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Air pollution and urban economic growth: A study based on dynamic models

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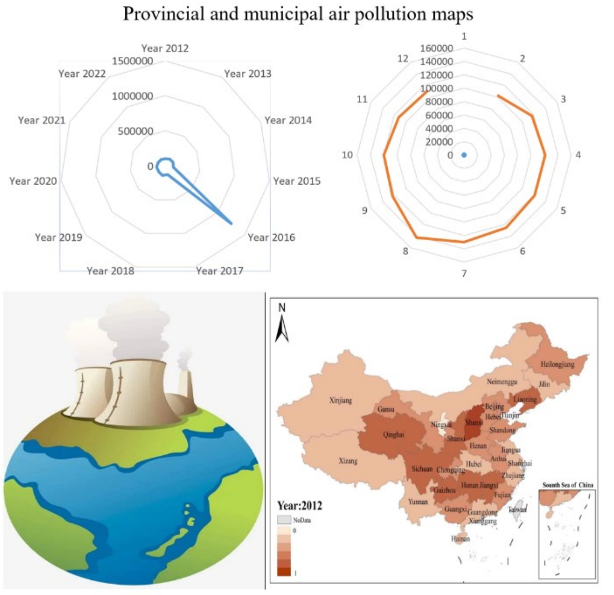
Graphical abstract



Abstract

With China's economic growth, the issue of air pollution has become increasingly prominent. As the core of political and economic development, 184 major cities in China face severe air pollution and significant environmental pressures due to high population density. Consequently, China has established key urban environmental monitoring stations in these cities to monitor pollution emissions in real time. This paper utilizes panel data from 184 Chinese cities spanning 2012-2022 and employs dynamic GMM models, fixed effects models, and mediation effect models to empirically examine the impact of air pollution on urban environmental pollution and its mediation mechanisms. From the perspective of cities with different income levels, a dynamic GMM model is established to determine the correlation between air pollution and various factors influencing urban economic growth. The study finds that air pollution significantly reduces economic growth in Chinese cities at the 1 per cent level, with each unit increase in air pollution reducing economic growth in Chinese cities by 0.84 units. Urbanization and human capital are identified as two crucial channels through which air pollution affects the economic development of Chinese cities. The negative impact of air pollution on economic growth is more pronounced in larger cities compared to smaller ones, and the adverse effects of haze pollution become increasingly significant over time. Therefore, policymakers should take the cultivation and application of new quality productivity as a key strategy to enhance the quality of economic development, and realise a win-win situation between economic growth and environmental protection through scientific and technological innovation and industrial restructuring. This will not only help alleviate the air pollution problem, but also inject new momentum into the high-quality development of China’s economy.

Keywords: Air pollution; urban economic growth; dynamic models; government governance; new quality productivity.

1. Introduction

Since the reform and opening up, China's economy has developed rapidly. However, the extensive development model has led to extensive resource consumption and pollutant emissions. Environmental pollution and its governance have attracted widespread social attention. Under the background of supply-side reforms, eliminating outdated production capacity, energy conservation, emission reduction, and pollution reduction are essential to finding a green development path that ensures long-term coordination between the environment and economy under the guideline of high-quality development. The current environmental situation in China is concerning. According to statistics from the China Environmental Monitoring Station, in 2022, 58.28% of 197 prefecture-level and above cities nationwide exceeded environmental air quality standards, with a compliance rate of only 29.3%. These cities experienced severe pollution for 2,311 days and serious pollution 802 times. Although the concentrations of PM10, sulfur dioxide, and carbon monoxide have decreased year-on-year to varying extents, nitrogen dioxide averages more than 20 micrograms per cubic meter, and ozone has risen by more than 10% on average, indicating serious new pollution governance challenges. Statistics on industrial exhaust emissions illustrate the severe environmental challenges facing China. **Figure 1** shows industrial exhaust emissions in 184 major cities from 2012 to 2022. **Figure 1** depicts the situation in 2016, while **Figure 2** illustrates the total industrial exhaust emissions over the past twelve years.

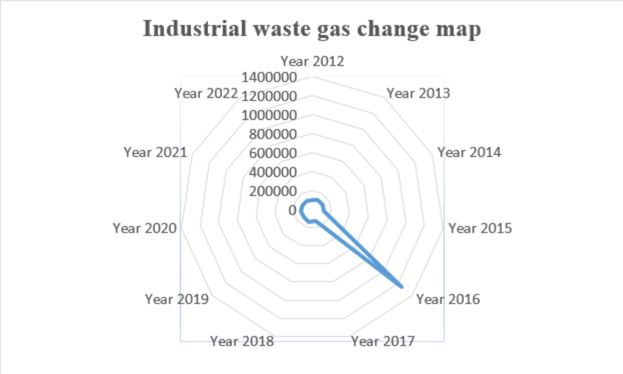


Figure 1. Industrial emissions from 184 major cities across the country in 2016 (in billion cubic metres)

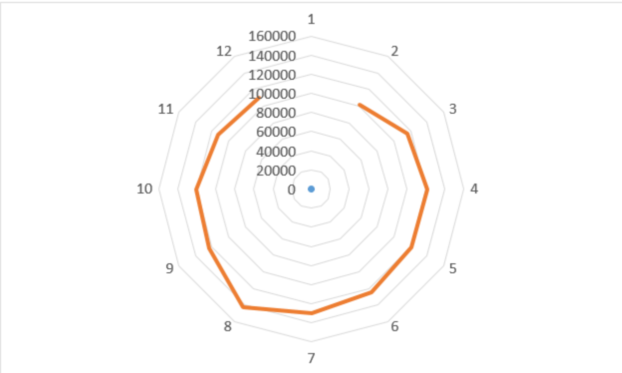


Figure 2. Industrial emissions from184 major cities , 2012-2022 (in billion cubic metres)

The severity of national pollution issues contrasts with uneven regional development, leading to differing economic development and environmental pollution conditions.184 major cities, as the core of their respective regional economies with high population densities, face significant environmental pressures amidst fragile ecological environments and socio-economic development contradictions. Existing historical literature mostly examines nationwide situations across all provinces or municipalities, or focuses on individual provinces or cities, without specifically selecting economically advanced cities with high population densities and significant environmental pressures for comprehensive study. In response, China has established key environmental monitoring stations in 184 major cities , and economically developed cities to monitor pollution emissions in real-time. However, research focusing on the relationship between environmental pollution and economic growth remains limited. This paper addresses this gap by focusing on China's 184 major cities, and economically developed cities, constructing a dynamic panel vector autoregressive (PVAR) model to analyze the current situation of representative environmental pollution indicators and economic growth from 2012 to 2022. It then employs empirical econometrics to explore the bi-directional dynamic relationship between them.

In light of this, this study focuses on the impact and mechanisms of air pollution on urban economic growth. Using panel data from 184 Chinese cities at or above the prefecture level from 2012 to 2022, it analyzes the effects of air pollution on urban economic growth, investigates the mediating effects and heterogeneity of air pollution's impact on urban economic growth, and provides robust empirical evidence and policy references for enhancing government efforts in reducing air pollution and promoting economic growth.

The potential contributions of this study are threefold: firstly, it enriches the literature on the impact of air pollution on urban economic growth by providing beneficial discussions from both theoretical and empirical perspectives, thereby expanding the research on environmental pollution influencing factors. Secondly, it explores the theoretical and empirical mechanisms through which air pollution affects urban economic growth, incorporating heterogeneity analysis to deconstruct the intrinsic logic between the two. Thirdly, by employing the dynamic GMM model to address endogeneity issues, the study ensures the robustness of its conclusions, thereby providing reliable empirical references to support urban economic growth through air pollution governance (Wen *et al.* 2024).

2. Literature review

2.1. Studies on economic growth

Internationally, research on economic growth has progressed through stages from "classical economics" to "neoclassical economics," "endogenous economic growth," and "economic growth incorporating environmental factors." Scholars such as Grossman (1995) and Keller & Levinson (2002) had examined the relationship between per capita income and environmental pollution using particulate matter and suspended particulate matter as environmental variables. They were the first to conceptualize the relationship between economic growth and the environment as a inverted U-shaped curve. Subsequent studies have extensively explored and applied variations of the traditional environmental Kuznets curve across multiple industries and sectors (Lu *et al.* 2017; Ongan *et al.* 2023; Mughal *et al.* 2022).

2.2. Studies on environmental pollution

Due to early industrialization in foreign countries, scholars had primarily analyzed pollution reduction from the perspective of emissions control (Amyaz *et al.* 2012; Brannlund 1995). Starting from the perspective of firm decision-making under pollution emission control, based on microeconomic producer equilibrium theory, it is considered that firms achieve equilibrium when the sum of pollution control costs and marginal costs equals marginal benefits (Zhu & Xu 2022; Ma *et al.* 2024). Incorporating risk factors into the production models of enterprises, it is argued that pollution control may lead firms away from economic optimality, resulting in negative economic impacts on the market. Amyaz et al. (2012) constructed a two-stage dynamic game model to study the strategic behavior of enterprises in response to government emission reduction policies, finding that implementing pollution tax policies incentivizes firms to increase governance costs to minimize tax burdens.

Additionally, studies have found that emissions of environmental pollutants are primarily influenced by factors such as economic scale, industrial structure, population density, economic policies, and technological progress. In recent years, many scholars, such as Yang et al. (2023), have studied the influencing factors of environmental pollution emissions from the perspectives of industrial agglomeration and industrial structure. Domestic research on environmental pollution lags behind foreign studies, often directly adapting and refining established theoretical frameworks from abroad, focusing on empirical research (Danish & Ulucak 2020). Domestic scholars hold divergent views on the relationship between environmental pollution and economic growth (Yu *et al.* 2022; Ali & Puppim de Oliveira 2018). Considering China's actual conditions, some scholars argue that pollution decreases with economic growth, while others suggest that economic growth increases pollution due to the significant environmental damage caused by past extensive development (Song *et al.* 2021; Addis & Cheng 2023; Wen *et al.* 2024).

2.3. Research on the relationship between environmental pollution and economic growth

Foreign scholars such as Arizala et al. (2013) mainly examined the relationship between environmental pollution and economic growth using the Environmental Kuznets Curve (EKC), while also exploring the economic mechanisms of pollution. Over time, many scholars have found that the EKC curve exhibits shapes other than just an inverted U-shape. Consequently, many scholars have studied the relationship between environmental pollution and economic growth from the perspective of pollution control limits. Hamamoto (2006), by examining the relationship between Japan's industrial economic growth and pollution limits from the perspective of total factor productivity, found that pollution limits indirectly enhance total factor productivity through technological pathways, driving Japan's economic growth, with this promoting effect increasing exponentially with scientific progress.

Research on the relationship between environmental pollution and economic growth has evolved from unidirectional effects to bidirectional interactions. Regarding the unidirectional impact of economic growth on environmental pollution, most scholars had empirically tested different provinces or regions based on the theory of the Environmental Kuznets Curve and endogenous growth theory, yielding varied conclusions on the role of economic growth in environmental pollution (Aminzadeh & Daei-karimzadeh 2021). Continuously exploring and updating methods for studying systematic bidirectional coupling, Rasool et al. (2020) used VAR models to study the relationship between environmental pollution and economic growth. However, the length of environmental pollution time series often fails to meet the requirements of VAR models, potentially impacting the validity of empirical results. Xie et al. (2017) demonstrated that China's current environmental impact on the economy exhibits adverse negative effects, albeit with varying severity across different regions. The adverse feedback mechanism of industrial pollution indicators in eastern regions is weakened, whereas that of residential pollution is more significant. In central and western regions, the adverse feedback from industrial pollution is pronounced, significantly constraining economic growth in western regions. PVAR models effectively combine the advantages of VAR models with less dependence on theoretical foundations, using data to establish mathematical relationships, which are crucial in regional economics requiring provincial or municipal panel data. Although Babalos & Stavroyiannis (2020) applied this model in financial and investment panel data studies, its application in regional environmental economics remains relatively scarce, presenting opportunities for further exploration.

3. Research content and methodology

Building upon a thorough review of relevant literature and theories, this study selected pertinent indicators and collected historical data to analyze the trends of air pollution and economic growth in China's direct-controlled 184 major cities , thereby providing empirical support. Subsequently, the study employed Generalized Method of Moments (GMM) estimation to examine the dynamic relationships between air pollution and urban economic growth.

The most commonly used estimation methods for panel data models are the fixed effects model and the random effects model, but the endogeneity problem exists in the model when the lagged terms of the explanatory variables are introduced as explanatory variables into the regression model, making the model dynamically explanatory. Therefore, Arellano (1995) and others proposed the so-called generalised method of moments (GMM), and the GMM estimation methods for dynamic panel data models are subdivided into DIF-GMM and SYS-GMM.Roodman (2005) argued that although the difference GMM method reduces the impact of endogeneity on model estimation, under the limited sample condition, the difference GMM method has a serious ‘weak instrumental’ problem. Roodman (2005) argued that although the difference GMM method reduces the impact of endogeneity on the model estimation, under limited sample conditions, the difference GMM method suffers from a serious problem of ‘weak instrumental variables’, which leads to poor accuracy of coefficient estimation. In this regard, a systematic GMM estimation method is proposed to solve the problems of autocorrelation, heteroskedasticity, endogeneity and weak instrumental variables, while Roodman (2005) pointed out that the necessary condition for the application of a systematic GMM model is that the number of cross-sections should be larger than the time dimension. As the number of periods increases, the system GMM generates by default a large number of instrumental variables that may outweigh the endogenous variables and weaken the model setting tests. Therefore, in order to make the results more reliable, we favour a two-step system GMM approach for estimating panel data.

3.1. Data sources

To ensure continuity and accessibility of sample data, observations from 2012 to 2022 were gathered from 184 cities at or above the prefecture level (excluding Hong Kong, Macau, and Taiwan). Pollution emission data and socio-economic indicators were sourced from *China Urban Statistical Yearbook*, *China Regional Statistical Yearbook*, as well as provincial and municipal statistical yearbooks and bulletins. To maintain dimensional consistency and symmetry, all variables underwent natural logarithmic or scale-free transformations (see **Table 1**). Specifically, per capita GDP was used as the dependent variable to measure urban economic growth.

Table 1. Data description and statistical description of variables

Variables	Metric or description	Unit	Original data sources	N	Mean	Median	Std
Urban economic development	Real GDP per capita	Hundred yuan	China Urban Statistical Yearbook	1678	340. 8	254. 7	305. 6
$PM_{2.5}$	$PM_{2.5}$ concentration	Microgram /m^3	Ma et al. (2016)	1678	64. 3	61. 6	21. 4
Financial development	Loans from financial institutions per capita	Hundred yuan	China Urban Statistical Yearbook	1678	277. 7	117. 8	465. 5
Open to the outside world	FDI /GDP	%	China Urban Statistical Yearbook	1678	14. 8	8. 6	16. 2
Government investment in R&D	Per capita fiscal expenditure on science and technology	Yuan	China Urban Statistical Yearbook	1678	100. 8	33. 0	232. 7
Infrastructure	Road construction area per capita	m^2	China Urban Statistical Yearbook	1678	10. 6	8. 6	27. 0
Share of secondary production	Secondary sector as a percentage of GDP	%	China Urban Statistical Yearbook	1678	51. 0	51. 6	12. 6
Share of heavy industry	Heavy industry as a share of industry	%	Database of industrial enterprises	1678	80. 8	83. 1	13. 4

Table 2. Benchmark regression results

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Core explanatory variable: current $PM_{2.5}$			**Core explanatory variable: $PM_{2.5}$ lagged by one period**		
	lnGDP	***lnGDP***	***lnGDP***	***lnGDP***	***lnGDP***	***lnGDP***
$lnPM_{2.5}$	-0.76*** (3.21)	-0.71*** (3.15)	-0.84*** (3.36)			
L. $PM_{2.5}$				-0.82*** (3.31)	-0.74*** (3.18)	-0.88*** (3.53)
Share of secondary production		6.16*** (3.48)	5.98*** (3.37)		6.78*** (3.59)	6.89*** (3.63)
Share of heavy industry			3.98*** (3.12)			4.12*** (3.21)
Financial development	0.78** (2.19)	0.81** (2.21)	0.82** (2.23)	0.79** (2.19)	0.83** (2.25)	0.80** (2.20)
Open to the outside world	0.32** (2.34)	0.38** (2.38)	0.33** (2.36)	0.37** (2.38)	0.35** (2.37)	0.39** (2.40)
Government investment in R&D	0.38** (2.38)	0.32** (2.33)	0.39** (2.41)	0.41*** (2.67)	0.46*** (2.73)	0.48*** (2.76)
Infrastructure	1.29** (2.34)	1.25** (2.31)	1.29** (2.35)	1.21*** (2.78)	1.28*** (2.83)	1.31*** (2.86)
Constant	4.39*** (3.98)	4.31*** (3.92)	4.28*** (3.87)	4.56*** (4.32)	4.61*** (4.49)	4.76*** (4.51)
City effect	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES
N	1678	1676	1676	1494	1492	1492
R^2	0.38	0.42	0.39	0.42	0.46	0.44

*Note: ***, ** and * denote significance at the 1, 5 and 10 per cent significance levels, respectively; numbers in parentheses are t-values. L. PM2.5 is a one-stage lagged operator.*

3.2. Model construction

To ascertain whether air pollution adversely affected urban economic growth, a fixed-effects panel data model was constructed as follows:

$$lnGDP_{it} = \alpha_0 + \alpha_1 \ln PM_{2.5it} + \alpha_2 C_{it} + u_i + v_t + \mu_{it} \quad (1)$$

Per capita GDP $_{it}$ represents the per capita real GDP of city i in year t, serving as a proxy for urban economic development quality. $PM_{2.5\,it}$ denotes the concentration of $PM_{2.5}$ particles in city i during year t, measuring urban air pollution levels. The coefficient α1 quantifies the impact of haze pollution on economic development quality, constituting a key parameter of interest. A negative and statistically significant α1 after controlling for various city-specific variables would indicate that air pollution reduces economic development quality. Otherwise, the opposite would hold true. Additionally, city and time fixed effects were controlled to further mitigate omitted variable bias. Finally, μ_{it} represents the error term.

In contrast to conventional pollutants such as SO_2, CO_2, CO, TSP, API, and PM_{10} utilized in most studies, this research focused on $PM_{2.5}$, a primary concern among various societal sectors. This approach not only supplements existing research but also contributes to current policy discussions on haze pollution. Particularly noteworthy is the comprehensive coverage of $PM_{2.5}$ concentration data across nearly all prefecture-level and above cities in China over a decade-long period, providing a robust data foundation for accurately discerning the impact of air pollution on China's economic development quality. Based on the economic literature available on China's air pollution, the utilization of $PM_{2.5}$ concentration data in this study represents the largest sample capacity.

The PM2. 5 concentration source data measurements used in this paper are from Ma et al. (2016). These data are derived from latitude and longitude grid data, calculated using a two-stage spatial statistical model integrating satellite and ground monitoring data. Using ArcGIS 10.6 software, the grid data were further processed to obtain $PM_{2.5}$ concentration data for 184 prefecture-level and above cities in China from 2012 to 2022. This $PM_{2.5}$ concentration data has been employed in high-level research outside the field of economics (e.g., He *et al.* 2016). In comparison to $PM_{2.5}$ concentration data derived from satellite monitoring published by the *Center for International Earth Science Information Network* (CIESIN) at Columbia University, the advantage of this study's data lies in its comprehensive use of indirect satellite monitoring data alongside direct ground monitoring data. Moreover, a two-stage spatial statistical model was employed to optimize the data, providing a more accurate reflection of haze pollution levels in China (Wang and Ma 2024; Wen, Ma and Su 2024).

In addition to the total effect indicated by Equation (1), air pollution may indirectly affect urban economic growth through certain mediating mechanisms. Based on previous research hypotheses, it is assumed that air pollution may reduce urban economic growth through urbanization effects and human capital effects. Thus, the following mediating effect model was established:

$$M_{it} = \beta_0 + \beta_1 \ln PM_{2.5it} + \beta_2 C_{it} + u_i + v_t + \mu_{it} \quad (2)$$

$$lnGDP_{it} = \gamma_0 + \gamma_1 \ln PM_{2.5it} + \gamma_2 M_{it} + \gamma_3 C_{it} + u_i + v_t + \mu_{it} \quad (3)$$

Here, *M* represents the mediating variables, specifically urbanization and human capital levels. The definitions of other variables are consistent with Equation (1). The term $\beta_1 \times \gamma_2$ denotes the mediating effect, indicating how air pollution influences urban economic growth through its impact on mediating variables.

4. Analysis of the impact of air pollution on urban economic development quality and its transmission mechanism

4.1. Baseline regression

Table 2 reports the regression results of the baseline model, Equation (1). From the results of the first column, after controlling for various city-specific variables and fixed effects, air pollution exhibits a significant negative correlation with urban economic development quality. Considering that economic development patterns simultaneously affect economic development quality and air pollution, particularly the imbalance in industrial structure and the expansion of heavy industry are crucial factors exacerbating haze pollution in China. Failure to effectively control these factors could lead to omitted variable bias, thereby affecting the reliability of the study results. The second column introduces the proportion of secondary industry to control the influence of industrial structure, and the results demonstrate that a significant negative relationship between air pollution and urban economic development quality persists. In the third column, the proportion of heavy industry is included in the regression equation to control for the influence of economic development patterns, and the results continue to show a significant negative correlation between air pollution and urban economic development quality. Finally, to mitigate reverse causality bias, since current economic development does not affect historical air pollution, columns 4 through 6 lag $PM_{2.5}$ by one period. The regression results indicate that the adverse impact of air pollution on economic development quality remains statistically significant. Furthermore, the coefficients of other control variables align closely with expectations.

4.2. Analysis of transmission mechanisms

The linear regression results of the baseline model indicate that overall, air pollution significantly reduced economic growth development in Chinese cities. Therefore, did air pollution initially negatively affect the quality of economic development in Chinese cities, or did this negative impact gradually emerge only after air pollution reached a certain level? Numerous studies suggest that the destructive impact of environmental pollution largely depends on its severity, potentially exhibiting a Kuznets curve effect on economic development.

The aforementioned research results demonstrate that air pollution has a negative impact on the quality of economic development in Chinese cities. What then are the reasons behind this phenomenon? In other words, what are the transmission mechanisms through which air pollution affects the quality of economic development in China? Building upon previous sections, this section explores the transmission mechanisms of haze pollution's impact on the quality of economic development in Chinese cities through urbanization processes and human capital channels. Considering significant spatial and temporal variations in Chinese air pollution, this subsection further conducts heterogeneous analysis through subsample regressions. Specifically, this study divides the sample based on city size and time period. We proceed to discuss the mechanisms through which air pollution affects the quality of economic development in Chinese cities via urbanization and human capital mechanisms.

Table 3. Urbanisation mechanisms

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Impact of urbanisation on GDP per capita		Impact of $PM_{2.5}$ on urbanisation				
	GDP per capita	GDP per capita	Full sample urbanisation	Urbanisation of large and medium-sized cities	Urbanisation of small cities	2012-2016 year	2017-2022 year
L. lnPM2.5			-0.54*** (-3.36)	-0.67*** (-3.67)	-0.29*** (-3.12)	-0.37*** (-3.03)	-0.39*** (-3.19)
Ln urbanisation	1.12*** (3.41)						
L. ln urbanisation		1.34*** (3.58)					
Constant	YES	YES	YES	YES	YES	YES	YES
Control effect	YES	YES	YES	YES	YES	YES	YES
City effect	YES	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES	YES
N	683	678	499	231	268	192	307
R^2	0.35	0.36	0.41	0.44	0.47	0.30	0.2

*Note: ***, ** and * denote significance at the 1, 5 and 10 per cent significance levels, respectively; numbers in parentheses are t-values. L. PM2.5 is a one-stage lagged operator.*

Table 4. Human capital mechanisms

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Impact of human capital on GDP per capita		Impact of $PM_{2.5}$ on human capital				
	GDP per capita	GDP per capita	Full sample human capital	Human capital in large and medium-sized cities	Human capital in small cities	2012-2016 year	2017-2022 year
L. lnPM2.5			-0.24*** (-2.86)	-0.47*** (-3.12)	-0.09*** (-2.72)	-0.17*** (-3.11)	-0.26*** (-3.34)
Ln human capital	3.43*** (4.41)						
L. ln human capital		4.12*** (4.79)					
Constant	YES	YES	YES	YES	YES	YES	YES
Control variables	YES	YES	YES	YES	YES	YES	YES
City effect	YES	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES	YES
N	1532	1421	1524	568	956	628	896
R^2	0.28	0.22	0.23	0.32	0.32	0.34	0.38

*Note: ***, ** and * denote significance at the 1, 5 and 10 per cent significance levels, respectively; numbers in parentheses are t-values. L. PM2.5 is a one-stage lagged operator.*

Firstly, air pollution can affect economic development in Chinese cities through urbanization processes. On one hand, urbanization serves as a crucial driver for enhancing economic quality by effectively reducing surplus rural labor, thereby promoting the development of manufacturing and service industries, ultimately driving overall economic progress. On the other hand, air pollution diminishes urban attractiveness, thereby slowing down the urbanization process (Hanlon 2016). To verify this mechanism, this study uses the proportion of non-agricultural population to total population as a proxy variable for urbanization. **Table 3** reports the corresponding empirical regression results. The regression coefficients of urbanization variables in columns 1–2 significantly positive indicate that urbanization promotes the quality of economic development in Chinese cities. The coefficients of urbanization variables in columns 3–7, which are significantly negative, indicate that air pollution slows down the urbanization process. It is noteworthy that urbanization processes often accompany population and industrial agglomeration, which may in turn affect air pollution. To address this endogeneity issue, columns 3–7 of **Table 3** use lagged one-period air pollution to examine its impact on urbanization. Furthermore, concerning the negative impact of air pollution on urbanization, major cities are more affected than smaller cities, consistent with the greater sensitivity of urban residents in major cities to haze pollution. Additionally, the negative impact of air pollution on urbanization intensifies with the passage of time, aligning with the worsening haze pollution in recent years, which has garnered widespread attention from various sectors of society.

Table 5. Heterogeneity analysis

Variables	**(1)**	**(2)**	**(3)**	**(4)**
	City heterogeneity		**Time heterogeneity**	
	Big, medium city	**Small city**	**2012-2016 year**	**2017-2022 year**
	lnGDP	**lnGDP**	**lnGDP**	**lnGDP**
lnPM2.5	-0.47*** (-3.16)	-0.35*** (-2.65)	-0.39*** (-2.64)	-0.48*** (-3.26)
L. lnPM2.5	-0.46*** (-3.52)	0.31*** (-3.11)	-0.34*** (-3.06)	-0.46*** (-3.47)
Constant	YES	YES	YES	YES
Control variables	YES	YES	YES	YES
City effect	YES	YES	YES	YES
Time effect	YES	YES	YES	YES
N	1468	1524	1678	1664
R^2	0.27	0.31	0.34	0.44

*Note: ***, ** and * denote significance at the 1, 5 and 10 per cent significance levels, respectively; numbers in parentheses are t-values. L. PM2.5 is a one-stage lagged operator.*

Table 6. Robustness analysis

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
	lnGDP	***lnGDP***	***lnGDP***	***lnGDP***	***GDP***
Annual precipitation				-0.06*** (-2.76)	
lnPM2.5	-0.34*** (-2.86)	-0.31*** (-2.75)	-0.27*** (-2.64)	-0.28*** (-2.66)	
L. lnPM2.5	-0.36*** (-3.02)	0.41*** (-3.12)	-0.44*** (-3.86)	-0.36*** (-3.67)	
PM2.5					-0.33*** (-2.78)
L.PM2.5					-0.23*** (-3.12)
Constant	YES	YES	YES	YES	YES
Control variable	YES	YES	YES	YES	YES
City effect	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES
N	1468	1524	1678	1664	1678
R^2	0.25	0.23	0.32	0.24	0.27

*Note: ***, ** and * denote significance at the 1, 5 and 10 per cent significance levels, respectively; numbers in parentheses are t-values. L. PM2.5 is a one-stage lagged operator.*

Secondly, another important mechanism through which air pollution affects the quality of economic development in Chinese cities is by influencing the accumulation of human capital. On one hand, human capital is one of the most critical factors driving the improvement of economic quality, particularly considering that current economic development has fully entered the era of the knowledge economy. On the other hand, air pollution significantly impairs the accumulation of human capital by affecting educational levels and health conditions (Zivin & Neidell 2012; Chang *et al.* 2016). This study uses the average years of education, widely used in the literature, as a proxy variable for human capital to empirically test the human capital mechanism through which air pollution affects the quality of economic development in China. **Table 4** shows that the human capital transmission mechanism is effectively validated, indicating that the accumulation of human capital enhances the quality of economic development while air pollution significantly reduces human capital. Furthermore, regarding the heterogeneity of how air pollution affects human capital, the impact of air pollution on human capital in major cities is higher than in smaller cities, and in recent years, the negative impact of air pollution on human capital has significantly increased. This aligns with the facts that air pollution in major cities in China is higher than in smaller cities and that haze pollution has intensified in recent years.

5. Heterogeneity analysis

The previous analysis of the transmission mechanisms of air pollution's impact on economic growth in Chinese cities indicates that the negative effects on urbanization processes and human capital, as intermediate variables, are significantly higher in large and medium-sized cities compared to small cities. Moreover, these negative impacts have been increasing over time. Clearly, if heterogeneity exists in how air pollution affects the quality of economic development in Chinese cities, similar results should be observable in the heterogeneity analysis. Building on this premise, this section proceeds to explore the heterogeneous impacts of air pollution on Chinese urban economic growth using the setup in **Table 5** as a baseline.

As shown in **Table 5**, the econometric results indicate that the negative impact of air pollution on the quality of economic development in large and medium-sized cities is significantly higher than in small cities, with a notable increase in the adverse effects of haze pollution in recent years. This finding corroborates the results of the previous transmission mechanism analysis. Additionally, we find that smaller cities exhibit better haze pollution control effects compared to larger and medium-sized cities. This seemingly "anomalous" result is economically intuitive: although smaller cities generally place less emphasis on environmental governance compared to larger and medium-sized cities, they are often more capable of directly controlling environmental pollution through immediate administrative orders and accountability mechanisms, given equal attention levels.

Results from columns 3 and 4 of the time heterogeneity regression in **Table 5** indicate that environmental governance effectiveness during 2017–2022 has been superior to that during 2012–2016, aligning with the increased intensity of government environmental governance policies in recent years.

6. Robustness analysis

6.1. Sample exclusion

To enhance the comparability of the study sample, this paper excludes samples of cities above the prefectural level, retaining only samples of prefectural-level cities. The regression results in **Table 6**, column 1, are highly consistent with the baseline scenario.

6.2. Outlier removal

Furthermore, to examine the influence of outliers in $PM_{2.5}$ concentrations on regression results, column 2 of **Table 6** excludes the top and bottom 1% of $PM_{2.5}$ concentration samples. The research findings remain largely unchanged.

6.3. Variable substitution

Given that $PM_{2.5}$ concentration is the core explanatory variable, this study further substitutes unit area emissions of SO_2 and particulate matter emissions for $PM_{2.5}$ pollution to assess their impacts on the quality of economic development in Chinese cities. The specific regression results in **Table 6**, column 3, show that the significance levels remain largely unchanged.

6.4. Instrumental variables approach

During rainy and snowy weather, haze pollution tends to significantly decrease. Both rainfall and snowfall are determined by meteorological systems and possess good exogeneity. Column 4 of **Table 6** employs annual precipitation transformed into rainfall and snowfall as additional instrumental variables for haze pollution. The results indicate that although the absolute value of the $PM_{2.5}$ concentration coefficient decreases, it remains significant at the 1% level, once again demonstrating the robustness of the study results.

6.5. Replacement of explanatory variables

Finally, the empirical analysis was conducted using the method of replacing the explanatory variables by replacing lnGDP with GDP in order to examine the sensitivity of the regression results to the model setup, and the empirical results, as shown in Column 5 in **Table 6**, indicate that the negative impact effect of air pollution on the economic development of the city is still significantly present.

7. Conclusion and recommendations

7.1. Conclusion

With economic growth, China's issues of resource scarcity and environmental pollution have gradually become more prominent.184 major cities, as core areas of political and economic development, face more severe environmental pollution due to their high population density. Environmental protection and economic development have always been perennial concerns for humanity, particularly as China enters a new era of development, intensifying global attention to these issues. The key questions of how to effectively combat pollution and promote high-quality economic development through government environmental governance are crucial. Achieving these dual goals depends on a comprehensive understanding of the relationship between environmental pollution and economic development, as well as on scientifically evaluating the effectiveness of government environmental governance.

This study focuses on 184 major cities, collecting per capita GDP data from 2012 to 2022, aligned with the background of China's new economic normal. Air pollution, measured by $PM_{2.5}$ indicators, reveals the following trends:

First, the study finds that air pollution significantly reduces economic growth in Chinese cities.

Second, urbanization and human capital are two critical transmission channels through which air pollution affects economic development in China.

Third, heterogeneity analysis indicates that the negative impact of air pollution on economic growth in large and medium-sized cities is significantly higher than in small cities, with the adverse effects of haze pollution becoming increasingly pronounced over time.

Overall, emissions of industrial gases have shown a declining trend year by year, with a significant decrease in urban living emissions due to environmental policy formulation and desulfurization technology updates at the end of the Eleventh Five-Year Plan and the beginning of the Twelfth Five-Year Plan. However, emissions have continued to rise in subsequent years. Based on the empirical findings, relevant policy recommendations are proposed to promote win-win outcomes for environmental protection and economic growth.

7.2. Recommendations

The conclusions drawn from this study carry significant policy implications. Historically, under the backdrop of economic development, the prevailing view has been that reducing haze pollution inevitably harms economic growth, leading some regions to passively tolerate haze pollution. However, the capacity of the environment is finite, and sustained economic growth through continuous pollution emissions is inherently unsustainable. Today, China faces the dual challenges of severe environmental degradation and the need to improve the quality of economic development. Extensive economic growth patterns have exacerbated haze pollution, which in turn affects the quality of China's economic development through processes like urbanization and human capital accumulation. Breaking such a vicious cycle and overcoming these dilemmas fundamentally requires the effective implementation of rational and efficient government environmental governance policies.

The policy recommendations in this paper emphasise the importance of technological innovation, knowledge accumulation, human capital enhancement and green development in environmental protection and economic growth. Based on the empirical results, this paper proposes strategic recommendations from the perspectives of industrial structure optimization, urban development, population policies, legal framework enhancement, and standardized emission trading markets to facilitate early formation of win-win situations for environmental protection and economic growth.

7.2.1. Cultivate new quality productivity and optimise industrial structure

In the context of supply-side reform, emphasising the cultivation and development of new-quality productive forces, seizing historical opportunities, eliminating outdated production capacity and improving the quality of economic development is a key way to reconcile the harmonious relationship between environmental protection and economic growth. Firstly, the proportion of the secondary industry should be adjusted in a targeted manner according to the specific conditions of each city, and the exit of high-energy-consuming and high-polluting industries should be accelerated from the internal structure of the industry, so as to promote the growth of green and recycling production capacity. Secondly, through the integration of advanced technologies such as the Internet and artificial intelligence, the technological content and added value of the traditional manufacturing industry should be improved to achieve the transformation of the industry from the low-end to the high-end, and to build a modern industrial system with competitiveness and sustainability. On this basis, it will vigorously develop strategic emerging industries, focusing on the layout of new materials, new energy and intelligent manufacturing, strengthening the drive of scientific and technological innovation, and improving the quality and efficiency of the industrial structure. As leaders of the regional economy, the 184 major cities should actively promote the transfer of industries, and realise the coordination and unity of industrial optimisation and upgrading and environmental protection with full consideration of the carrying capacity of the environment. Thirdly, the proportion of tertiary industries should be raised, and the natural endowments of Kunming, Guilin and other cities should be brought into full play to develop green eco-agriculture and tourism, so as to construct a diversified and green industrial development pattern, and to comprehensively promote the high-quality and sustainable development of the economy.

7.2.2. Establish environmental audits, improve emission trading markets

Per capita GDP and air pollution indicators are the most potent explanatory factors for self-change, with per capita GDP explaining high levels of environmental pollution. The main reason for this is that China's GDP statistics have yet to incorporate environmental costs into its scope, so the growth of per capita GDP can explain changes in pollution through mechanisms such as industrial structures and population agglomeration, but pollution changes lack feedback mechanisms in GDP statistics. Moreover, the incomplete emission trading market makes the internalization effect of negative externalities of pollution poor, and the ability of enterprises to earn income does not provide good feedback for economic growth. Therefore, it is necessary to establish an environmental audit system to correct the GDP development dominated by one. GDP statistics have not yet considered environmental factors, and GDP has to a certain extent condoned environmental damage. From a theoretical and methodological perspective, environmental factors are included in GDP statistics and updated based on this, continuously exploring the content, procedures, and methods of environmental audits, issuing corresponding government accounting standards and corporate accounting standards, gradually forming industry norms, and ultimately formulating applicable to the green development of China's green accounting system and revising or abolishing the law regulations.

Then the emissions trading market should be regulated. Environmental pollution is essentially an external effect, and the clarification of property rights is an effective way to solve it. Since the 1980s, China has begun to explore the establishment of a sewage trading market, but many problems still exist today. It is necessary to start from the top-level design, establish corresponding laws and regulations, formulate relevant rules and regulations to stipulate the scope, rules and procedures of trading and other matters, do a good job of building the basic system for the local government's emissions trading market, and formulate a standardised trading system to attract the participation of enterprises, so as to make the cost of the externality internalised. Rationally plan the initial quota according to the actual situation, and then price the quota according to the market situation. Emissions trading needs to play its market effectiveness through the activity of the secondary market, so the government should retreat as a regulator rather than intervene as a participant in the market when it operates. Appropriate decentralisation can activate the market potential and bring the market into play.

7.2.3. Enhancing urban infrastructure development and innovating urban policies

Empirical results indicate that urban agglomerations exhibit significant emissions of residential pollutants, highlighting a mutual reinforcement between emissions from 184 major cities and economic growth. However, shock results reveal that this growth diminishes the effectiveness of economic growth and may even impose constraints, thereby presenting an environmental bottleneck phenomenon in this indicator. This underscores the substantial pressure of residential pollution faced by 184 major cities . Consequently, it is imperative to enhance urban infrastructure development, innovate urban policies, and gradually reduce urban pollution emissions.

Firstly, it is crucial to enhance the construction of urban pollution treatment plants while improving their accompanying pipeline facilities. This includes refining waste gas collection systems and recycling systems in central urban areas, as well as bolstering efforts to construct waste gas facilities in suburban areas to address the pressure of residential emissions resulting from urban expansion and population migration from city centers to peripheries. Moreover, there is a need to enhance the operational efficiency of waste gas treatment facilities by fully utilizing idle or inefficient facilities, thereby improving waste gas treatment efficiency and reinforcing tertiary treatment capabilities. Given the financial difficulties stemming from the public nature of the waste gas treatment industry, targeted increases in fiscal appropriations and subsidies are warranted.

Secondly, innovative urban policies are essential. Urban residential pollution pressure primarily arises from population aggregation, necessitating a combination of emission reduction and population diversion strategies to ameliorate severe urban residential pollution. Initially implemented in densely populated cities, traffic restrictions should be enforced to reduce tailpipe emissions. Cities already implementing such restrictions should innovate policies to counter the diminishing effectiveness caused by rising automobile ownership. Simultaneously, promoting and innovating green and healthy modes of transportation can effectively reduce urban emissions from the source. Furthermore, major cities should devise talent introduction policies based on their respective strengths to achieve population diversion objectives through competitive talent acquisition policies, thereby promoting their own development while alleviating environmental pressures on areas experiencing population outflows.

7.2.4. Strengthening environmental policy guidance and implementing relevant legal accountability

Empirical results indicate that the significance of model estimates for certain indicators is weak, suggesting that some environmental pollution indicators cannot be solely explained by economic growth and their own lagged terms within specific regions, likely due to the strong influence of external factors such as policies and natural conditions. Pulse results for certain pollution indicators and economic growth reveal that the impact response lasts for a considerable period before eventually converging, indicating that current economic growth will continue to exert a sustained influence on pollution emissions for a prolonged period without immediate effective governance, highlighting the strong lag in environmental policy implementation.

Therefore, enhancing policy perfection and strengthening relevant legal regulations play a crucial role in guidance and supervision. Environmental accountability must be implemented from a legal perspective, fostering government self-restraint. Strengthening environmental inspection and law enforcement, and implementing vertical management systems to rigorously punish environmental violations are essential. Despite "green" becoming the cornerstone of China's new economic development stage, there have been instances where some leading cadres pursue short-term political achievements regardless of environmental pollution. Winning the battle against pollution prevention and control requires ingraining a correct green performance view into the minds of officials, taking a highly responsible attitude towards projects for the people and future generations. Establishing a comprehensive green performance evaluation system and resolutely enforcing a veto system for environmental protection work, making environmental protection a crucial indicator in the performance evaluation of leading cadres, and implementing a lifelong accountability system for environmental issues, including lifelong criminal accountability for serious environmental issues occurring during their tenure, enhances government vigilance and promotes self-restraint.

8. Limitations

Due to limitations in academic capabilities and data retrieval, this paper has its shortcomings:

Firstly, it primarily explores the dynamic relationship between air environmental pollution and urban economic growth based on pollution indicators. However, the study of the interaction transmission mechanism between environment and economy is not sufficiently deep. Additionally, more comprehensive considerations could be made in the selection of pollution indicators, attempting to choose from multiple perspectives while minimizing data collinearity. These shortcomings indicate directions for further in-depth research in this study.

References

Addis, A. K. and Cheng, S. (2023). The nexus between renewable energy, environmental pollution, and economic growth across brics and oecd countries: A comparative empirical study. *Energy Reports*, **10**, 3800–3813.

Ali, S. H. and Puppim de Oliveira, J. A. (2018). Pollution and economic development: an empirical research review. *Environmental Research Letters*, **13**(12), 123003.

Aminzadeh, K. and Daei-karimzadeh, S. (2021). Environmental Pollution and Economic Growth based on the Theory of Environmental Kuznets Curve (EKC) in Iran's Provinces (1997-2017). *Environmental Energy & Economic Research*, **5**(4).

Amyaz A C. and Polasky J S. (2012). Dynamic Environmental Policy with Stragetic Firms: Prices versus Quantities. *Journal of Environmental and Management*, **45**, 356–376.

Arizala, F., Cavallo, E. and Galindo, A. (2013). Financial development and TFP growth: cross-country and industry-level evidence. *Applied Financial Economics*, **23**(6), 433–448.

Babalos, V. and Stavroyiannis, S. (2020). Pension funds and stock market development in OECD countries: Novel evidence from a panel VAR. *Finance Research Letters*, **34**, 101247.

Brannlund. (1995). Determinants of CO2 emissions in a small open economy. *Ecological Economics*. **45**, 133–148.

Chang, T., Graff Zivin, J., Gross, T. and Neidell, M. (2016). Particulate pollution and the productivity of pear packers. *American Economic Journal: Economic Policy*, **8**(3), 141–169.

Danish. and Ulucak, R. (2020). The pathway toward pollution mitigation: does institutional quality make a difference?. *Business Strategy and the Environment*, **29**(8), 3571–3583.

Grossman, G. M. and Krueger, A. B. (1995). Economic growth and the environment. *The quarterly Journal of Economics*, **110**(2), 353–377.

Hamamoto, M. (2006). Environmental regulation and the productivity of Japanese manufacturing industries. *Resource and Energy Economics*, **28**(4), 299–312.

Hanlon, W. W. (2016). *Coal smoke and the costs of the industrial revolution* (No. w22921). National Bureau of Economic Research.

He, Q., Zhang, M. and Huang, B. (2016). Spatio-temporal variation and impact factors analysis of satellite-based aerosol optical depth over China from 2002 to 2015. *Atmospheric Environment*, **129**, 79–90.

Keller, W. and Levinson, A. (2002). Pollution abatement costs and foreign direct investment inflows to US states. *Review of Economics and Statistics*, **84**(4), 691–703.

Lu, Z. N., Chen, H., Hao, Y., Wang, J., Song, X. and Mok, T. M. (2017). The dynamic relationship between environmental pollution, economic development and public health: Evidence from China. *Journal of Cleaner Production*, 166, 134–147.

Ma, Z., Hu, X., Sayer, A. M., Levy, R., Zhang, Q., Xue, Y. and Liu, Y. (2016). Satellite-based spatiotemporal trends in PM2. 5 concentrations: China, 2004–2013. *Environmental Health Perspectives*, **124**(2), 184–192.

Ma, S. L., Wen, L., Q. and Yuan, Y. (2024), Study on the coupled and coordinated development of tourism, urbanization and ecological environment in shanxi province, *Global NEST Journal*, **26**(4), 05907.

Manuel Arellano and Stephen Bond (1991). Some tests of specification for panel data: monte carlo evidence and an application to employment equations. *The Review of Economic Studies*, **58**(2), 277-297.doi: 10.2307/2297968.

Mughal, N., Arif, A., Jain, V., Chupradit, S., Shabbir, M. S., Ramos-Meza, C. S. and Zhanbayev, R. (2022). The role of technological innovation in environmental pollution, energy consumption and sustainable economic growth: Evidence from South Asian economies. *Energy Strategy Reviews*, **39**, 100745.

Ongan, S., Işık, C., Amin, A., Bulut, U., Rehman, A., Alvarado, R. and Karakaya, S. (2023). Are economic growth and environmental pollution a dilemma?. *Environmental Science and Pollution Research*, **30**(17), 49591–49604.

Rasool, H., Malik, M. A. and Tarique, M. (2020). The curvilinear relationship between environmental pollution and economic growth: Evidence from India. *International Journal of Energy Sector Management*, **14**(5), 891–910.

Roodman, D.M. and Lenssen N. (2005). A building revolution: how ecology and health concerns are transforming construction. 1995, Washington.

Song, Y., Wei, Y., Zhu, J., Liu, J. and Zhang, M. (2021). Environmental regulation and economic growth: A new perspective based on technical level and healthy human capital. *Journal of Cleaner Production*, **318**, 128520.

Wen, L.Q., Ma, S.L. and Su, Y. (2024), Analysis of the interactive effects of new urbanization and agricultural carbon emission efficiency, *Global NEST Journal*, **26**(4), 05927.

Wen, L., Ma, S., Zhao, G. and Liu, H. (2024). The Impact of Environmental Regulation on the Regional Cross-Border E-Commerce Green Innovation: Based on System GMM and Threshold Effects Modeling. *Polish Journal of Environmental Studies*.

Wang, Z. Q. and Ma, S. L. (2024), Research on the impact of digital inclusive finance development on carbon emissions–Based on the double fixed effects model, *Global NEST Journal*, **26**(7), 06227.

Xie, R. H., Yuan, Y. J. and Huang, J. J. (2017). Different types of environmental regulations and heterogeneous influence on "green" productivity: evidence from China. *Ecological economics*, **132**, 104–112.

Xiong, J. and Xu, D. (2021). Relationship between energy consumption, economic growth and environmental pollution in China. *Environmental Research*, **194**, 110718.

Yang, R., Hu, Z. and Hu, S. (2023). The failure of collaborative agglomeration: from the perspective of industrial pollution emission. *Journal of Cleaner Production*, **387**, 135952.

Yu, Y., Duan, C., Li, S., Peng, C., Yang, J., Yan, K., and Zou, P. (2022). Relationship between environmental pollution and economic development in late-developing regions shows an inverted V. *Science of The Total Environment*, **838**, 156295.

Zhu, J. and Xu, J. (2022). Air pollution control and enterprise competitiveness–A re-examination based on China's Clean Air Action. *Journal of Environmental Management*, **312**, 114968.

Zivin, J. G. and Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review*, **102**(7), 3652–3673.