According to the above analysis, the implementation of this innovative city pilot policy will notably amplify the effect of haze reduction. To demonstrate that innovative city pilot policies can affect how cities manage their environment through both formal and informal environmental regulation in terms of governmental and public concerns to reduce haze pollution, the following model is created in this paper after taking Wang's research approach into consideration.

$$M_{it} = \beta_0 + \beta_1 policy_{it} + \delta X_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (3)$$

$$pol_{it} = \beta_0 + \beta_1 policy_{it} + \beta_2 policy_{it} * M_{it} + \delta X_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (4)$$

where M_{it} indicates the impact mechanism variables to be verified: government attention (er) and public attention ($aware$). The coefficient β_1 indicates the effect of the pilot policy on the degree of government attention and public attention. Equation 3 confirms the pilot policy's impact on the mechanism variables, i.e., government concern and public concern, and for the purpose of examining the mechanisms by which formal and informal environmental regulations have an impact, a term used to describe the variables' interplay affecting the pilot policy and the mechanism is introduced in Eq. 4.

Table 6 presents the estimation results of formal and informal environmental regulation as mechanism variables. Based on the regression results obtained, it is clear that the innovative cities' pilot policies have significantly strengthened both formal and informal environmental regulation. The pilot policy effectively advances the government's concern for environmental protection in terms of formal environmental regulation, and the policy continues to have a significant contribution to haze reduction. In addition, the impact mechanism variable of interest in this paper is the cross-product coefficient, and the cross-product of government concern and pilot policies suggest that, as a formal environmental regulation becomes more stringent, the government has a greater incentive to promote environmental governance. As a result, the increasing impact of innovative city pilot policies on haze reduction provides support for hypothesis 2 in this study: innovative city pilot construction triggers a sense of urgency in local governments and strengthens their environmental concerns. Regarding informal environmental regulation, the innovative city pilot policy positively encourages people to be concerned about environment protection. It is worth noting that the positive coefficient of the interaction term between public concern and the pilot policy indicates that the amplification of the haze reduction effect of informal environmental regulation in the pilot policy is somewhat limited due to the fact that public-led informal environmental regulation does not have the characteristic of immediate effect compared to government-led formal environmental regulation. A high degree of public concern does not directly lead to the immediate realization of the haze reduction effect, but works through a certain transmission mechanism. From a short-term perspective, the implementation of informal environmental regulations, while enhancing the overall effectiveness of haze reduction as a whole, may bring unintended side effects: in the absence of strict policy constraints and clear penalty mechanisms, such regulations may not be able to immediately stop the polluting behavior of enterprises, and may even lead to an increase in haze pollutant emissions in the short term due to imperfections in regulation. Since technological and production changes require a certain amount of time and capital investment, enterprises will continue their existing production mode and technological path for a period of time. However, from a long-term perspective, increased public attention will force enterprises to complete the innovation and application of greening technologies, and this shift will eventually lead to a reduction in haze pollutant emissions. Therefore, although informal environmental regulation will lead to an increase in haze emissions in the short term, the trend will shift under continued public attention and pressure, and enterprises and the government will work together to promote the haze reduction effect of the innovative city pilot policy.

5.5 Space DID

Using the theoretical mechanism analysis presented in this paper as a foundation leads to the conclusion that innovative city pilot policies have spatial effects. To better capture the spatial spillover effects of such policies, this paper further considers spatial factors, especially the effects of innovative city pilot policies on haze reduction effects. To this end, this paper introduces a new spatial analysis method, the spatial double difference model, aiming to strengthen support for a deeper understanding of the spatial impact of innovative city pilot policies and further improving our knowledge and understanding of the spatial effects of the policies. The spatial double difference model is as follows:

$$pol_{it} = \beta_0 + \beta_1 policy_{it} * W + \beta_2 policy_{it} * W + \delta X_{it} + \beta X_{it} * W + \mu_i + \eta_t + \varepsilon_{it} \quad (5)$$

Equation 5 is the spatial Durbin model (SDM), and is the spatial weight matrix, which mainly includes 2 types of weight matrices: the first type is a matrix of economic distance weights, where the elements of the matrix are the inverse of the differences in absolute GDP *per capita* between cities; the second type is the composite matrix of economic scale and geographical inverse, and the elements in the matrix are the product of the inverse of the geographical distance between two cities and their economic scale, and this is used to measure the spatial relationship between cities. Table 7 displays the outcomes.

The findings of the study indicate a significant reduction in haze due to innovative city pilot policies, as evidenced by the geographic inverse composite matrix and the economic distance matrix. Additionally, the positive and significant spatial lag term provides further evidence of the positive spatial spillover effect resulting from innovative city pilot policies, thus supporting their necessity and importance. At the same time, there is a "cohort effect" of haze reduction between the same cities, i.e., the pilot policies have a certain transmission effect between cities in the same region. However, this study concludes that the two policies' direct effects are not particularly significant. In order to assess the impact of pilot policies on haze reduction and comprehensively analyze their spatial implications in innovative cities, we need to analyze them through utility decomposition.

TABLE 6 Mechanism test.

	Formal regulation		Informal regulation	
	Government Concern(er)	$PM_{2.5}$	Public attention (aware)	$PM_{2.5}$
policy	0.0004***	−5.837***	15.960**	−10.806***
	[0.000]	[1.836]	[6.839]	[0.897]
er*policy		−12.148***		
		[2.848]		
aware*policy				0.032***
				[0.006]
Obs	4,205	4,205	2,809	2,809
R-squared	0.3	0.807	0.691	0.77

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively. Parentheses surround robust standard deviations.

TABLE 7 Spatial double difference regression.

Variables	Economic distance	Composite matrix
	$PM_{2.5}$	$PM_{2.5}$
policy	−0.221	−0.054
	[0.350]	[0.172]
Wx: policy	−3.428***	−1.110***
	[0.753]	[0.407]
Spatial: rho	0.820***	0.993***
	[0.011]	[0.002]
sigma2_e	17.072***	4.669***
	[0.376]	[0.102]

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively. Parentheses surround robust standard deviations.

The outcomes of the decomposition of the spatial effect on the effect of haze reduction are displayed in Table 8. Based the outcomes, it is clear that, utilizing the economic distance weight matrix and the composite matrix weights, the pilot policy of innovative cities on haze reduction has considerable direct and indirect benefits. In the economic distance matrix, the pilot policy has a detrimental direct impact on haze reduction, indicating that the haze concentration in the region is reduced after the implementation of the policy, while the indirect impact on haze reduction is detrimental, indicating that innovative pilot cities have a certain spatial spillover effect, and thus can improve the policy effect in neighboring regions, economically similar regions and transportation convenient regions, thus further reducing the haze concentration. In the composite matrix, the pilot policy's direct and indirect effects on haze reduction are both significantly negative, indicating that the region and its surroundings may experience some improvement from the policy in terms of haze levels. This outcome indicates the significance of the policy's impact on spatial impacts and further validates the pilot policy's actual impact in innovative cities.

In addition, there is some variation in the effectiveness of haze reduction in different regions. Under economic distance weighting, the difference in the haze reduction effect between regions is mainly influenced by the spatial spillover effect, while under composite matrix weighting, it is mainly influenced by the geographical distance and economic scale between regions. Therefore, when implementing the pilot policy of innovative cities, different policy measures should be formulated based on the distinctive features of different regions to further improve the policy effect.

In recent years, the importance of innovative city pilot policies in haze governance has received some attention. The results of this study and the findings of Chen and Chen (2018) confirm the important role of government governance in reducing haze pollution and promoting the quality of economic development. In addition, the study by Ran et al. (2022) similarly points out that the construction of innovative city pilots can effectively reduce urban haze pollution, further validating the reliability of this study.

There are differences in the focus and mechanism analysis between this study and previous literature. For example, the study by Ding et al. (2021) emphasized the indirect promotion of innovative city pilots in suppressing haze pollution through the adjustment of industrial structure, the improvement of technological innovation efficiency, and human capital

TABLE 8 Spatial double difference effect decomposition.

Effect decomposition	Economic distance	Composite matrix
	$PM_{2.5}$	$PM_{2.5}$
Direct: policy	−0.805**	−0.852***
	[0.337]	[0.312]
Indirect: policy	−19.407***	−175.230***
	[3.473]	[66.018]
Total: policy	3.132**	137.650***
	[1.471]	[43.494]

Note: The symbols ***, **, and * denote significance at 1%, 5%, and 10%, respectively. Parentheses surround robust standard deviations.

agglomeration. In contrast, this paper incorporates urban innovation, environmental regulation and haze governance into a unified analytical framework. Starting from two types of environmental regulation, formal and informal, it studies the role played by heterogeneous environmental regulation in the process of innovative city pilot policy for haze reduction, which enriches the research results in the existing field and provides a new research perspective for haze governance.

6 Conclusion and insights

The innovation-driven development strategy has injected new momentum for environmental pollution management, and technological innovation in cities has provided new directions for the codevelopment of the ecology and economy. The pilot policy of innovative cities, as a typical example that blends time and space, fuels this development model of innovation-led green. Panel data on 282 Chinese prefecture-level cities were collected between 2006 and 2020. In this study, an innovative city pilot strategy implemented in 2008 was assessed for its impact on reducing urban haze pollution using a multiperiod two-difference model.

The following findings were obtained. First, the effect of haze reduction will be considerably enhanced by the pilot construction of innovative cities. Second, the implementation of the pilot innovative city policy will trigger a sense of urgency among local governments and strengthen the government's commitment to environmental protection. Third, the pilot policy will further awaken people's concerns about the environment and force enterprises to use clean and sustainable production methods, thus achieving the effect of accelerated haze reduction.

Based on the aforementioned analysis, this paper offers the following policy recommendations for the continued advancement of the innovative city pilot policy. First, it is important to improve the pilot city selection criteria in accordance with location characteristics and industrial development, and urban innovation and policy concepts should be put into practice in accordance with regional circumstances. In the meantime, the pilot cities should take advantage of the chance provided by policy implementation to boost technological innovation spending, adjust the industrial structure, and integrate urban innovation and green development. Second, the government should exert its leading role in promoting policy implementation and pollution control, improve and optimize the assessment and evaluation system for local government leaders, and give better play to the public's restraint and supervision role in environmental control. Third, pilot policies of innovative cities should address spatial impacts during the promotion process and consider measures to increase their spatial spillover impacts. As the number of pilot cities in the policy is gradually increased, the effectiveness of regional haze management can be improved.

In delving into the haze effect of the innovative city pilot policy and the role environmental regulation plays in it, this study provides valuable insights and conclusions. However, as a preliminary exploration, this study still suffers from a number of limitations that provide directions for further exploration in future research.

First, the time horizon of the data in this study limits, to some extent, the comprehensive assessment of the long-term effects of the policy. Since the far-reaching effects of the innovative city pilot policy take a longer time to emerge, the 15-year data range covered in this paper may not be sufficient. Second, due to the limitations of the data and research methodology, some of the more important potential impact factors have not received sufficient attention. For example, in addition to the innovative city pilot policy, other national or local policies, economic development levels, and socio-cultural factors may have an impact on haze management in China. In addition, this study mainly focuses on the macro analysis at the city level, ignoring the complex interactions and behaviors at the micro level, such as those of individuals, households, or enterprises. These micro factors may have positive or negative impacts on haze governance.

Considering the above limitations, future research could take the following directions: first, further extend the data time horizon so as to more fully capture the long-term dynamics of policy effects. Second, incorporate more data sources and research methods, such as qualitative in-depth interviews and case studies, to reveal more nuanced impact mechanisms. Finally, future explorers can explore in greater depth the heterogeneous effects of innovative city pilot policies in different geographic regions, economic conditions, and socio-cultural contexts, to provide references for local governments to formulate more targeted strategies.

In summary, this study has analyzed the haze reduction effect of innovative city pilot policies in some depth, but there are still many issues that deserve further exploration. It is hoped that future researchers will be able to conduct more comprehensive studies on this basis and make greater contributions to the realization of sustainable development and environmental protection.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YX: Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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