Economics

The Heterogeneous Effect and Transmission Paths of Air Pollution on Housing Prices

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The Heterogeneous Effect and Transmission Paths of Air Pollution on Housing Prices

——Evidence from 30 large and medium-sized cities in China

ABSTRACT: Using panel data from 30 large and medium-sized cities in China between 2003 and 2018, this study employs the Bootstrap method to explore the heterogeneous impact of air pollution on housing prices and its underlying mechanisms. The research findings indicate that the increase in concentrations of various air pollutants has a restraining effect on housing prices, with a greater influence observed for the main components of haze. Air pollution indirectly affects the level of housing prices by influencing urban economic development and the development of the tertiary industry, while population density and the development of the secondary industry do not play a mediating role in this relationship. Finally, policy recommendations are provided for air pollution control, industrial structure layout, and real estate development, aiming to provide insights for promoting the stable development of the real estate industry.
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1. Introduction

In the 21st century, with rapid economic development and continuous urbanization, the ecological environment in China has been deteriorating, particularly in economically developed regions. In 2013, China experienced a severe haze problem, with peak concentrations of PM_{10}和 and $PM_{2.5}$ (as shown in Figure 1). The current state of air pollution has garnered widespread attention. A joint research report released in 2012 by the Asian Development Bank and Tsinghua University revealed that seven of the ten most polluted cities globally were located in China. Furthermore, the air quality in Chinese cities significantly deviated from the standards set by the World Health Organization, with less than 1% of cities meeting those standards (Zhang and Crook, 2012). Since then, China’s central and local governments have introduced numerous environmental protection and energy-saving policies to improve the air pollution situation. The scope of environmental monitoring has also been expanded to include various prefecture-level cities. Although in recent years, under effective policy guidance, residents and economic entities have become more aware of environmental protection, and the air pollution problem has gradually eased, the concentrations of various air pollutants remain high, and Chinese cities still face a severe environmental situation. Data from the 2022 Report on the State of China's Ecological Environment revealed that out of 339 cities at the prefecture level or above, only 213 cities had achieved the standard for environmental air quality, representing a compliance rate of 62.8% (Ministry of Ecology and Environment of China, 2023).

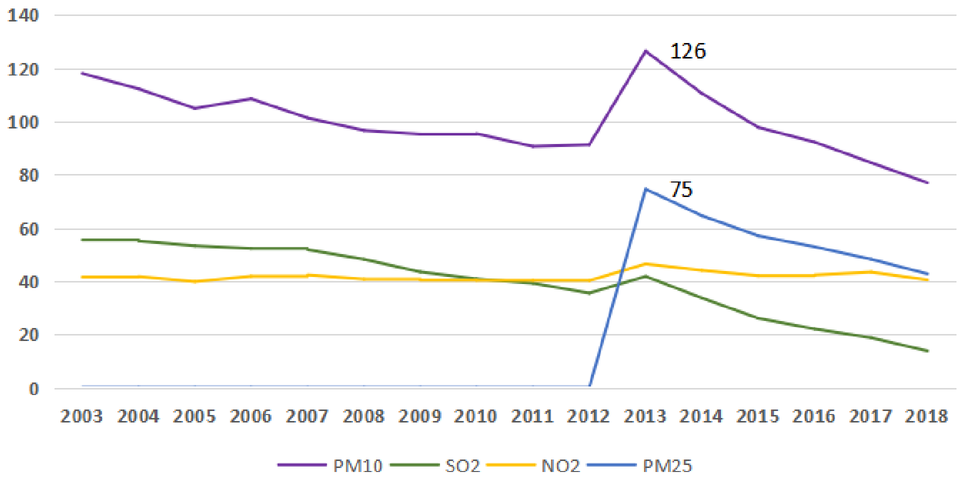

Figure 1 Concentration of each air pollutant (Unit:$\mu g/m^3$)

The real estate industry is a pillar industry of the Chinese economy and plays a significant role in economic development. The more developed the economy and the better the quality of life in the city, the more people's requirements for housing externalities and cost performance will be reduced. Even in the face of greater living pressure, when making purchase decisions, residents with purchasing power will still choose to live in first-tier cities. Compared with first-tier cities, regional differences in housing price growth will be more obvious in new first-tier cities. Coastal open cities such as Hangzhou, Tianjin, and Nanjing have relatively better economic development levels and more suitable living environments, which is usually the preferred choices for homebuyers. On the other hand, cities like Chongqing and Changsha have slower growth in housing prices and relatively lower housing prices, mainly because these inland cities have relatively poorer livability and slower economic development. Cities with higher livability experience faster increases in housing prices, such as Xiamen, Fuzhou, and Dalian, whereas less attractive cities like Lanzhou and Nanning may even have housing prices lower than the national average. No matter the level of economic development or urban livability, third-tier cities are relatively poor, so the level of housing prices is relatively low. Therefore, in addition to macroeconomic conditions, factors such as housing characteristics, urban livability, resident location preferences, and population mobility contribute to the fluctuation of housing prices in Chinese cities.

Currently, existing research mainly focuses on the causes of housing price fluctuations from the perspectives of resident income and consumption behavior, economic development level, policy factors, and so on. However, with the increasing demands of residents for housing, it is significant to study the impact of housing externalities on housing prices. As one of the characteristics of the urban environment, air pollution has become an important reference index for housing selection decisions, and determining the level of urban housing prices to a certain extent. Nevertheless, unfortunately, the existing research has not analyzed the heterogeneous impact of different types of air pollutants on housing prices, and has not deeply analyzed the impact mechanism of air pollutants on housing prices. According to the hypothesis of preference theory, people tend to choose places with beautiful natural environments to settle, live, and work, while avoiding those cities with severe air pollution, which will lead to a decrease in housing prices due to reduced demand. In addition to preference theory, the theoretical basis for the impact of air pollution on housing prices also stems from the theory of urban spatial equilibrium, which suggests that differences in residential environments between cities can be reflected in housing price levels through capitalization (Zhou and Wang, 2018). With the continuous improvement of residents' quality of life, air quality, as an externality feature of housing, has gradually received attention from the academic community. Currently, scholars mainly focus on two aspects:

Firstly, scholars mainly used the hedonic pricing model to analyze the direct effects of air pollution on housing prices, and most researchers have concluded that air pollution has a negative impact on housing prices. For example, Ridker et al. (1967) found that a decrease in air pollution concentration would lead to an increase in housing prices in the Lewis area. Yusuf et al. (2006) took Jakarta as an example and also concluded that air pollution was negatively correlated with housing prices. However, Boennec et al. (2017) analyzed the Nantes region in France and found no causal relationship between air pollution and local housing prices. Wang et al. (2019) found that air pollution indeed exerts a negative impact on housing prices, and this impact exhibits regional variations. Specifically, residents in the eastern regions demonstrate a higher sensitivity to air pollution. Chen et al. (2018), utilizing the hedonic pricing method, estimated residents' marginal willingness to pay for urban clean air. Apart from confirming the adverse effect of air pollution on housing prices, their study also sheds light on the differential willingness to pay for air quality improvement among various income groups.

Secondly, scholars mainly used econometric analysis methods to analyze the heterogeneity effects of air pollution on housing prices, and explored its internal mechanism. Wang and Shi (2019) believe that air pollution does have a negative impact on the level of housing prices, and the impact has regional differences, which is reflected in that residents in eastern China are more sensitive to air pollution. Wang et al. (2022) found that air pollution in large-sized cities in China was significantly positively correlated with local housing prices, while air pollution in small and medium-sized cities was negatively correlated with local housing prices. In addition, air pollution has a significant negative impact on housing prices in western regions, while it has no significant impact on eastern and central regions. Chen and Hao (2018) estimated residents' marginal willingness to pay for urban clean air, which not only confirmed the negative impact of air pollution on housing prices, but also further demonstrated that different income groups have significant differences in their willingness to pay for air quality improvement. Zhang et al. (2021) applied the spatial Dubin model to analyze spatial heterogeneity and concluded that within a range of 100 kilometers when the total amount of air pollutants in neighboring cities doubled, local housing prices would drop by 6%. In this process, the city's geographical location and governance policies play a moderating role. Dong et al. (2020) analyzed the mechanism of air pollution inhibiting housing prices and found that the higher the level of urban economic development, the stronger the negative impact of air pollution on housing prices. In addition, it is also found that if the government departments strengthen macro-control or the economy is in a downward stage, the impact of air pollution on the rise of housing prices will become relatively limited.

In summary, the majority of scholars are more concerned about the magnitude and regional heterogeneity of the effects of air pollution on housing prices. However, research explaining the mechanisms through which air pollution impacts housing prices is limited. Although Liu et al. (2022) propose that poor air quality adversely affects housing prices through channels such as hindering human capital, slowing down urbanization processes, and reducing people's housing price expectations, their study primarily analyzes the impact using PM2.5 or industrial emissions as explanatory variables. They did not compare the different effects of various air pollutants on housing prices, resulting in limited findings. Importantly, research on the impact of air pollution on housing prices through four potential channels—urban population conditions, economic development levels, industrialization degree, and the level of public service facilities—has not received due attention.

To address this literature gap, the present study, grounded in the theory of revealed preferences, endeavors to investigate the heterogeneous impacts of various air pollutants on urban housing prices. On one hand, considering the perspectives of residents' housing purchase decisions and economic development, we examine the divergent effects of each air pollutant on urban housing prices. On the other hand, employing the hedonic pricing model, we categorize air pollutants into two major types: industrial pollution and haze, facilitating a unified method for comparative analysis of their impacts on housing prices. This approach aids in further exploring residents' sensitivity to different types of air pollution. Additionally, a quantitative comparative analysis of influencing pathways is conducted, revealing that air quality can directly or indirectly affect socio-economic variables such as urban economic development and the level of development in the tertiary sector, subsequently impacting urban housing prices. The study estimates the long-term effects of air pollution on housing prices, providing a more targeted basis for the implementation of pollution control measures.

One significant issue with traditional cross-sectional hedonic price models is the omission of variables. To address this problem, we employ an enhanced hedonic price model that determines long-term impacts within a panel data framework. As suggested by Massetti et al. (2011), the omission of variables can be significantly reduced in a panel framework with fixed effects. Additionally, we test the sensitivity of our findings to alternative explanatory variables by incorporating various control variables, revealing comparable results.

China stands out as one of the countries with the most severe pollution globally, with over 80% of its population living under PM2.5 concentrations classified as unhealthy for sensitive groups. Despite multiple action plans and policy regulations implemented by the Chinese government to control air pollution, certain regions in the central plains still experience relatively severe air pollution, with particulate concentrations during winter exceeding national standards by twice the limit, as reported by Liao et al. (2021). Given the persistent and challenging nature of air pollution, it has become one of China's most formidable threats. Considering the severity of air pollution in China, it is imperative to conduct specialized research to comprehensively understand the value of air quality. Thus, this study focuses on Chinese cities. However, due to the limited disclosure of air pollution data in the statistical yearbook by the National Bureau of Statistics for only 31 key environmental protection cities, this study selects 31 large and medium-sized cities as its subjects. Due to some missing data for Lhasa in certain years, and considering data integrity and continuity, Lhasa is excluded from the dataset, and the analysis is conducted on the remaining 30 large and medium-sized cities.

Our findings indicate that air pollution significantly inhibits housing price increases, and the impact varies for different air pollutants, with a more pronounced effect observed for the main components of haze. A 10% increase in PM2.5 and SO2 concentrations results in a respective decrease of 1.55% and 3.19% in urban housing prices. Although CO concentration also negatively impacts urban housing prices, this effect is not significant as urban characteristics increase. Regarding the mechanism of impact, the increase in concentration has a direct negative effect on housing price increases. Simultaneously, it indirectly suppresses housing price increases by impeding the rise in per capita GDP and the development of the tertiary sector. Both paths exhibit partial mediating effects. Population density and the share of the secondary sector do not show significant mediating effects. Through testing, the mediating effect proportion of the per capita GDP path is 32.03%, and the tertiary sector's share path is 17.21%. This indicates a negative impact of air pollution on urban economic levels and the development of the tertiary sector. Residents' housing choices are primarily influenced by the current economic development and public infrastructure conditions of the city.

2. Research hypothesis

2.1 Overall and heterogeneous impact of air pollution on Housing Prices

As a public resource, air quality has a direct impact on residents' lives. Previous studies have shown that atmospheric pollutants can cause severe damage to human physical and mental health, which is irreversible and cannot be compensated for by improvements in other conditions (Liu et al, 2021). Severe air pollution greatly inconveniences residents in their daily lives and social interactions, leading people to reduce outdoor activities. In the context of promoting the improvement of people's livelihoods, the general improvement in residents' quality of life will increase their demands for housing features and also place more emphasis on the environmental quality of the cities they choose to live in. Since 2013, China has gradually made public the air quality information of various cities, and the corresponding indicators have become important factors in assessing urban environmental quality. At the same time, residents have increasingly diverse channels for accessing information and can obtain real-time urban air pollution data through the Internet, mobile applications, and other means, further increasing their sensitivity to changes in pollution concentrations. Therefore, when making housing location decisions, consumer groups will gradually pay more attention to the current state of urban air pollution. Additionally, air pollution reduces urban vitality, restricts enterprise development, and affects the level of economic development, thus exerting a negative impact on urban housing prices.

The severity of the real-life situation has sparked lively discussions in the academic community, and many scholars have analyzed the fluctuations in housing prices in relation to the current state of air pollution in China. In terms of industrial pollutants, fossil fuels generally contain impurities such as sulfur and nitrogen, which produce pollutants such as SO_2 and NO_2 during combustion. Currently, China's energy consumption structure is still dominated by coal, and the consumption of coal is high in most industrial sectors. In cities with serious industrial pollution, industrial layouts are also more concentrated. Although this can boost economic output, it is not conducive to improving urban livability, thus reducing the attractiveness to housing consumer groups. The higher the emission intensity of industrial SO_2 and NO_2, the stronger their negative impact on housing prices (Li et al, 2020). Moreover, winter heating policies mainly rely on the burning of coal, natural gas, and other resources, which also result in air pollution problems. Since atmospheric pollution is harmful to physical and mental health, residents do not prefer to settle in cities with severe industrial pollution. However, while SO_2 is one of the main atmospheric pollutants, its concentration is relatively low, and with the introduction of deindustrialization plans in some cities, residents have relatively low sensitivity to its pollution changes. Both NO_2 and SO_2 belong to industrial pollutants, so they are expected to have similar impacts on housing prices. Secondly, in recent years, haze has gained more attention. Compared to industrial pollutants, particulate pollutants pose a greater threat to human health, with wider sources and higher concentrations. Government departments find it difficult to formulate precise policies to address haze problems, thus residents pay more attention to the main pollutants causing haze. An increase in PM_{10} and $PM_{2.5}$concentrations in the atmosphere reduces urban vitality and residents' willingness to purchase homes, thus exerting a restraining effect on housing price increases. Since the gradual disclosure of atmospheric pollutant information in 2013, PM_{10} and $PM_{2.5}$information has been more comprehensive and has received greater attention from residents. Therefore, the public availability of air quality indicators will strengthen the negative impact of air pollution on housing prices. PM_{10} and $PM_{2.5}$are similar pollutants, differing only in particle size, so their overall impact on housing prices will tend to be consistent. Based on this, this study proposes hypothesis 1:

Hypothesis 1: The increase of the concentrations of PM_{10}, SO_2, NO_2, and $PM_{2.5}$ will have a negative impact on urban housing prices, but the influence levels are different. The impact of industrial pollutants SO_2 and NO_2 will be relatively smaller, while the impact of haze components PM_{10} and $PM_{2.5}$ will be greater.

2.2 Transmission paths of air pollution impact on housing prices

According to Tiebout's "voting with their feet" theory, residents, given a sufficient budget, prefer to settle in cities that can meet their needs for physical and mental health as well as better living conditions. In recent years, residents' awareness of environmental protection and health has been continuously strengthened, and they are more concerned about the current air pollution status in cities. As air pollution has been proven to have serious detrimental effects on physical and mental health, residents, considering a healthy lifestyle and better quality of life, are more inclined to migrate to cities with good air quality. Some studies have also confirmed that the labor force is a major driving force behind population mobility. Considering job substitutability, highly skilled labor is more sensitive to air pollution (Sun et al, 2019), and more inclined to move to cities with clean air for employment, resulting in population migration driven by employment. Scholars have also confirmed that population mobility among prefecture-level cities is an important factor influencing housing prices in relation to air pollution (Chen and Hao, 2018). Additionally, with the increasing attention from various sectors of society to urban air pollution and the government's further promotion of green lifestyles, residents' sensitivity to air pollution will also increase. In other words, the more severe the air pollution problem in a city, the more likely human capital will be lost, and residents' willingness to migrate out will be stronger, affecting the local population density. Based on this, we propose hypothesis 2(a):

Hypothesis 2(a): The increases in the concentration of urban air pollutants will lead to a decrease in local population density, which will alleviate the phenomenon of housing supply-demand imbalance and indirectly restrain housing price increases.

The level of economic development is an important indicator of a city's vitality and a primary factor considered by people when choosing a place to live. However, air pollution has a significant negative impact on the level of urban economic development (Chen and Chen et al, 2018). The Ministry of Ecology and Environment of China released the "Report on China's Economic-Ecological Production and Development" in 2018, which disclosed the Gross Economic-Ecological Product (GEEP) of each province and municipality in 2015. The provinces and municipalities with the highest GEEP were economically underdeveloped regions such as Tibet and Qinghai. However, regions with higher economic levels actually suffered significant ecological environment loss costs, with Hebei and Shandong ranking the highest. In 2015, the total GDP amounted to 72.3 trillion yuan, with pollution loss costs as high as 2 trillion yuan, reflecting the adverse impact of environmental pollution on urban economic development. With the continuous disclosure of smog-related information, air pollution has become an urgent urban pollution issue that needs to be addressed. Studies have shown that the economic costs of outdoor air pollution will continue to increase, even reaching 1% of the global GDP, with China having the highest proportion of GDP loss (Elisa et al, 2018). Unregulated emissions of air pollutants not only reduce the attractiveness of cities and limit local industrial development but also disrupt the accumulation of human capital, thereby restraining economic development. Cities with severe air pollution will also see a corresponding impact on corporate investment willingness, leading to a decrease in the value of commercial real estate. Regardless of the perspective, air pollution will have a negative impact on the local level of economic development.

As a pillar industry of the national economy, the real estate sector exhibits a growth trend similar to that of GDP, indicating a close correlation between real estate development and economic levels. Theoretically, as the economic level of a city increases, the average income of local residents will correspondingly rise, leading to increased consumption capacity. As the main consumers of housing, the improvement in residents' purchasing power directly promotes the rise in housing prices. Therefore, an increase in the per capita GDP level in a city will contribute to housing price increases, reflecting a positive impact. Additionally, urban economic growth also facilitates local industrial development, the improvement of public infrastructure, and subsequently increases the value of housing, exerting a positive influence on housing price increases. Based on this, this study proposes hypothesis 2(b):

Hypothesis 2(b): An increase in air pollution concentration will hinder urban economic development, and a decrease in economic level implies a decline in residents' purchasing power, indirectly restraining housing price increases.

The process of urbanization in China reflects the level of industrialization significantly. In recent years, the rapid urbanization in China has driven a series of industrial developments, mainly in the secondary and tertiary sectors. The secondary sector primarily includes the industrial and construction sectors. Although its rapid development has improved urban economic conditions, it has also led to more severe air pollution issues. Industrial production generates pollutants such as SO_2, NO_2, and particulate matter. The construction sector is also one of the main culprits for smog, as construction dust increases the concentration of particulate pollutants, and activities like heating and cooling contribute to the rise in pollutant concentrations such as SO_2 and $PM_{2.5}$. Therefore, the secondary sector is the main source of urban air pollutants, meaning that cities with a higher degree of industrialization tend to have higher concentrations of air pollutants. Conversely, the current air pollution situation can also reflect the local level of industrialization to some extent. Cities with more severe air pollution are likely to have higher levels of local economic development and industrialization, creating a "vicious cycle" (Wang et al, 2021). Therefore, with the introduction of the "carbon peak" and "carbon neutrality" goals, the country pays great attention to the pollution emissions from high-polluting industries and power generation enterprises. Under a series of governance policies, the increase in urban air pollutant concentrations will restrict the development of the secondary sector. For instance, the public sector formulates SO_2 emission limits and imposes carbon taxation policies, which will reduce the proportion of thermal power generation. In the post-industrial era, some cities may experience a trend of deindustrialization, which is unfavorable for local industrial development. Therefore, the development of the secondary sector is closely related to the current state of urban air pollution. Under a series of stringent control measures such as emission limits and price controls, an increase in air pollutant concentrations will have a negative impact on the development of the urban secondary sector.

In recent years, there has been an increasing call for a healthy lifestyle, with a preference for living in cities with excellent air quality. Although the accelerated process of industrialization implies continuous economic development, the increase in the proportion of the secondary sector in cities often brings about more severe air pollution issues, affecting the quality of life for residents. Therefore, as some cities reach a saturation point in their level of industrialization, the severity of air pollution issues becomes increasingly prominent, leading more people to be unwilling to settle in industrialized areas, which is reflected in a negative impact on housing prices. Based on this, hypothesis 2(c) is proposed:

Hypothesis 2(c): An increase in air pollution concentration will inhibit the development of the urban secondary sector, and a decrease in the proportion of the secondary sector will have a positive impact on the increase in local housing prices, reflecting an intermediary effect.

Another characteristic of urbanization in China is achieving modernization, which involves vigorously promoting the development of the tertiary sector, fostering technological advancements, and enhancing overall cultural strength. The tertiary sector primarily includes industries such as services and commerce, representing the level of construction of urban public service facilities. With the continuous improvement of living standards, residents generally pay attention to the level of public services in cities and prefer to settle in cities with strong economic vitality, well-equipped medical facilities, and good educational resources. Different levels of public service supply result in variations in residents' quality of life, thereby influencing their decisions on place of residence. Moreover, cities with higher economic levels tend to have more complete public service facilities, which exert a strong appeal for population mobility. Consequently, the phenomenon of "housing supply unable to meet demand" becomes more prominent, leading to a sustained increase in housing prices. Therefore, under the policy emphasis on improving people's livelihoods, an increase in the proportion of the tertiary sector will attract human capital, resulting in property premiums, and significantly promote the rise in housing prices. On the other hand, air pollution reduces urban vitality, hinders the attraction of human capital, and negatively affects the city's level of economic development. Thus, it also brings certain negative impacts on the local level of public services. Furthermore, severe pollution weather restricts residents' outdoor activities, lowers the utilization rate of certain public infrastructure, affects local businesses' investments in public services, reduces demand for commercial real estate, and consequently leads to a decline in housing prices. Additionally, the severe air pollution situation increases the government's cost of governance, reduces the willingness to invest in fixed assets, and redirects investments toward the environmental protection industry. Based on these observations, this study proposes hypothesis 2(d):

Hypothesis 2(d): An increase in air pollution concentration will inhibit the development of the tertiary sector, and a decrease in the proportion of the tertiary sector will lower the local housing price level, indirectly exerting a negative impact on the increase in local housing prices.

Based on the research hypotheses mentioned above, the potential impact path of air pollution on housing prices is illustrated in Figure 2. This study will quantitatively analyze four mediating paths: population density, level of economic development, proportion of the secondary sector, and proportion of the tertiary sector.

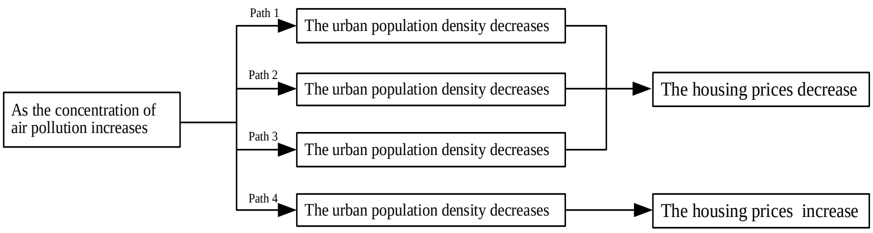

Figure 2 The influence paths of air pollution on housing price

3. Variable selection and model construction

3.1 Data sources

The aim of this study is to investigate the impact of air pollution on housing prices in large and medium-sized cities, covering the period from 2003 to 2018. Since the National Bureau of Statistics only discloses air pollution data for 31 key environmental cities in their yearbooks, this study selects these 31 large and medium-sized cities as the research objects. Due to the relatively unique economic development of Lhasa City and the missing data in certain years, considering data integrity and continuity, Lhasa City is excluded from the dataset. Therefore, the analysis is conducted on the data of the remaining 30 large and medium-sized cities (as shown in Table 1). Based on the timing of the National Bureau of Statistics' information disclosure on $PM_{2.5}$, the study period is divided into two parts: the first part includes long-term data from 2003 to 2018, and the second part includes short-term data from 2013 to 2018. Under the premise of obtaining available data, reasonable control variables are selected to explore the effects of various air pollutant concentrations on housing prices. The focus of the analysis is primarily on the regression results of the long-term data. During the data compilation process, the original data range was from 2003 to 2019. However, due to the lack of data disclosure for some control variables in 2019, accurate data cannot be obtained in accordance with consistent standards. Therefore, the data for 2019 is excluded. The main sources of data for this study are the Statistical Yearbooks from 2004 to 2019. Housing price data is derived from the "China Real Estate Statistical Yearbook," air pollutant concentration data is sourced from the "China Statistical Yearbook," and control variable data mainly comes from the "China Urban Statistical Yearbook." For certain missing data, references are made to provincial and municipal statistical yearbooks as well as national economic and social development statistical bulletins published by municipal governments.

Table 1 Classification of the 30 large and medium-sized cities

Category	City
Northeast China	Harbin, Changchun, Jilin
Northern China	Beijing, Tianjin, Shijiazhuang, Taiyuan, Hohhot, Jinan
Central China	Wuhan, Changsha, Zhengzhou, Hefei, Nanchang
Western Region	Xi'an, Lanzhou, Xining, Yinchuan, Urumqi, Chengdu, Kunming, Nanning, Chongqing, Guiyang
Coastal cities	Guangzhou, Shanghai, Hangzhou, Fuzhou, Haikou, Nanjing

3.2 Variables selection

3.2.1 Independent and dependent variables

Taking into consideration the main sources and social hazards of air pollution, this study focuses on industrial pollution and haze as the primary objects of analysis. Four common air pollutant concentration indicators, namely PM_{10}, SO_2, NO_2, and $PM_{2.5}$, are selected as independent variables. As for the dependent variable, this study chooses the average selling price of commercial housing (HP). The descriptive statistics of each variable are presented in Table 2. SO_2 and NO_2 belong to industrial pollutants, while PM_{10} and $PM_{2.5}$are both particulate matter pollutants. Since PM_{10} includes $PM_{2.5}$and there is limited data available for $PM_{2.5}$ (2013 to 2018), the analysis is conducted from two dimensions: long-term and short-term. The long-term dimension includes the independent variables PM_{10}, SO_2, and NO_2, while the short-term dimension focuses on $PM_{2.5}$as the independent variable.

Table 2 Descriptive statistics for independent and dependent variables

Variables	Definition	Observations	Average	Standard deviation	Minimum value	Maximum value
PM_{10}	Annual average concentration of respirable particulate matter ($\mu g/m^3$)	480	101.61	31.46	30.00	305.00
SO_2	Annual average sulphur dioxide concentration ($\mu g/m^3$)	480	40.53	23.28	5.00	152.00
NO_2	Annual average concentration of nitrogen dioxide ($\mu g/m^3$)	480	42.40	12.08	11.94	73.00
$PM_{2.5}$	Annual average concentration of fine particulate matter ($\mu g/m^3$)	180	57.78	21.19	18.00	154.00
HP	Average sales price of commercial properties (RMB/m^2)	480	6584.38	4597.64	1498.00	33820.00

3.2.2 Control variables

There are multiple factors that influence housing prices. However, given that this study focuses on residential preferences and urban development as the research perspective, the analysis primarily examines the impact of air pollution on urban housing prices. Therefore, in selecting control variables, the emphasis is placed on choosing variables that describe the economic development of the city and the residents' purchasing power. Drawing on previous research, this study selects population density, per capita GDP, the proportion of GDP from the secondary and tertiary sectors, the number of doctors, the number of full-time teachers, and the number of books as control variables (Hong et al., 2020; Xiang et al., 2019). The descriptive statistics of each variable are presented in Table 3.

Table 3 Descriptive statistics for control variables

Variables	Definition	Observations	Average	Standard deviation	Minimum value	Maximum value
GDP_per	Gross regional product (yuan/person)	480	65355.72	45999.29	3514.33	246329.20
GDP_ratio2	Share of secondary sector GDP (%)	480	43.35	8.39	18.14	60.13
GDP_ratio3	Share of tertiary sector GDP (%)	480	51.38	9.23	36.20	80.98

$Doctor$	Practitioner (including Assistant Practitioners) Number (persons)	480	22253.23	16144.03	2462.00	109376.00
$Teacher$	Number of full-time teachers (persons)	480	86986.85	51387.03	15337.00	305738.00
$Book$	Total Public Library Book Collection (million volumes)	480	1036.99	1426.57	31.00	7894.00
Pop	Population density (person/km^2)	480	620.94	412.35	123.95	2305.63

The current population status of a city is closely related to the level of housing supply and demand. Therefore, population density is used to describe the population status and reflect the housing demand situation. Per capita GDP serves as a measure of the local economic development and, to some extent, reflects the residents' living standards and purchasing power. The level of urbanization is measured by the industrial composition, with the proportion of the secondary sector indicating the level of industrial development and the proportion of the tertiary sector reflecting the development of the service industry. This analysis further explores the sensitivity of potential housing consumers to the city's industrial characteristics.

As residents' living standards continue to improve, the level of urban public services has become an important external feature of housing and a significant factor influencing housing purchase intentions and price fluctuations. The number of doctors, the number of full-time teachers, and the total collection of books in public libraries are used to measure the medical and educational levels of different cities.

3.2.3 Selection of mediating variables

Based on the research hypotheses proposed, this study needs to investigate four potential causal pathways and, therefore, selects four variables for the analysis of the mediating effects. Both air pollution and housing prices are closely related to the development status of the cities in which they occur. The level of public services can be used to measure a city's development potential, with higher levels indicating better local industrial development and livability. To avoid mutual interference and reverse causality issues among the pathways, this study includes the level of public services as a control variable when examining the mediating paths. In Pathway 1, the mediating variable is population density (Pop) to test Hypothesis 2(a); in Pathway 2, the mediating variable is per capita GDP (GDP_per) to test Hypothesis 2(b); in Pathway 3, the mediating variable is the proportion of GDP from the secondary sector (GDP_ratio2) to test Hypothesis 2(c); and in Pathway 4, the mediating variable is the proportion of GDP from the tertiary sector (GDP_ratio3) to test Hypothesis 2(d).

To eliminate heteroscedasticity and enhance stability, this study first performs a logarithmic transformation on the data. Additionally, to eliminate the influence of price factors and improve the accuracy of the results, this study applies deflation to variables measured in monetary units. Referring to previous research, the Consumer Price Index (CPI) for each city is calculated using the year 2003 as the base period, and this index is used to deflate various types of housing prices, GDP, and per capita GDP data. The descriptive statistics of the deflated variables are presented in Table 4.

Table 4 Descriptive statistics for deflator variables

Variables	Definition	Observations	Average	Standard deviation	Minimum value	Maximum value
HP	Average sales price of commercial properties (RMB/m^2)	480	5148.39	3286.02	1498.00	24401.36
GDP	Gross regional product (billion yuan)	480	3119.91	3064.00	144.83	15783.74
GDP_per	Gross regional product (yuan/person)	480	53818.01	84172.04	1214.99	747272.50

3.3 Model construction

3.3.1 Main effect model

(1) Long-term data:

$$lnHP_{it} = \beta_0 + \beta_k X_{kit} + \rho_j lnC_{jit} + \varepsilon_{it} \qquad \text{(Model 1)}$$

(2) Short-term data:

$$lnHP_{it} = \gamma_0 + \gamma_1 lnPM_{2.5\,it} + \rho_j lnC_{jit} + \varepsilon_{it} \qquad \text{(Model 2)}$$

The model is used to analyze the overall effect of air pollution on house price levels and to explore the level of significance of each variable. Where i denotes city, and t denotes time, and C_j ($j \in (1,2,\dots,7)$ are the control variables, denote Pop, GDP_per, GDP_ratio2, GDP_ratio3, $Doctor$, $Teacher$ and $Book$. The ε_{it} are residual terms. Model 1 focuses on the effect of each air pollutant on house prices, with X_k is the logarithmic form of each explanatory variable, and $k = 1,2,3$ represent PM_{10} , SO_2 and NO_2. Since there are some synergistic effects among the pollutants, in order to avoid multicollinearity, this paper substitutes each of PM_{10} , SO_2 and NO_2 for the analysis. Model 2 examines the effect of $PM_{2.5}$ on house prices, as $PM_{2.5}$ is the main component of haze and is cross-sectioned with PM_{10} data, this regression only includes $PM_{2.5}$ as an explanatory variable.

3.3.2 Mediating effects model

This section is used to examine the mediating effect of air pollution on house prices. Taking the explanatory variable PM_{10} for example, a stepwise regression is first used to determine whether urban PM_{10} concentration will indirectly cause house price fluctuations by affecting four variables: population size, GDP per capita, share of secondary industry and share of tertiary industry. Secondly, on the basis of the stepwise regression, Bootstrap tests are conducted for each influence path to quantify the mediating effect of air pollution on urban house prices. The model for analysing each impact path is shown below:

(1) Validation of pathway 1 -PM_{10} Whether concentrations indirectly affect house prices by influencing urban population density:

$$lnHP_{it} = \alpha_1 + m_1 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it}, j \in (5,6,7) \qquad \text{(Model 3)}$$

$$lnPop = \sigma_1 + b_1 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it} \qquad \text{(Model 4)}$$

$$lnHP_{it} = \alpha_1' + m_1' PM_{10} + n_1 lnPop + \rho_j' lnC_{jit} + \varepsilon_{it} \qquad \text{(Model 5)}$$

(2) Validation of pathway 2 - PM_{10} Whether concentration indirectly affects house

prices by affecting the level of GDP per capita:

$$lnHP_{it} = \alpha_2 + m_2 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it}, j \in (5,6,7) \quad \text{(Model 6)}$$

$$lnGDP\_per = \sigma_2 + b_2 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it} \quad \text{(Model 7)}$$

$$lnHP_{it} = \alpha_2' + m_2' PM_{10} + n_2 lnGDP\_per + \rho_j' lnC_{jit} + \varepsilon_{it} \quad \text{(Model 8)}$$

(3) Validation of pathway 3 -PM_{10} Whether concentration indirectly affects house prices by influencing the share of the secondary sector:

$$lnHP_{it} = \alpha_3 + m_3 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it}, j \in (5,6,7) \quad \text{(Model 9)}$$

$$lnGDP\_ratio2 = \sigma_3 + b_3 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it} \quad \text{(Model 10)}$$

$$lnHP_{it} = \alpha_3' + m_3' PM_{10} + n_3 lnGDP\_ratio2 + \rho_j' lnC_{jit} + \varepsilon_{it} \quad \text{(Model 11)}$$

(4) Validation of Pathway 4 -PM_{10} Whether the concentration indirectly affects house prices by influencing the share of the tertiary sector:

$$lnHP_{it} = \alpha_4 + m_4 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it}, j \in (5,6,7) \quad \text{(Model 12)}$$

$$lnGDP\_ratio3 = \sigma_4 + b_4 PM_{10} + \rho_j lnC_{jit} + \varepsilon_{it} \quad \text{(Model 13)}$$

$$lnHP_{it} = \alpha_4' + m_4' PM_{10} + n_4 lnGDP\_ratio3 + \rho_j' lnC_{jit} + \varepsilon_{it} \quad \text{(Model 14)}$$

4. Empirical analysis

4.1 Data stability test

4.1.1 Unit root test

To ensure the accuracy of the results and avoid spurious regression, this study initially tests the presence of a unit root in the time series of each variable. However, separate unit root tests were not conducted for the $PM_{2.5}$variable due to its short time series, which spanned only 6 years and lacked clear regularity. Instead, the LLC, IPS, ADF, and PP tests were conducted for the other long-term variables individually. Considering the large values of the data, the variables were logarithmically transformed in this study. The null hypothesis (H_0) formulated originally was that the panel data contained unit roots. The results of the unit root tests indicated that some of the variables in the original series did not pass the test, suggesting that these variables are not stable over time. The specific test results are presented in Table 5.

Table 5 Unit root test results for original series data

Variables	LLC	IPS	ADF	PP
$lnHP$	-6.103***	-5.519***	89.052***	110.290***
$lnPM_{10}$	-6.337***	-5.732***	89.115***	89.673***
$lnSO_2$	-0.925	-3.358***	145.217***	78.556*
$lnNO_2$	-5.334***	-5.124***	143.613***	96.485***
$lnPop$	-4.466***	-5.862***	82.008**	141.538***
$lnGDP\_per$	-7.762***	-3.633***	136.306***	93.040***
$lnGDP\_ratio2$	-5.097***	-0.797	102.833***	82.671**
$lnGDP\_ratio3$	-2.957***	0.189	167.261***	95.534***

$lnDoctor$	-5.623***	-6.116***	112.066***	142.434***
$lnTeacher$	-4.494***	-5.374***	122.571***	146.508***
$lnBook$	-6.581***	-6.427***	113.581***	127.224***

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

Since some of the data in the original series did not pass the unit root test, this study performed first-order differencing on each data series and conducted the unit root test again. The results indicated that the first-order differenced series exhibited stationarity. The specific test results are presented in Table 6.

Table 6 Unit root test results for first order difference data

Variables	LLC	IPS	ADF	PP
$lnHP$	-7.147***	-10.058***	105.027***	372.170***
$lnPM_{10}$	-10.772***	-10.659***	89.070***	320.149***
$lnSO_2$	-5.634***	-8.655***	124.360***	311.678***
$lnNO_2$	-13.173***	-10.404***	110.754***	429.073***
$lnPop$	-7.993***	-11.003***	128.971***	356.088***
$lnGDP\_per$	-8.289***	-10.448***	101.190***	283.955***
$lnGDP\_ratio2$	-8.012***	-8.746***	94.328***	280.264***
$lnGDP\_ratio3$	-9.834***	-9.348***	138.046***	310.964***
$lnDoctor$	-13.304***	-11.100***	134.451***	560.737***
$lnTeacher$	-8.826***	-10.700***	113.154***	437.427***
$lnBook$	-9.888***	-10.968***	121.792***	417.070***

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

4.1.2 Co-integration test

Although first-order differencing can yield stationary series for variables with unit roots, it is important to note that in general, first-order differencing may affect the interpretation of variables and introduce differences in economic meaning compared to the original series. Therefore, in regression analysis, it is desirable to use the original series data. To address this issue, this study conducted cointegration tests using the Kao test based on the Engle-Granger two-step method. The analysis revealed that all the data used in the model passed the cointegration test, indicating the presence of a long-term stable relationship among the variables, thus enabling empirical analysis. The results of the cointegration test are presented in Table 7.

Table 7 Results of the basic model Kao test

Models	ADF	
	Statistical quantities	P-value

Model 1	(1) $lnPM_{10}$	-3.4689***	0.0003
	(2) $lnSO_2$	-4.0711***	0.0000
	(3) $lnNO_2$	-3.6858***	0.0001
Model 2	(1) $lnHP$	-1.8268**	0.0339
	(2) $lnBS$	-2.9560***	0.0016
	(3) $lnRD$	-6.2373***	0.0000
Model 3			
$lnPop$	Model 1	-3.3967***	0.0003
	Model 2	-2.7464***	0.0030
	Model 3	-3.4551***	0.0003
$lnGDP\_per$	Model 2	-3.8408***	0.0001
	Model 3	-2.7341***	0.0031
$lnGDP\_ratio2$	Model 2	-3.0914***	0.0010
	Model 3	-4.2853***	0.0000
$lnGDP\_ratio3$	Model 2	-3.5823***	0.0002
	Model 3	-4.4111***	0.0000

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

4.2 Impact of air pollution on urban house prices

The process of urbanization, while promoting economic growth, also facilitates industrial agglomeration and, to some extent, gives rise to urban air pollution issues [21], indicating an endogenous influence. To address endogeneity concerns, this study employs lagged one-period air pollution data in the regression analysis when dealing with long-term data and includes control variables by dimension. Additionally, the F-test and Hausman test will be applied to select the appropriate model, ensuring the accuracy of the regression results.

(1) PM_{10} Impact on urban house prices

The model results indicate a significant negative effect of PM_{10} concentration on housing prices, which is consistent with the research hypothesis that higher PM_{10} concentration in cities has a substantial negative impact on housing prices. As the control variables that describe other city characteristics are included, the negative effect of PM_{10} on housing prices gradually diminishes. The regression results are shown in Table 8.

Table 8 The effect of PM_{10} concentration on housing prices

Variables	(1)	(2)	(3)	(4)
	$lnHP$	$lnHP$	$lnHP$	$lnHP$
$lnPM_{10}$	-0.715***	-0.687***	-0.281***	-0.155***
$lnPop$		1.168***	0.005***	-0.027

$lnDoctor$			0.553***	0.209***
$lnTeacher$			0.916***	0.481***
$lnBook$			0.013	-0.007
$lnGDP\_per$				0.426***
$lnGDP\_ratio2$				-0.157
$lnGDP\_ratio3$				0.644***
Constant	11.729***	4.311***	-6.107***	-4.479***
Observations	450	450	450	450
R^2	0.14	0.24	0.75	0.83
F-statistic	22.52***	17.38***	33.45***	39.37***
Hausman Test	4.38	25.87***	118.51***	75.85***

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

First, in column (1), this study directly analyzes the independent impact of PM_{10} on housing prices and finds that a 10% increase in PM_{10} concentration leads to a 7.18% decrease in local housing prices. This suggests that higher PM_{10} concentration significantly hampers the development of the local real estate industry. Building upon this, in column (2), the study incorporates the population density variable for analysis, and the negative effect of PM_{10} on housing prices diminishes, indicating a close relationship between the negative impact of PM_{10} on housing prices and city characteristics. At the same time, population density has a positive effect on housing prices, reflecting the effect of population agglomeration. That is, the higher the population density in a city, the faster the increase in housing prices. Due to limited land supply, the growth in population further intensifies housing demand, leading to scarcity of land resources and subsequent price increases. This conclusion aligns with the findings of other researchers (Chen et al., 2017) .

The level of public services in the city affects the quality of life of residents and may bring a premium to property. Therefore, in column (3), this paper adds control variables for the public service dimension (number of doctors, number of teachers and number of book collections) and finds thatPM_{10} that the negative effect of concentration on urban house prices will be significantly reduced. The data suggest that whenPM_{10} This further indicates that the level of public services in the city significantly contributes to the increase in urban house prices and can mitigate the negative impact of air pollution on the development of the urban real estate industry to a certain extent. And in column (4), this paper adds GDP per capita and industry share control variables, as GDP per capita and tertiary industry share have a facilitating effect on the rise of house prices, at this timePM_{10} the degree of impact of concentration on urban house prices is reduced to 1.55%. However, even if the good characteristics of the city help to offset the negative effect of air pollution on house prices, it still does not change the fact that this negative effect is significant. In addition to this, and in contrast to the findings of existing studies, a rising share of urban secondary industries may have a negative effect on urban house price inflation, reflecting the fact that residents may increasingly prefer to live in less industrialised cities with better developed service industries.

(2) SO_2 WithNO_2 Impact on urban house prices

The model results show that SO_2 and NO_2 concentrations also have a negative impact on urban housing prices, but overall, this impact is not significant. This suggests that for urban residents, these two air pollutants may not be the primary factors influencing housing price expectations. Firstly, the main sources of these two air pollutants are industrial pollution, which is more related to industrial clustering and less related to residents' normal production activities. Secondly, compared to PM_{10}, the concentrations of SO_2 and NO_2 are relatively low. Therefore, when making location decisions, residents are more concerned about the primary components of haze in pollutants, and they pay relatively less attention to industrial pollutants. The regression results are shown in Table 9.

Table 9 The effect of SO_2 and NO_2 concentrations on housing prices

Variables	SO_2				NO_2			
	(1) $lnHP$	(2) $lnHP$	(3) $lnHP$	(4) $lnHP$	(1) $lnHP$	(2) $lnHP$	(3) $lnHP$	(4) $lnHP$
$lnSO_2$ $/lnNO_2$	-0.448***	-0.415***	-0.102***	-0.014	0.303***	0.244***	-0.124**	-0.434
$lnPop$		0.612***	-0.316	-0.028		1.330***	-0.038	-0.028
$lnDoctor$			0.521***	0.201***			0.726***	0.208***
$lnTeacher$			0.868***	0.480***			0.250**	0.499***
$lnBook$			0.009	-0.008			0.031	-0.006
$lnGDP\_per$				0.447***				0.444***
$lnGDP\_rat$				-0.180				-0.166
$lnGDP\_rat$				0.621***				0.659***
Constant	10.038***	6.102***	-5.922***	-5.080***	7.318***	-0.752	-1.417**	-5.468***
Observations	450	450	450	450	450	450	450	450
R^2	0.40	0.43	0.74	0.83	0.09	0.12	0.73	0.83
F-statistic	30.33***	21.91***	24.60***	30.66***	16.49***	12.84***	38.84***	44.79***
Hausman Test	2.28	8.44**	107.50***	93.83***	0.95	27.10***	121.92***	77.34***

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

First, let's analyze the negative impact of SO_2 concentration on urban housing prices. In column (1), it can be observed that when the SO_2concentration increases by 10%, the local housing prices will decrease by 4.48%, indicating that SO_2 does hinder the rise in housing prices. After including the population density variable, the negative impact of SO_2 on housing prices decreases to some extent due to population agglomeration effects, but it remains significant. In column (3), after incorporating variables related to public services, the adverse effect of SO_2 on housing price increases is significantly reduced (1.02%), further highlighting the promoting role of urban public services in housing price increases. However, it still cannot compensate for the expected devaluation caused by air pollution. In column (4), when other control variables are added, it is found that the decrease in housing prices is not significant when the SO_2concentration increases, indicating that urban SO_2concentration does not significantly affect residents' expected housing prices. Similar to the regression results for PM_{10}, an increase in lnGDP_per and lnGDP_ratio3 promotes local housing price increases. This phenomenon suggests that when urban features meet residents' expectations and air pollutant concentrations are relatively low, air pollution may not strongly negatively affect housing price increases.

Compared to the results for SO_2, the negative impact of NO_2 on housing prices is relatively low. The low R^2 values in columns (1) and (2) indicate a weak explanatory power of NO_2 on urban housing prices, and the estimated results may contain errors. Therefore, further control variables need to be included. In column (3), after incorporating variables related to public services, the model fit is better, and at a significance level of 10%, a 10% increase in NO_2 concentration is associated with a 1.24% decrease in local housing prices, indicating a certain negative impact. However, when other control variables are added, similar to the SO_2 results, the negative impact of increasing NO_2 concentration on urban housing prices is not significant. These regression results indicate that the increase in SO_2 and NO_2 concentrations may not be the main reasons hindering housing price increases.

(3) $PM_{2.5}$ Impact on urban house prices

Due to limitations in data availability, the number of observations in this model is relatively small, which may introduce bias into the regression results. However, the research findings indicate a significant negative impact of $PM_{2.5}$ concentration, one of the main components of haze, on urban housing prices, consistent with the hypothesis of this study. The degree of influence of $PM_{2.5}$ concentration on urban housing prices is presented in Table 10.

Table 10 The effect of $PM_{2.5}$ concentration on housing prices

Variables	(1)	(2)	(3)	(4)
	$lnHP$	$lnHP$	$lnHP$	$lnHP$
$lnPM_{2.5}$	-0.498***	-0.531***	-0.339***	-0.319***
$lnPop$		-0.133	-0.127	-0.109
$lnDoctor$			0.336***	0.294***
$lnTeacher$			0.203	0.126
$lnBook$			-0.049**	-0.053**
$lnGDP\_per$				0.120
$lnGDP\_ratio2$				-0.387
$lnGDP\_ratio3$				-0.357

Constant	10.721***	11.685***	5.634**	8.332**
Observations	180	180	180	180
R^2	0.02	0.54	0.59	0.60
F-statistic	95.16***	57.49***	35.79***	27.50***
Hausman Test	4.50	19.78***	19.93***	18.00**

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

Firstly, the negative impact of $PM_{2.5}$concentration on urban housing prices is evident, as shown in column (1). A 10% increase in $PM_{2.5}$concentration leads to a decrease of 4.98% in local housing prices, indicating a significant effect. After introducing control variables such as population density and dimensions of public services in column (3), the negative impact of $PM_{2.5}$ concentration on urban housing prices decreases to 3.39%. This finding aligns with the regression results of $PM_{10}$and demonstrates the mitigating effect of improved urban public services on the influence of air pollution. However, the direction of the effect of population density on housing prices changes to negative, although it is not statistically significant. In column (4), when additional control variables are included, the negative impact coefficient of $PM_{2.5}$ on urban housing prices further decreases, but variables such as population GDP and industry ratio do not show a significant relationship with housing prices. The possible reasons for these results are the short data series, which may lack long-term stability, and the fact that population density only partially represents the level of population mobility in the city, leading to deviations in short-term regression. The low R^2 value also indicates room for further improvement in data fitting. Nevertheless, the regression results of this model confirm that an increase in $PM_{2.5}$ concentration hinders the rise in urban housing prices, aligning with the perspectives of other scholars. Studies focusing on various prefecture-level cities commonly recognize a negative correlation between $PM_{2.5}$ and housing prices.

By comparing the differential impacts of various air pollutants on urban housing prices, it can be concluded that all air pollutants exhibit a negative correlation with housing prices, with PM_{10} and $PM_{2.5}$, the primary components of haze, having a greater influence. Hypothesis 1 is validated as a 10% increase in PM_{10} and $PM_{2.5}$ concentrations leads to a respective decrease in housing prices by 1.55% and 3.19%. The negative impacts of increasing SO_2 and NO_2 concentrations on housing prices are not statistically significant. however, they may still cause a decline in expected housing prices. This suggests that residents pay less attention to industrial air pollution when making housing decisions but are more sensitive to changes in PM_{10} and $PM_{2.5}$ concentrations in the atmosphere.

(4) Transmission paths of air pollution impact on housing prices

Based on the aforementioned analysis, this study conducts a mediation analysis using the variable PM_{10}, which exhibits the most significant negative impact on housing prices, to verify the pathway through which air pollution affects urban housing prices, building upon the long-term data-based regression model. Firstly, a stepwise regression method is employed to verify whether PM_{10} concentration influences population density, per capita GDP, and industrial composition. Secondly, it is examined whether PM_{10} indirectly affects housing prices by influencing these three aspects. Based on the research hypothesis, a total of four potential pathways need to be tested for mediation.

In Table 11, this study examines whether PM_{10} concentration indirectly affects housing prices by influencing urban population density and economic development level. The non-significant regression results of PM_{10} on population density suggest that changes in urban population density may not be the main pathway through which PM_{10} concentration affects housing prices, indicating that hypothesis 2(a) fails to pass the test. This result may be attributed to the relatively low proportion of floating population in the total population of some cities, leading to biased analysis results. Taking Shanghai, a city with a relatively developed economy, as an example, its net migration rate in 2016 was 4.56%, accounting for a relatively small proportion of the total population. In 2018, Urumqi had a negative net migration rate, which would not significantly affect the city's population density indicator. Therefore, population mobility has a relatively greater impact on population density in prefecture-level cities. However, when focusing on provincial capital cities, although severe air pollution conditions may lead residents to consider outward migration, they also face significant migration costs, which reduce this influence. Analyzing the situation based on urban population mobility may yield different results.

Table 11 The mediating effects of PM_{10} concentration on house prices

Variables	Path 1			Path 2		
	(1)$lnHP$	(2)$lnPop$	(3)$lnHP'$	(1)$lnHP$	(2)$lnGDP\_per$	(3)$lnHP'$
$lnPM_{10}$	-0.281***	-0.008	-0.281***	-0.281***	-0.199***	-0.191***
$lnPop$			0.004			
$lnGDP\_per$						0.453***
$lnDoctor$	0.553***	0.030	0.553***	0.553***	0.499***	0.327***
$lnTeacher$	0.917***	0.264***	0.916***	0.917***	0.934***	0.495***
$lnBook$	0.012	0.026**	0.013	0.012	0.045*	-0.008
Constant	-6.092***	3.250***	-6.107***	-6.092***	-4.336***	-4.129***
Observations	450	450	450	450	450	450
R^2	0.75	0.20	0.75	0.75	0.71	0.80
F-statistic	36.50***	576.61***	33.45***	36.50***	196.53***	38.71***

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

The results of the test for Path 2 indicate that an increase in PM_{10}concentration has a significant negative impact on urban per capita GDP. In the regression results, both coefficients, b_2 = -0.199 and n_2 = 0.453, are significant, and the product of the coefficients, $b_2 * n_2$ = -0.09 < 0, is negative. It is consistent with m_2' = -0.191, suggesting the possible existence of a mediating effect, and hypothesis 2(b) is validated. Additionally, by observing the third column of the regression results, it can be observed that PM_{10}has a significant negative impact on urban housing prices as well. This mediating effect is partial, meaning that an increase in PM_{10} concentration directly affects housing prices and also indirectly suppresses price increases by hindering the increase in per capita GDP.

In Path 3 of Table 12, this study verifies whether PM_{10}concentration indirectly affects housing price levels through its impact on the share of the secondary industry in cities. The research results show that at a significance level of 5%, an increase in PM_{10}concentration has a certain positive impact on the share of the secondary industry in cities. This finding differs from hypothesis 2(c) of this study but aligns with the conclusions of some scholars. There are two main reasons why hypothesis 2(c) did not pass. First, the secondary industry still acts as a driving force for economic development, and an increase in air pollution concentration indicates a favorable environment for the development of the secondary industry in the local area. In some cities, to achieve economic growth, local governments may have a lower proactive approach to pollution control, resulting in a positive impact of air pollution on the increase in the share of the secondary industry. Second, it is possible that the lagged variable method used in this study does not fully address the bidirectional causality between industrialization and air pollution. The improvement in the level of urban industrialization may have a reverse effect on the level of air pollution, causing bias in the regression results. Using instrumental variables such as ventilation coefficient and pollution control policies can to some extent alleviate the reverse causality between the two. However, according to the regression results, $b_3 * n_3 = -0.035 < 0$, which is consistent with $m_3' = -0.246$, indicating that the share of the secondary industry in cities may also be one of the pathways affecting housing prices. Since an increase in PM_{10}concentration directly affects housing prices, this mediating effect is also partial.

Table 12 PM_{10} Mediated effects of concentration on house prices

Variables	Path 3			Path 4		
	(1)$lnHP$	(2)$lnGDP\_ratio2$	(3)$lnHP'$	(1)$lnHP$	(2)$lnGDP\_ratio3$	(3)$lnHP'$
$lnPM_{10}$	-0.281***	0.063**	-0.246***	-0.281***	-0.050**	-0.234***
$lnGDP\_ratio2$			-0.558***			0.950***
$lnGDP\_ratio3$						
$lnDoctor$	0.553***	-0.170***	0.459***	0.553***	0.165***	0.397***
$lnTeacher$	0.917***	-0.046	0.892***	0.917***	0.061	0.860***
$lnBook$	0.012	0.000	0.012	0.012	-0.001	0.013
Constant	-6.092***	5.634***	-2.946***	-6.092***	1.866***	-7.865***
Observations	450	450	450	450	450	450
R^2	0.75	0.27	0.77	0.75	0.39	0.79

F-statistic	36.50***	47.94***	36.16***	36.50***	41.68***	34.26***

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

In Path 4, this study verifies whether an increase in PM_{10} concentration indirectly affects housing price levels through its impact on the share of the tertiary industry in cities. The results show that an increase in PM_{10}concentration directly suppresses housing price increases, and the effect is significant (m_4' = -0.234). In the mediating path, an increase in PM_{10}concentration has a significant inhibitory effect on the development of the tertiary industry in cities (b_4 = -0.050), indicating that severe air pollution conditions are unfavorable for the development of the local service industry, thereby affecting the level of public services in cities. Furthermore, since b_4 * n_4 = -0.048 < 0, and it is consistent with m_4' = -0.234, an increase in PM_{10} concentration may indirectly affect local housing price levels by hindering the development of the tertiary industry in cities, validating hypothesis 2(d). This indirectly demonstrates the promoting effect of improving the level of urban public services on housing price increases.

Due to the potential influence of the stepwise regression method on the significance of mediating effects, to further compare the magnitude of the pathways through which PM_{10}concentration affects housing prices, this study conducts Bootstrap tests on each mediating path to illustrate their indirect effects. The test results are shown in Table 13. It can be observed that the indirect effect of Path 1 is 0, indicating that population density is not the pathway through which PM_{10}affects urban housing prices, consistent with the results of the stepwise regression method. The test results for Path 2 indicate that when PM_{10}concentration increases by 10%, it directly leads to a 1.91% decrease in housing prices, indirectly causing a 0.9% decrease through the pathway of per capita GDP, and both direct and indirect effects are significant, indicating a partial mediating effect, with the mediation proportion being 32.03%.

Table 13 Bootstrap test for impact paths

	Path 1			Path 2		
	Indirect effects	Direct effects	Total effect	Indirect effects	Direct effects	Total effect
Coefficient	-0.0000	-0.2810***	-0.2810***	-0.0900**	-0.1910***	-0.2810***
Statistical quantities	-0.0100	-4.8200***		-2.1500**	-3.2300***	
Confidence interval.						
Lower limit	-0.0071	-0.3960		-0.1723	-0.3074	
Upper limit	0.0071	-0.1669		-0.0078	-0.0753	

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

Table 14 presents the pathway analysis of industrial structure. The confidence interval of Path 3 includes 0, indicating that the mediating effect is not established. Therefore, it can be concluded that PM_{10} concentration does not indirectly affect local housing price levels through its impact on the share of the secondary industry. This finding may also be related to the reverse causality between urban industrialization and air pollution. In the test for Path 4, when PM_{10} concentration increases by 10%, it directly leads to a 2.34% decrease in housing prices, and indirectly causes a 0.48% decrease through its impact on the share of the tertiary industry. Both the direct and indirect effects are significant. This pathway also exhibits a partial mediating effect, with the mediation proportion being 17.21%.

Table 14 Bootstrap test for impact paths

	Path 3			Path 4		
	Indirect effects	Direct effects	Total effect	Indirect effects	Direct effects	Total effect
Coefficient	-0.0350*	-0.2460***	-0.2810***	-0.0480**	-0.2340***	-0.2820***
Statistical quantities	-1.7000*	-4.0000***		-1.9800**	-4.3600***	
Confidence interval.						
Lower limit	-0.7571	-0.3670		-0.0951	-0.3387	
Upper limit	0.0053	-0.1256		-0.0003	-0.1288	

Note:*、**、*** indicates significant at the 10%, 5% and 1% levels, respectively.

In summary, this study analyzed the impact of PM_{10}concentration and found that it not only directly affects housing prices negatively but also has indirect effects through its influence on per capita GDP and the development of the tertiary industry. This confirms the existence of mediating effects and partially validates Hypotheses 2(b) and 2(d). However, Hypotheses 2(a) and 2(c) were not supported. In terms of the magnitude of the mediating effects, the indirect effect through per capita GDP is greater than that through the share of the tertiary industry. Furthermore, due to endogeneity issues and limited data sources, neither population density nor the proportion of the secondary industry showed significant mediating effects, suggesting that they may not be the primary pathways through which air pollution indirectly affects housing prices.

5. Conclusions and Suggestions

5.1 Conclusions

Most scholars commonly focus on regulatory policies, income, and economic levels. From the perspective of air pollution, there is limited research that delves into the und erlying mechanisms between these factors. In this study, we employ various types of p ollutants to analyze the pathways through which air pollution affects urban housing pr ices, quantifying the magnitude of each intermediate path. Our findings reveal that air pollution significantly hampers the upward trajectory of housing prices, and different air pollutants exhibit varying degrees of impact on housing prices, with the primary co mponents of haze having a more pronounced effect. Our empirical results align with e xpectations and existing research. As a residential characteristic, air quality can be refl ected in housing prices by influencing the marginal willingness to purchase a residenc e. It is widely acknowledged that prolonged exposure to polluted air poses risks to ph ysical and mental health, such as cardiovascular diseases, infant mortality rates, and d epressive symptoms. As awareness of these pollution-related hazards and a heightene d consciousness of healthy living grow, the public is increasingly concerned about the risks of air pollution and tends to avoid areas with air pollution when deciding on resi dential locations. This explains the negative correlation between air pollution and hou sing prices.

Air pollution significantly inhibits the rise in housing prices, and different air pollutants have varying degrees of impact, with a greater influence observed for primary components of haze, namely PM_{10} and $PM_{2.5}$. A 10% increase in $PM_{10}$and $PM_{2.5}$ concentrations will respectively lead to a decrease in urban housing prices by 1.55% and 3.19%. While SO_2 and NO_2concentrations also negatively affect housing prices, their impact is not significant as urban characteristics increase. Higher concentrations of PM_{10} and $PM_{2.5}$, coupled with repeated emphasis on haze issues by government authorities, draw more attention from residents compared to industrial pollutants. Rational control of urban air pollution would contribute to promoting the development of the local real estate industry.

Air pollution has a negative impact on urban housing prices through mediating pathways. The research findings indicate that an increase in PM_{10}. concentration directly affects the rise in housing prices negatively. Additionally, it indirectly suppresses the increase in housing prices through two pathways: impeding the improvement of per capita GDP and hindering the development of the tertiary industry. Both pathways exhibit partial mediating effects. The reason lies in the fact that the level of public services in a city directly impacts the quality of life. Residents are particularly concerned about conditions such as healthcare and education in the city they inhabit. The improvement in the level of public services has a facilitating effect on the increase in housing prices and can, to a certain extent, alleviate the cost losses resulting from air pollution. Additionally, the rise in per capita GDP and the proportion of the tertiary sector play a driving role in the increase of urban housing prices. In some cities, an increase in the proportion of the secondary sector, on the contrary, hinders the rise in urban housing prices. This reflects a preference among residents to live in cities with lower levels of industrialization and a well-developed service sector, aiming to avoid air pollution issues from the source as much as possible.

However, there is no significant mediating effect observed for population density and the proportion of the secondary industry. Through testing, it is determined that the mediating effect of the per capita GDP pathway accounts for 32.03%, while the mediating effect of the tertiary industry proportion pathway accounts for 17.21%. This indirectly reflects the negative impact of air pollution on urban economic levels and the development of the tertiary industry. It also highlights that residents' property purchase decisions are primarily influenced by the current economic development status and the state of public infrastructure in the city.

Our study also has limitations that warrant further investigation. Firstly, empirical estimates primarily focus on heterogeneity analysis but lack causal identification tests, underscoring the importance of validating the causal relationship between air pollution and housing prices. Secondly, we did not conduct any mechanistic analysis of the impact of air pollution on housing prices. Additionally, Researchers have conducted a study examining the impact of the household registration system, highlighting that, among the population decline attributed to air pollution, half consists of residents maintaining their household registration, i.e., non-mobile population. The study also contrasts the effects of air pollution on mobile migrants and registered migrants. In China, the substantial migration costs associated with the household registration system may lead to an underestimation of people's willingness to pay for air quality improvement. Consequently, investigating the role of the household registration system has become a crucial direction for future research.

5.2 Suggestions

Air pollution not only affects the physical and mental health of residents but also has negative impacts on urban housing prices and industrial layout, making it an urgent problem to be addressed. Effective control of urban air pollution would improve residents' quality of life, enhance urban livability, and promote the development of the real estate industry. Based on this, the following policy recommendations are proposed in this study:

(1) Establish an air quality information disclosure system and consider incorporating air pollution losses into real estate valuation in heavily polluted areas. Implement an environmental monitoring system that enables government agencies and enterprises to analyze the spatiotemporal patterns of air pollution and propose targeted pollution prevention and control measures. Given the significant negative impact of air pollution on urban housing price increases, considering the cost of air pollution losses in real estate valuation in heavily polluted regions would lead to a more accurate assessment of real estate development costs, thereby avoiding profit losses caused by air pollution. Additionally, adopting pollution taxes during property transactions for different income groups can reduce government expenditure on pollution control and enhance residents' environmental awareness.

(2) Strengthen efforts to control air pollution, promote industrial transformation, and facilitate the healthy development of the real estate industry from the source. In addition to formulating pollution prevention and control measures, it is necessary to impose environmental pollution taxes or carbon emission taxes on enterprises and strengthen the regulation of pollution emissions. Mandatory and incentive-based measures should be implemented to encourage enterprises to control pollutant emissions at the source. Government agencies should also arrange industrial layouts rationally, relocating heavily polluting industries out of core cities, implementing stringent market access regulations, and raising mandatory standards for energy consumption and exhaust emissions by enterprises. By addressing air pollution at its source and improving urban livability, the extent of pollution-related losses in the real estate sector can be reduced, thereby safeguarding the healthy development of the industry.

(3) When formulating housing price control policies, local pollution conditions should be appropriately considered. In areas with intensive industries and severe pollution, government agencies should primarily adopt mandatory measures to control air pollution emissions and intensify promotion efforts for environmental protection and low-carbon living. When implementing real estate control policies, estimating pollution losses would prevent excessive housing prices from causing further brain

drain, and developers should further enhance housing facilities to increase their attractiveness. In cities with less severe pollution and higher levels of economic development, government agencies need to prevent adverse effects of air pollution on real estate by implementing mandatory and incentive-based measures to improve air quality. During housing price regulation, a more flexible estimation of pollution-related costs can be considered.

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