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Assessing the Impact of Pollution on Urban Scale in China: A New Perspective from Residents' Health

Li He [1] and Xukun Zhang [2,*]

[1] Department of Public and International Affairs, City University of Hong Kong, Hong Kong, China; lihe28-c@my.cityu.edu.hk
[2] College of Social Sciences, Shenzhen University, Shenzhen 518060, China
* Correspondence: xukunzhang@szu.edu.cn

Abstract: Environmental pollution significantly impacts the urbanization process. Despite the well-documented influence of urban scale on pollution, understanding of the specific effects of pollution at the urban scale remains limited. This study aims to further the understanding of the impact of pollution on urban scales by analyzing pollution variations and mechanisms. This study investigated city-level panel data in China, specifically assessing different pollutant emissions and their linkage to resident health. This study found that pollution has contrasting effects on urban land and population scales. It leads to expansion in urban land but has crowding-out effects on population scales. Notably, pollution from haze was found to increase urban mortality to a greater extent than pollution from industrial sources. Furthermore, this research found that increasing healthcare expenditures for urban residents can offset the negative impact of pollution on population growth and promote coordinated urbanization. This study emphasizes the importance of local government investment in medical services and public expenditures to mitigate the harmful effects of pollution on health, which can substantially prevent population outflows. Furthermore, stronger environmental protection measures can prevent urban land development sprawl resulting from pollution. In conclusion, this study highlights the need for a balanced approach to pollution control and urban development to achieve sustainable and high-quality urbanization.

Keywords: environmental pollution; urban scale; residents' health; mediating effects; China

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1. Introduction

Urbanization is a critical and profound transformation of land, industry, and population in modern society [1]. During the complicated process of urbanization, rural factors are converted to urban factors, resulting in rural–urban migration and the expansion of existing cities [2]. China's remarkable economic growth has been accompanied by an observable expansion in the urban scale, evident in both population migration and land use change (Figure 1, similar trends at the city level also captured by figures in Supplementary Materials Part S2). According to data from the National Bureau of Statistics of China [3], over the past two decades, China's urban population has almost doubled, surging from 524 million to 921 million. Simultaneously, the total urban built-up area has also experienced a remarkable increase. This process has boosted economic growth by improving productivity and resulting in the agglomeration effect (or scale effect); however, it has also resulted in growing environmental pollution and health risks. Figure 1 illustrates that urban industrial pollutant emissions, particularly $PM_{2.5}$ ($PM_{2.5}$, or particulate matter 2.5, refers to tiny particles or droplets in the air that are two and one half microns or less in width) concentrations, have not exhibited a significant and consistent reduction since 2004. Moreover, the negative influences of pollution on human health and the relevant interactions between them have been examined from the perspective of disease incidence or death rates [4–7]. For instance, the Lancet published a report revealing that outdoor air pollution in China caused

1.23 million premature deaths and 25 million years of life lost in the year 2010, making China one of the countries with the greatest burden of environmental diseases in the world [8].

Under these circumstances, environmental protection and relevant health risks have become the focus of policymakers and the public. Given these circumstances, a growing focus on high-quality urbanization and sustainable development calls for research into the nexus between urban scale, urban pollution, and residents' health in the Chinese context. Additionally, plenty of research has discussed the ecological or environmental effect of urbanization, e.g., [9–11], while this study attempts to fill in the research gap by providing relatively new insights into the effect of environmental pollution on urbanization.

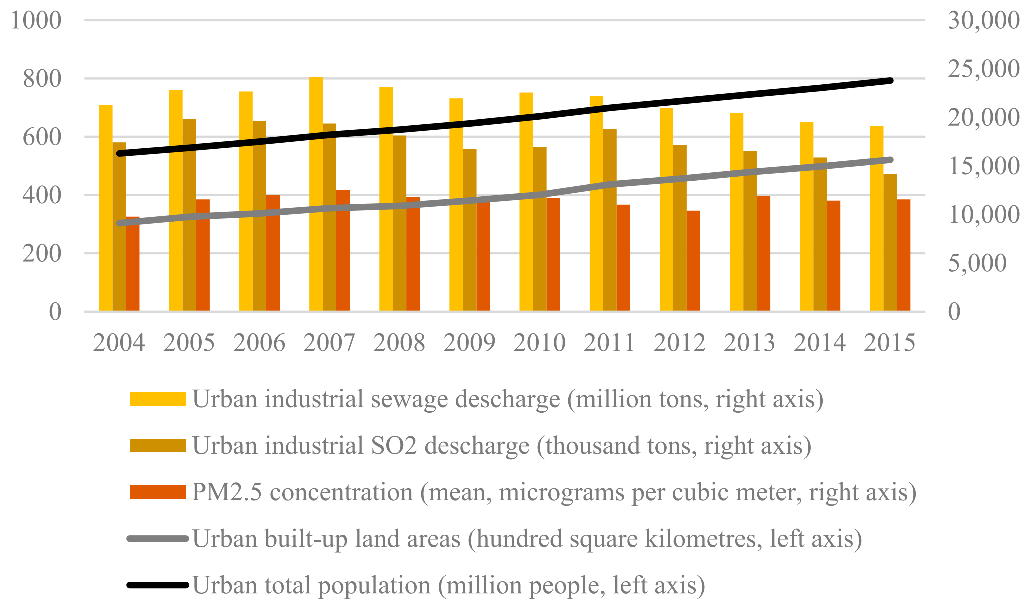

Figure 1. Evolution of urban scale and urban pollution discharge in China (2004–2015). Sources: *China Statistical Yearbook* [3], *China City Statistical Yearbook* [12], and Columbia University (the basic data are available at: https://sedac.ciesin.columbia.edu/ accessed on 10 May 2023).

The objectives of this study are twofold. First, taking different measures of urban scale and various pollutants into consideration, the present study investigates the direct but heterogeneous effects of pollution on the urban scale. Second, this study further explores the influencing mechanisms from the perspective of residents' health. Accordingly, this study poses two research questions: does pollution lead to a larger urban scale? What are the heterogeneous effects of pollutants on urban population scale and urban land scale, and what are the mechanisms driving such effects?

Additionally, the contributions of this paper are as follows: First, previous studies on the impact of pollution on the urban scale generally focused on a specific measure of pollutants or an urban scale, such as haze pollution [13,14] and population scale [15–17]. However, few studies have considered the heterogeneity of such impacts. However, different pollutants and their sources will have differentiated effects on urban populations and land use [18], which merits further exploration. Additionally, the single proxy for urban scale and the ignorance of urban built-up land expansion may be against Chinese land-dominated urbanization as a result of dualistic land experienced by most Chinese cities [19]. Therefore, relying solely on the urban population does not accurately reflect the scale of the city. Given these, this paper analyzes the heterogeneous impacts of pollution on the urban scale in China at the city level based on the effects of various emissions on both the urban population scale and the urban land scale. Second, although environmental pollution has been studied extensively with respect to its health effects, limited research has simultaneously identified the logical chain or examined the relationship among environmental pollutants, resident health, and urban scale. Therefore, this study attempted to bridge these concepts by validating the mechanisms underlying residents' health in terms of environmental pollution and urban scale. Using city-level data, the mediation effect empirical method was applied based on the theoretical model. This paper attempts to clarify the logical chain among pollution, health, and urban scale by identifying the mediating role of human health in the nexus between environmental pollution and urban scale from the aspects of urban residents' health levels and health costs. In short, this study establishes an innovative and relatively comprehensive analytical framework for probing into the effects and mechanisms of environmental pollution on an urban scale.

2. Literature Review

2.1. Urban Scale and Its Factors

The urban scale usually refers to the size of a city. It serves as an important indicator of urban development and urbanization. This measure is often based on both the total population of an urban area and the overall built-up area of the city [20–24]. Furthermore, the non-agricultural population proportion and urban population density are also used to depict the urban scale [20,25,26].

The process of urbanization involves the conversion of population, industry, and land use. Thus, the urban scale is affected by migration, production, and policy priorities that are generally associated with, or even result from, various factors related to economic growth, social development, and the natural environment. Owing to the complexity of the determinants, city size is considered the result of the optimal trade-off between positive and negative externalities, along with urban development [27]. Regarding the urban population scale, empirical evidence has shown that industrial agglomeration, public service supply, productivity, living amenities, land use efficiency, and financial development exert positive impacts on urbanization [28–32]. Conversely, increasing capital costs, high housing prices, migration friction, and capital efficiency inhibit urban population growth [28,30,33]. On the other hand, the effects of economic growth, population migration, globalization, land revenue, transport costs, and urban planning on the urban land scale have been examined [34–40]. Interestingly, the critical role and profound impacts of institutional factors in China, including development strategy, migration policy, and urban policy, on urban growth and urbanization have been emphasized by Song and Zhang [41] and Zhong et al. [39].

2.2. Nexus between Pollution and the Urban Scale

A considerable amount of research has investigated the relationship between urban scale and urban environment, e.g., [9–11,18,21], although most of these studies have focused on the eco-effects of urban scale or urbanization. In general, the proximity and concentration of activities are not only preconditions for social interactions and economic efficiency but also the source of resource depletion, environmental damage, and human health problems [42–44]. As specified by the conventional IPAT and STIRPAT models (as York et al. [45] introduced, the IPAT model denotes the formula: I = f (P, A, T), which was first derived from the Ehrlich-Holdren/Commoner debate in the early 1970s to capture the human impact (I) on the environment as a function of population (P), affluence (A), and technology (T) and has been commonly used, particularly in the domain of environmental studies since then. Additionally, the STIRPAT model has been developed as an extension of the IPAT model, which represents the Stochastic Impacts by Regression on Population, Affluence, and Technology), the population is a key theoretical driving factor of pollutant emissions. By revisiting and extending these models, extensive research has been conducted to decompose the population term into population scale and population structure, and further introduce urban scale and urbanization into the theoretical framework for analyzing key drivers of pollutant emissions [15–17,46,47]. Empirically, Oke [48] highlighted that there is a positive correlation between population scale and urban heat islands. Moreover, the positive impacts and causal links between urban size and pollution levels have been verified by several studies [11,16,17,42,47,49–51].

Focusing on the land scale, Hien et al. [52] and Zhou et al. [53] analyzed the close and coupled relationship between urban land expansion and environmental pollution. The former revealed that patterns of pollution landscapes are characterized by concentric urban expansion around the city center, while the latter illustrated that continuous construction land expansion has little impact on $PM_{2.5}$ concentrations. Moreover, Huang and Du [10] found a positive impact of urban land expansion on pollution, while Yu et al. [14] showed opposite results. Furthermore, following the Environmental Kuznets Curve (EKC) theory, numerous studies have extensively examined and validated the nonlinear impact of urbanization on pollution, shedding light on the intricate decoupling relationship involved [45,54,55]. In short, despite the abundance of research on the environmental effects of urbanization, a consensus has not yet been reached.

In turn, the optimal urban scale has been previously discussed, and the role of the environment has been preliminarily investigated. For example, Capello and Camagni [42] suggested that urban residents experiencing environmental externalities (such as pollution and disasters) in their city area tended to relocate to the surrounding area. Wu et al. [56] used a multi-level index system along with threshold models and concluded that environmental pollution hindered China's urbanization. In addition, many studies have claimed that environmental pollution is a contributing factor to emigration, e.g., [13] and [57–60]. Among these, Chen et al. [58] performed robust investigations into the significant effect of air pollution on migration and specified that independent changes in air pollution could reduce both floating migration inflows and population through net outmigration in China. Interestingly, Cao et al. [13], Chen et al. [58], and Liu et al. [61] found that well-educated people and high-income groups are more sensitive to pollution. In addition, Zhao et al. [62] confirmed that pollution would negatively affect migrants' settlement intentions, which essentially echoes previous findings about the pollution-migration relationship. Nevertheless, it is worth noting that beyond the perspective of population scale, there has been little research on the effects of environmental pollution on urban land use or land scale.

2.3. Nexus between Pollution and Residents' Health

As a negative externality of production, pollution is harmful to health status and leads to further healthcare costs or economic losses for residents. Recent studies have focused on the health effects of environmental pollution, primarily from two aspects: health level and health costs.

Health levels are often depicted as health damage or disease. The effects of air pollution on human health can be either acute or chronic and may affect several different systems and organs. Symptoms may include respiratory disease, heart disease, lung cancer, and chronic bronchitis and may aggravate pre-existing heart and lung disease or asthmatic attacks [63]. As a potential disease outcome, short-term and long-term exposure to pollution are both believed to be connected to premature mortality and reduced life expectancy. In other words, the health-related effects of pollution differ between long-term and short-term exposures. The mortality risk associated with pollution is generally estimated to be higher with long-term exposure due to the potential for larger and more persistent cumulative effects [64]. Additionally, the association and positive causal relations between exposures to various pollution and health risk or mortality have been verified by Ebenstein et al. [4], Lu et al. [7], Moradi et al. [65], Brunekreef and Holgate [66], Qi and Lu [67], and Mehmood et al. [43,68].

On the other hand, health costs would increase owing to environmental problems and pollution, particularly in the area of hospitalizations and medications used to treat or prevent diseases. Bai et al. [69] reviewed several studies on health costs accounting for China's air pollution and revisited their association and interactions based on different accounting model specifications. Cui et al. [70] suggested that increases in air pollution would significantly increase the monetary cost of either curing or preventing associated diseases, while increases in health insurance coverage could have the opposite effect. Through estimating economic losses caused by pollution-related health damage, Cao and Han [71] emphasized that the health costs associated with haze pollution in Beijing were considerable, and that although in some cases such costs increased with a higher growth rate than GDP, these could be moderated by government efforts to control pollution. Moreover, economic losses resulting from pollution or the positive impacts of emissions on health costs have also been verified by Yazdi and Khanalizadeh [5], Chen and Chen [6], Miraglia et al. [72], Matus et al. [73], Jakubiak-Lasocka et al. [74], and Liao et al. [75]. More importantly, increasing medical and health costs could reinforce the inhibiting effect of environmental pollution on urbanization in China [56], while constructing district heating networks could bring significant advantages in terms of reducing health impacts, costs associated with urban development, and pollutant emissions in some cases [44].

In summary, numerous studies have focused on the urbanization–pollution relationship and revealed the associated bi-dimensional impacts and interactions [49]. However, most have concentrated on how urbanization affects environmental pollution, while few have focused on how pollution influences urban development. In addition, although the effects of different pollutants and their sources on urban population and land use differ [18], the heterogeneity of such impacts, however, has not been adequately considered in many studies. Additionally, the single proxy for urban scale and the ignorance of urban built-up land expansion may be against the Chinese land-centered urbanization context. Furthermore, the mechanisms and heterogeneity of the relationships or effects have not been fully explored. Thus, to investigate the nature of sustainable urbanization and high-quality development, this study establishes a relatively comprehensive analytical framework to investigate the effects of pollution on the urban scale. Using city-level data from China, the heterogeneity of the direct effects of pollution on the urban scale is revealed by using different measures of both pollutant emissions and the urban scale. By incorporating the urban land scale, which is another critical proxy for urban development, this study extends previous research that has mostly focused on the urban population scale. Second, given the impacts on residents' health, the influencing mechanisms of environmental pollution on the urban scale are empirically and specifically examined. Compared with Wu et al. [56], the present study aims to provide more extensive insights by elaborating on the mediating effects of health-related factors in terms of both health level and health cost. Using city-level data, the present study attempts to conduct more detailed investigations and offer targeted insights. In short, this study seeks to extend related knowledge, and provide a better understanding of the role of health-related factors in not only addressing environmental problems but also balancing pollution control and urban development.

3. Data and Models

3.1. Empirical Framework

Based on the previous literature on an urban scale, pollution, and residents' health, this study constructs the following urban scale function:

$$lnscale_{it} = f(lnpollution_{it}, lnhealth_{it}, control\ variables_{it})$$

where the subscripts i and t represent city i in year t. Following Mao et al. [26] and Yao et al. [23], this study uses city-level urban total population and urban built-up areas to measure the urban scale.

The key explanatory variable $lnpollution_{it}$ represents the measure of urban pollution. It is deemed a key factor affecting or even shaping not only the migration choices of individuals but also the location and production choices of enterprises [59] in terms of increasing health risks or relevant costs. Accordingly, $lnhealth_{it}$ denotes the mediating factors concerning urban residents' health in the mechanism analysis, and $control\ variables_{it}$ include a series of factors relating to the endowment and economic level, which also affect the urban scale. These are specified in the following sections.

3.2. Model Specifications

3.2.1. Baseline Regression

The impact of pollution on the urban scale is initially investigated using a baseline regression. A panel model is constructed and employed as follows:

$$lnscale_{it} = \beta_0 + \beta_1 \cdot lnpollution_{it} + \gamma \cdot X'_{it} + \phi_i + \varphi_t + \mu_{it} \quad (1)$$

where $scale_{it}$ and $pollution_{it}$ denote the proxies for urban scale and pollutant emissions of city i in year t, respectively; and ϕ_i, φ_t, and μ_{it} represent the region-fixed effect, time-fixed effect, and residual term, respectively. In this study, multidimensional variables and data are used for the analysis. The urban scale ($scale_{it}$) is depicted by two types of variables associated with population and land scales. Specifically, pop and area denote the total population and built-up land areas in the urban area, respectively. Larger values for *pop* and *area* indicate a greater urban scale. Furthermore, the close connections and significant causal links between rapid urbanization, industrial emissions, and haze pollution incidents have been widely verified and emphasized [11,76–78]. In this study, pollution ($pollution_{it}$) is measured and analyzed by these two commonly discussed pollutant emissions. Based on the definition of the three industrial wastes and the availability of relevant data from the National Bureau of Statistics of China (relevant definitions and data can be viewed and accessed at: https://data.stats.gov.cn/easyquery.htm?cn=E0103 accessed on 10 May 2023), industrial pollution consists of three types of pollutants: industrial wastewater (*water*), industrial SO_2 (*so2*), and industrial smog (*smog*), which were also examined by Guo et al. [79]. To analyze aggregate industrial emissions, this study referred to the research of Liu and Lin [80] and He et al. [81], which also included the composite index (pollution) in their empirical analyses. In addition, haze pollution was analyzed as a proxy for another crucial air pollution by calculating the city-level data of the annual mean $PM_{2.5}$ concentration (*pm25*).

In addition, X'_{it} consists of several control variables (CVs) related to the urban scale. According to the factors reviewed in Section 2.1, in the process of urban planning and development, population structure, productivity level, investment level, industrialization development, government support, and public service supply play key roles. As a result, variables associated with urbanization, urban fiscal pressure, urban productivity, urban individual income, urban medical services, urban infrastructure construction, urban investment, urban industrial structure, and urban education services have been included in the empirical models as CVs.

β_1 is the focus of the empirical analysis. According to the research of Weng and Yang [82] and Mao et al. [26], the estimates of this coefficient are expected to be significantly positive when the dependent variable is the population scale but negative when the dependent variable is the urban land scale. Correspondingly, relevant hypotheses can be developed as follows:

H1. *Impacts of pollution on the urban scale show the heterogeneity among various pollutants and different measures of the urban scale. Specifically,*

H1a. *Pollution negatively impacts the urban population.*

H1b. *Pollution has a positive impact on the urban built-up area.*

3.2.2. Mediating Effect Analysis

Given the research aims, this study explores the mechanisms from the perspective of residents' health, which are deemed to exert impacts on and bear the effects of both environmental pollution and urban development. Echoing the literature concerning the impacts of pollution on residents' health reviewed in Section 2.3, this study then conducted a relevant review for mechanism analysis from the following two aspects. First, individual health levels are believed to have a direct influence on labor mobility and migration decisions by affecting the cost or quality of living [83]. Second, specific expenditure concerning healthcare reflects either the bias in the policy at the macro level or the cost of living at the micro level, which has been viewed as the key mediating or moderating factor in investigations of the urbanization–pollution nexus [14,56]. Given the availability of related data, the present study considers mortality rate and healthcare expenditure as mediating factors.

Methodologically, the mediating effect model has been employed for the mechanism analysis. In addition to Equation (1), the following equations are applied:

$$lnhealth_{it} = a_1 + b \cdot lnpollution_{it} + \gamma' \cdot X'_{it} + \phi'_i + \varphi'_t + \mu'_{it} \tag{2}$$

$$lnscale_{it} = a_2 + \beta' \cdot lnpollution_{it} + c \cdot lnhealth_{it} + \gamma'' \cdot X'_{it} + \phi''_i + \varphi''_t + \mu''_{it} \tag{3}$$

where the mediating factor ($lnhealth_{it}$) consists of two variables: the urban mortality rate (*lnhealth_d*) and the total healthcare expenditure of urban residents (*lnhealth_cost*). According to relevant research, the former is usually regarded as the risk and undesirable outcome of pollution exposure, which can further affect the migration decisions of individuals, while the latter is conducive to addressing or even treating the damage caused by pollution, primarily by preventing or curing disease. Thus, both mediating factors are expected to be positively affected by increases in urban pollution but exert opposite impacts on the urban population and land scale. Accordingly, the hypothesis can be established as:

H2. *The impacts of pollution on the urban scale can be determined by the mortality rate and healthcare expenditures of urban residents. That is,*

H2a. *Decreasing the health levels of urban residents can mediate or help realize the impacts of pollution on either urban population scale or urban land scale.*

H2b. *Increasing the health costs of urban residents can mediate or help realize the impacts of pollution on either urban population scale or urban land scale.*

Based on the literature review and hypotheses discussed above, Figure 2 illustrates the relationships among environmental pollution, urban scale, and resident health analyzed in this study.

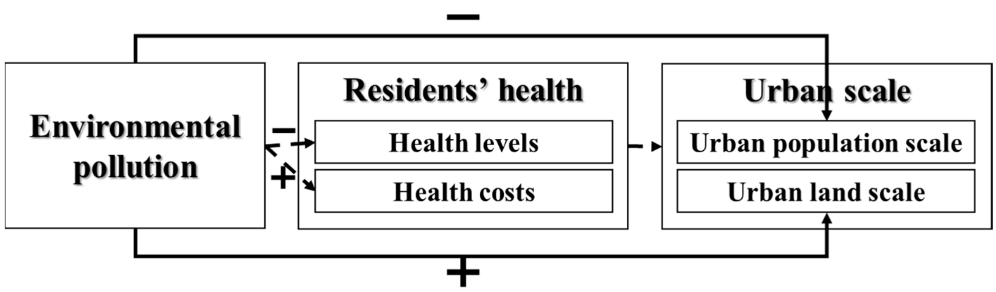

Figure 2. Logic of the analyses and hypotheses of this study. Notes: The solid and dashed arrows in the figure represent the direct effects and indirect impacts through the mediating effect analysis, respectively.

3.3. Data Sources and Variable Selections

3.3.1. Data Sources

Although this study is interested in collecting data on intercity population migration in China, it is important to acknowledge the considerable difficulty in obtaining accurate information, especially when it comes to tracking panel data. This difficulty has also been noted by other scholars, such as Liu et al. [61]. To map a more overall picture of changes in urban population and land use in China, the authors have collected city-level panel data for analysis covering 290 prefecture cities belonging to all 31 provinces of mainland China based on data availability. For validation and visualization, the list and a location map for the selected Chinese cities for empirical analysis are given by Table S1 in Supplementary Materials Part S1 and the following Figure 3, respectively.

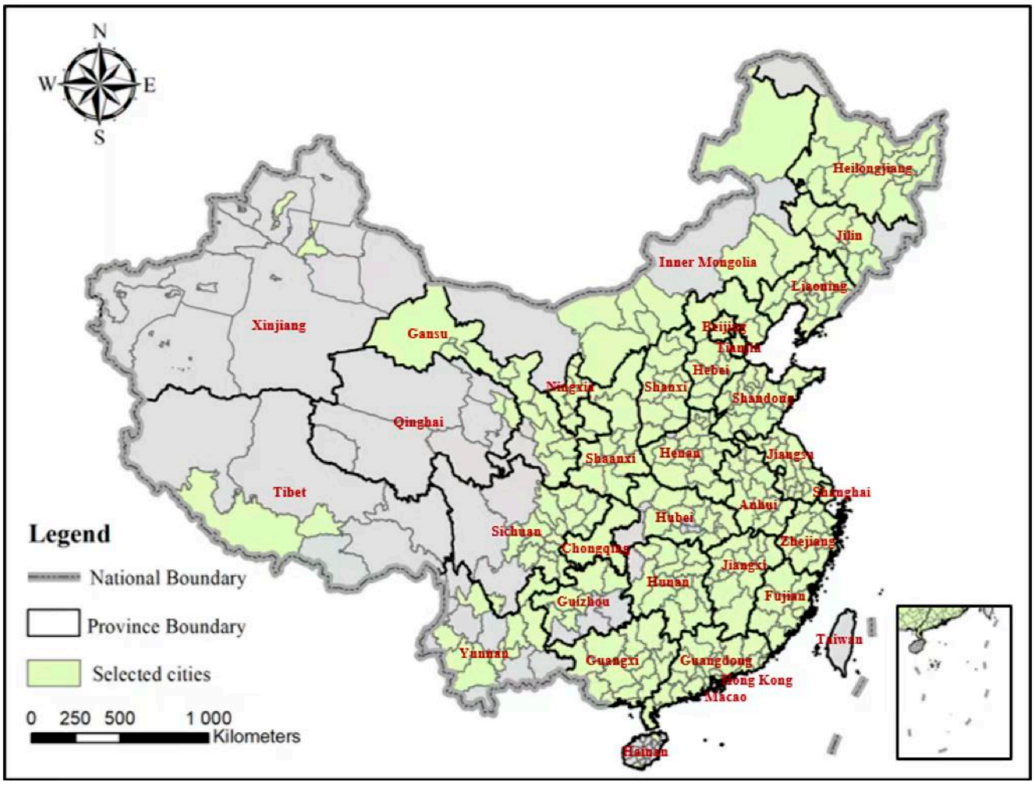

Figure 3. The location map for the Chinese cities analyzed in this study. Notes: China mask source: http://bzdt.ch.mnr.gov.cn/index.html (GS (2019)1719), no modification of the base map. The vector data of administrative division was collected from the National Geomatics Center of China (2019 version).

Data for the year-end resident population and built-up area are released annually by the National Bureau of Statistics, which reflects the general growth of the urban scale and has been used in much relevant research, e.g., [20,23,51]. Additionally, data for industrial pollution and haze pollution were collected from the *China City Statistical Yearbook* [12] and the Socioeconomic Data and Application Center (SEDAC) of Columbia University, respectively. The basic haze pollution data can be accessed at https://sedac.ciesin.columbia.edu/ (19 August 2023). With regard to $PM_{2.5}$ concentrations, based on the aerosol optical depth measured by the Moderate-Resolution Imaging Spectroradiometer and Multi-angle Imaging Spectroradiometer, relevant data could be transformed into raster data [84] for further calculation. The data sources are elaborated in Table 1.

In summary, this study's contributions to data collection and analysis are twofold. First, this study collected city-level data and then matched macroeconomic data with environmental pollution data, focusing specifically on $PM_{2.5}$ concentration. This approach sets this research apart from the majority of studies that operate at the cross-country or cross-provincial level, typically relying on a certain measure of air pollution.

Table 1. Descriptions of variables.

Variables	#	Denotations	Measurements	Data Sources
Dependent variables (DVs, urban scale)	1	*lnpop*	The natural logarithm of urban total population	*China City Statistical Yearbook*; *China Health Statistical Yearbook*; *The Statistical Yearbooks of Provinces*; CEInet database; Wind database; Columbia University.
	2	*lnarea*	The natural logarithm of urban built-up area	
Independent variables (IVs, environmental pollution)	1	*lnwater*	The natural logarithm of urban industrial sewage discharge	
	2	*lnso2*	The natural logarithm of urban industrial SO_2 discharge	
	3	*lnsmog*	The natural logarithm of urban industrial smog discharge	
	4	*lnpollution*	The natural logarithm of the composite index of industrial pollution	
	5	*lnpm25*	The natural logarithm of $PM_{2.5}$ concentrations	
Mediators (residents' health)	1	*lnhealth_d*	The natural logarithm of the urban mortality rate	
	2	*lnhealth_cost*	The natural logarithm of the total healthcare expenditures of urban residents	
Control variables (CVs)	1	*lnurban_r*	The natural logarithm of registered urbanization rate	
	2	*fiscgap*	The ratio of fiscal gap to GDP	
	3	*lnprod_labor*	The natural logarithm of the ratio of the secondary and tertiary GDP to urban employment	
	4	*lnprod_land*	The natural logarithm of the ratio of the non-agricultural GDP to urban built-up area	
	5	*lnwage*	The natural logarithm of the average wage of urban employees	
	6	*lnmedi*	The natural logarithm of the number of beds in urban medical institutions per capita	
	7	*lnroad*	The natural logarithm of road area per capita	
	8	*lnreal*	The natural logarithm of the investment in urban real estate development	
	9	*lnis*	The natural logarithm of the ratio of the GDP of secondary industry to the one of tertiary industry	
	10	*lnedu*	The natural logarithm of the ratio of the fiscal expenditure on education to the number college students	

Notes: Due to the existence of a negative value of the ratio of a fiscal gap to GDP, the relevant data are contained in the empirical models in the form of a ratio instead of in the logarithmic form.

3.3.2. Variable Selections

As previously mentioned, to perform a relatively comprehensive analysis, the present study selects two variables, urban population and land area, to depict the urban scale. Moreover, this study utilized emission data for three industrial pollutants (i.e., industrial wastewater, industrial SO_2, and industrial smog) along with $PM_{2.5}$ concentrations as proxies for pollution in the empirical models.

Additionally, this study explored the impact of environmental pollution on the urban scale through two key mechanisms: the health level (measured by the mortality rate) and the health cost (measured by healthcare expenditure) of urban residents. As previously mentioned, the study also considered CVs related to urban development—population structure, fiscal pressure, factor productivity, individual income, medical services, infrastructure construction, investment level, industrial structure, and education services. Detailed information about all variables is specified in Table 1.

The composite index of industrial pollution, which can reflect the overall discharge of industrial pollutants, is calculated using the entropy weight method (EWM, a weighting method that measures value dispersion). EWM is an efficient method for the comprehensive index evaluation of multiple variables, which can objectively calculate the weight of each indicator based on information entropy theory [85]. This method has been found to provide higher accuracy than the principal component analysis method [86] and has begun to be widely applied in the assessment of environmental pollution and sustainable development [81,87,88]. Moreover, data for urban healthcare expenditure per capita are available at the provincial level. Therefore, this study estimated the city-level total healthcare expenditure of urban residents as the product of provincial healthcare expenditures and the share of the city's urban population. Table 2 reports the descriptive statistics for all basic data.

Table 2. Statistical descriptions of the basic data.

	Variable	Observations (Obs.)	Mean	Std. Dev.	Min.	Max.
Dependent variables (DVs)	*lnpop*	5220	4.550	0.796	−0.777	8.068
	lnarea	5220	4.258	0.930	−0.916	7.311
	lnwater	5220	8.186	1.428	0.000	12.127
Independent variables (IVs)	*lnso2*	5220	10.142	1.801	0.000	14.251
	lnsmog	5220	9.526	1.676	0.000	15.458
	lnpollution	5220	9.739	1.232	0.000	14.639
	lnpm25	4640	3.419	0.589	0.000	4.509
Mediators	*lnhealth_d*	5220	1.251	0.850	−3.912	3.235
	lnhealth_cost	5220	11.179	1.347	0.000	15.438
Control variables (CVs)	*lnurban_r*	5220	−1.290	0.682	−4.711	0.354
	fiscgap	5220	−0.071	0.165	−9.837	3.303
	lnprod_labor	5220	11.189	1.184	0.000	15.269
	lnprod_land	5220	10.170	1.131	0.000	15.270
	lnwage	5220	9.858	1.064	0.000	12.856
	lnmedi	5220	3.963	0.645	−6.166	7.614
	lnroad	5220	2.085	0.750	−3.912	6.093
	lnreal	5220	12.253	1.936	−0.274	17.038
	lnis	5220	0.121	0.532	−2.198	5.263
	lnedu	5220	9.501	2.055	0.000	15.865

Notes: Missing data have been estimated using linear interpolation. Thus, balanced panel data have been used for the empirical analysis.

Limited by the data availability, the time span of $PM_{2.5}$ concentrations is 2001–2016, while that of data for other variables ranges from 2001 to 2018. The data samples cover 290 prefecture cities in China. For ease of comparison, data for variables concerning GDP, wage, expenditure, and investment were converted to the constant price level of the base year 2001. Moreover, to avoid the incompatibility resulting from different units of variables and eliminate the influence of heteroscedasticity, it is necessary to estimate the parameters using logarithmic transformation or weighted regression [89]. Thus, excluding the fiscal gap, all non-negative variables in the empirical models were transformed into the natural logarithmic form for analysis. The fiscal gap variables retained their actual values due to predominantly negative estimates. This step in data processing ensures the reliability of this study by creating a compatible city-level dataset for analysis, which can also serve as a valuable reference for other related empirical research.

4. Results

To directly explore the empirical connection between environmental pollution and urban scale or resident health, this study first fitted the linear curves to establish preliminary correlations.

Figure 4a illustrates the positive correlations between environmental pollution and urban scale based on cross-city data (figures in Supplementary Materials Part S2 presenting the related specific patterns of different cities). Moreover, Figure 4b highlights significant positive relationships between pollution and resident health costs, although such associations between pollution and health levels are less pronounced. These data confirm the observed correlations and display some patterns for preliminary analysis. However, it is essential to note that these correlations encompass bidirectional impacts, and thus the findings may differ from those derived from the subsequent causality analysis using cross-city panel data and regression models. In this regard, to obtain more specific conclusions and focused insights into the impacts and mechanisms, this study presents the results of further regression analysis below.

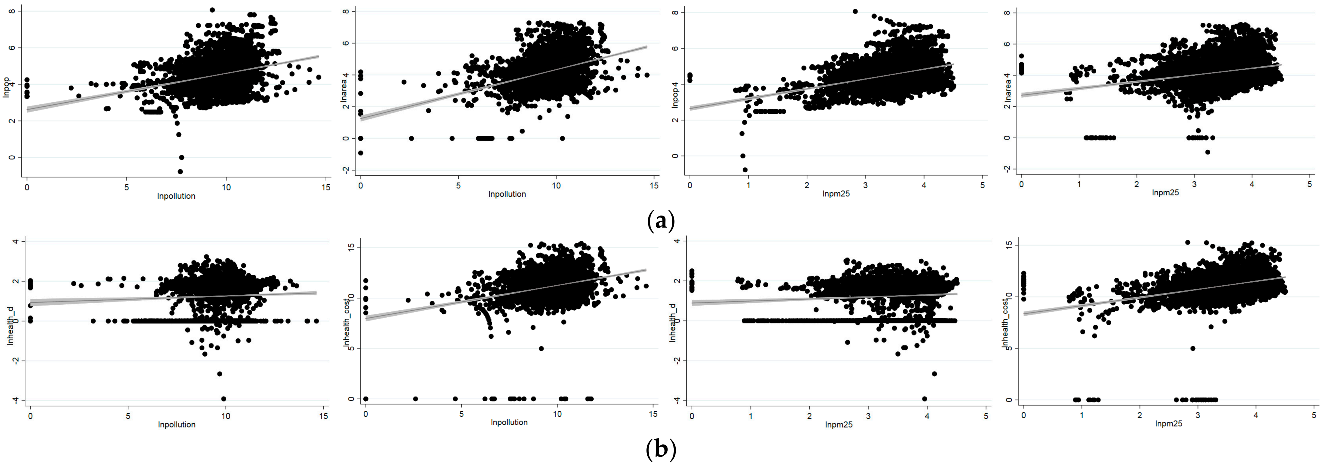

Figure 4. Fitted linear curves of the correlations between environmental pollution and urban scale (**a**) and resident health (**b**).

4.1. Baseline Results: Panel Regression Models

4.1.1. Pollution and Urban Population Scale

Following a body of research on an urban population scale [23,31], the present study uses the total year-end resident population to capture the scale of the urban population. Table 3 summarizes the results of the baseline regressions and shows that the negative effect of pollution on the urban population scale is generally validated.

Table 3. Pollution and urban population scale.

lnpop	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnpollution			−0.017 * (0.0090)	−0.0001 (0.003)			−0.007 (0.008)	0.0004 (0.007)
lnpm25					−0.070 ** (0.0321)	−0.041 ** (0.0189)	−0.071 ** (0.032)	−0.041 ** (0.019)
lnwater	−0.010 (0.010)	−0.001 (0.003)						
lnso2	−0.014 *** (0.004)	−0.001 (0.001)						
lnsmog	0.020 *** (0.006)	0.001 (0.002)						
CVs	No	Yes	No	Yes	No	Yes	No	Yes
Hausman test	133.550 *** [0.000]	881.820 *** [0.000]	69.080 *** [0.000]	825.020 *** [0.000]	29.590 *** [0.000]	635.490 *** [0.0000]	65.010 *** [0.000]	787.820 *** [0.000]
F test	6.760 *** [0.000]	357.820 *** [0.000]	5.590 * [0.059]	404.970 *** [0.000]	17.760 *** [0.000]	190.610 *** [0.000]	17.620 *** [0.000]	184.640 *** [0.000]
R square	0.029	0.339	0.094	0.340	0.002	0.293	0.004	0.294
Obs.	5220	5220	5220	5220	4640	4640	4640	4640

Notes: ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively. Numbers in '()' are the corresponding standard errors, and those in '[]' denote the corresponding p-values. The results of the Hausman test indicate that fixed-effects (FE) models are appropriate. All estimates were adjusted using the robust standard error. The empirical models used to estimate the results of columns (5)–(7) control for time and individual effects. Furthermore, the ten CVs introduced in Table 1 are included in the empirical models. Results of relevant tests on the multicollinearity based upon Variance Inflation Factor (VIF) are also summarized in Supplementary Materials Part S3, suggesting that there is no significant multicollinearity issue (i.e., VIF < 10).

In general, it is shown that pollutant emissions in urban areas are detrimental to urban population growth (i.e., H1a is supported). Specifically, the negative effects of industrial SO_2 emissions and haze pollution are statistically significant.

With regard to different pollution measures, such negative impacts are relatively stable, which can be interpreted as a *crowding-out* effect of pollutant emissions on the local population by affecting individual migration and enterprise location decisions. These have also been captured by Cao et al. [13] and Mao et al. [26].

4.1.2. Pollution and the Urban Built-Up Land Scale

From the perspective of land expansion, this study uses an urban built-up land area to depict the urban land scale. Table 4 reports the relevant results of the baseline regressions, thereby validating the positive effect of pollution on the urban land scale.

Table 4. Pollution and urban land scale.

lnarea	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
lnpollution			0.070 ** (0.028)	0.071 *** (0.026)			0.129 *** (0.027)	0.083 *** (0.025)
lnpm25					0.451 *** (0.047)	0.041 (0.037)	0.371 *** (0.055)	0.004 (0.037)
lnwater	0.031 *** (0.011)	0.031 *** (0.010)						
lnso2	0.018 ** (0.008)	0.017 ** (0.008)						
lnsmog	0.013 ## (0.008)	0.011 # (0.007)						
CVs	No	Yes	No	Yes	No	Yes	No	Yes
Hausman test	224.760 *** [0.000]	471.420 *** [0.000]	106.260 *** [0.000]	408.690 *** [0.000]	0.080 [0.963]	285.950 *** [0.000]	48.000 *** [0.000]	351.350 *** [0.000]
F test	68.770 *** [0.000]	80.690 *** [0.000]	76.550 *** [0.000]	84.170 *** [0.000]	93.050 *** [0.000]	58.900 *** [0.000]	65.600 *** [0.000]	60.150 *** [0.000]
R square	0.194	0.494	0.180	0.497	0.078	0.588	0.201	0.618
Obs.	5220	5220	5220	5220	4640	4640	4640	4640

Notes: *** and ** represent significance at the 1% and 5% levels, respectively. ## and # represent p-values of 0.107 and 0.110, respectively. Numbers in '()' show the corresponding standard errors, and those in '[]' are the corresponding p-values. Except for column (4), the results of the Hausman test show that FE models are appropriate for other cases. All estimates were adjusted using the robust standard error. The empirical models used to estimate the results of columns (1)–(4) control for time and individual effects. Furthermore, the ten CVs introduced in Table 1 are included in the empirical models. Results of relevant tests on the multicollinearity given in Supplementary Materials Part S3 suggest that there is no significant multicollinearity issue (i.e., VIF < 10).

Interestingly, Table 4 shows that increased pollutant emissions in urban areas empirically contribute to the expansion of urban built-up land (i.e., H1b is supported). More specifically, the positive impacts of haze pollution and industrial pollutant emissions are both statistically significant.

Similarly, with different pollution measures, the positive impacts are stable and consistently confirmed. Such positive correlations echo the findings of Mao et al. [26] and Weng and Yang [82], and can be described as the *expansionary* effect of pollution on local land use.

4.2. Mediating Effect Analysis

Tables 5–7 report the empirical results of the mechanism analysis from the perspectives of residents' health levels and health costs based on the mediating effect models.

Table 5. Direct effects of pollution on mediating factors concerning residents' health.

DVs		lnhealth_d				lnhealth_cost		
Models	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
lnpollution		−0.010 (0.011)		−0.009 (0.012)		0.069 # (0.052)		0.059 (0.056)
lnpm25			0.147 ** (0.072)	0.146 ** (0.072)			0.157 * (0.084)	0.160 * (0.083)
lnwater	−0.014 (0.012)				0.018 (0.016)			
lnso2	−0.007 ## (0.004)				0.010 (0.025)			
lnsmog	−0.003 (0.006)				0.027 ** (0.013)			
CVs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hausman test	57.170 *** [0.000]	53.280 *** [0.000]	53.530 *** [0.000]	56.450 *** [0.000]	605.120 *** [0.000]	563.340 *** [0.000]	359.360 *** [0.000]	450.720 *** [0.000]
F test	5.020 *** [0.000]	5.230 *** [0.000]	4.720 *** [0.000]	4.570 *** [0.000]	511.740 *** [0.000]	536.140 *** [0.000]	584.820 *** [0.000]	543.280 *** [0.000]
R square	0.012	0.010	0.010	0.009	0.603	0.603	0.583	0.596
Obs.	5220	5220	4640	4640	5220	5220	4640	4640

Notes: As noted in Table 3. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively. However, in this table, ## and # represent p-values of 0.102 and 0.181, respectively. Moreover, all empirical models were used to control for the time effect and individual effect.

Table 6. Results of the mediating effect analysis on urban population scale, pollution, and mediating factors concerning residents' health.

DVs				lnpop				
Models	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
lnpollution		0.001 (0.005)		0.0004 (0.007)		−0.003 (0.006)		−0.003 (0.007)
lnpm25			−0.042 ** (0.018)	−0.042 ** (0.018)			−0.050 ** (0.020)	−0.050 *** (0.020)
lnwater	0.003 (0.004)				0.001 (0.004)			
lnso2	−0.002 (0.002)				−0.002 (0.002)			
lnsmog	0.001 (0.002)				−0.001 (0.002)			
lnhealth_d	0.005 (0.012)	0.005 (0.012)	0.005 (0.012)	0.005 (0.012)				
lnhealth_cost					0.057 ** (0.027)	0.057 ** (0.027)	0.058 ** (0.028)	0.059 ** (0.028)
CVs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hausman test	904.730 *** [0.000]	838.110 *** [0.000]	643.840 *** [0.000]	809.050 *** [0.0000]	1661.510 *** [0.000]	1645.760 *** [0.000]	1465.140 *** [0.000]	1474.200 *** [0.000]
F test	227.130 *** [0.000]	240.270 *** [0.000]	183.770 *** [0.000]	178.390 *** [0.000]	216.410 *** [0.000]	226.220 *** [0.000]	184.820 *** [0.000]	176.480 *** [0.000]
R square	0.318	0.318	0.293	0.293	0.366	0.365	0.337	0.336
Obs.	5220	5220	4640	4640	5220	5220	4640	4640

Notes: As noted in Table 3. *** and ** represent significance at the 1% and 5% levels, respectively. Moreover, all empirical models were used to control for the time effect and individual effect.

Table 7. Results of the mediating effect analysis on the urban land scale, pollution, and mediating factors concerning residents' health.

DVs Models	(1)	(2)	(3)	*lnarea* (4)	(5)	(6)	(7)	(8)
lnpollution		0.071 *** (0.026)		0.080 *** (0.028)		0.066 *** (0.021)		0.077 *** (0.024)
lnpm25			−0.144 *** (0.045)	−0.140 *** (0.041)			−0.158 *** (0.044)	−0.152 *** (0.040)
lnwater	0.031 *** (0.010)				0.030 *** (0.009)			
lnso2	0.016 ** (0.008)				0.016 ** (0.007)			
lnsmog	0.011 ## (0.007)				0.009 # (0.006)			
lnhealth_d	0.002 (0.023)	−0.004 (0.022)	−0.023 (0.024)	−0.019 (0.023)				
lnhealth_cost					0.077 * (0.043)	0.076 * (0.041)	0.069 * (0.042)	0.063 * (0.036)
CVs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hausman test	485.870 *** [0.000]	419.600 *** [0.000]	285.730 *** [0.000]	354.190 *** [0.0000]	846.640 *** [0.000]	806.020 *** [0.000]	874.160 *** [0.000]	823.900 *** [0.000]
F test	78.240 *** [0.000]	81.660 *** [0.000]	88.170 *** [0.000]	83.350 *** [0.000]	84.620 *** [0.000]	86.340 *** [0.000]	91.290 *** [0.000]	86.550 *** [0.000]
R square	0.494	0.498	0.349	0.422	0.564	0.565	0.407	0.471
Obs.	5220	5220	4640	4640	5220	5220	4640	4640

Notes: As notes of Table 3. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively. However, in this table, ## and # represent p-values of 0.110 and 0.137, respectively. Moreover, all empirical models used control for the time effect and individual effect.

4.2.1. Pollution and Urban Population Scale

Following the previous analysis, this section first investigated the direct and indirect effects of mediating factors on the urban population scale.

Table 5 demonstrates that the direct positive impacts of haze pollution on the urban mortality rate are statistically significant, while those of industrial pollution are relatively inconsistent and insignificant. Additionally, all analyzed pollutants have a positive influence on the total healthcare expenditure of urban residents, and the impacts of industrial smog pollution and haze pollution are statistically significant. These findings echo the conclusions drawn by Chen and Chen [6], and Cui et al. [70].

In Table 6, the significant negative effect of haze pollution on the urban population scale is revalidated. Moreover, total healthcare expenditure exerts a statistically significant positive impact on the urban population.

In general, both analyzed mediating factors are preliminarily considered effective mechanisms based on the direct effect analysis in Table 5 (i.e., H2 is supported). However, the mediating effect of residents' healthcare expenditures is more prominent. To some extent, the salient mediating effect of pollution on residents' healthcare expenditure is more consistently significant and relatively more indirect, while the promoting impact of pollution on the mortality rate is more direct but constrained by haze pollution.

Specifically, Table 5 confirms that growing haze pollution can significantly increase both the mortality rate and healthcare expenditures of urban residents. Importantly, Table 6 shows that these two proxies for resident health, especially healthcare expenditures, have a mitigating effect on urban population loss resulting from growing pollution. The suppressing effect (given the paradigm of the mediating effect analysis, the indirect effect of mediating factors can be elaborated as the suppressing effect (if the sign of β_1, b, and c, as estimated by Equations (1)–(3) in the above Section 3.2, are not the same) or partial mediating effect (if the estimated sign of β_1, b and c are the same). Here, the explanatory power of the suppressing effect can be calculated as follows: $|b{\cdot}c/\beta_1|$) of the *lnhealth_cost* variable is approximately 22.21% for haze pollution and 23.14% for industrial pollution. That is, the *crowding-out* effect of pollution, particularly haze pollution, on the urban population scale can be significantly *offset* by increasing the scale of local healthcare expenditures (i.e., H2 and particularly H2b are supported). The significant mediating role of healthcare expenditure is consistent with the findings of Wu et al. [56].

4.2.2. Pollution and the Urban Built-Up Area Scale

Furthermore, the direct and indirect effects of mediating factors on the urban built-up land scale are analyzed.

With regard to the urban land scale, Table 7 revalidates that the significant positive effect of industrial pollution is revalidated. Similarly, the positive impact of total healthcare expenditure on urban built-up land is statistically significant.

Combining these results with the findings presented in Table 5 regarding the impact of pollution on the urban land scale, the present study concludes that the salient mediating effect of pollution on residents' healthcare expenditure is consistent and of statistical significance. Unfortunately, the mediating effect of the mortality rate is relatively insignificant.

Specifically, Table 7 shows that the increase in total healthcare expenditure of residents will have partial mediating effects on urban built-up land area growth (the explanatory power of the partial mediating effect (given the paradigm of mediating effect analysis, the explanatory power of the partial mediating effect can be calculated as follows: $b{\cdot}c/\beta_1$) of *lnhealth_cost* is approximately 26.42% for haze pollution and 7.39% for industrial pollution). In other words, the *expansionary* effect of pollution, particularly industrial pollution, on the urban land scale can be significantly *realized or supported* by increasing the scale of local healthcare expenditures (i.e., H2 and particularly H2b are supported).

To conclude, including analyses on both the direct and indirect impacts of environmental pollution on the urban scale, the logic of results can be clarified as the following Figure 5 shows.

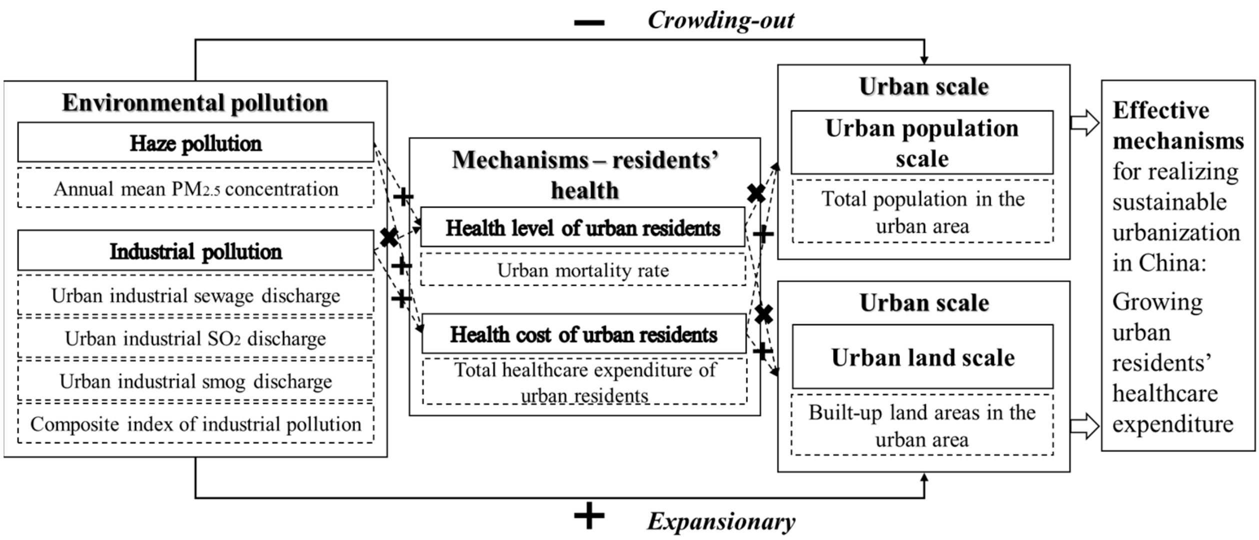

Figure 5. The logic of the results of this study. Notes: The solid and dashed arrows in the figure represent the direct effects and indirect impacts through the analyzed mechanisms, respectively.

5. Discussion

5.1. Heterogeneous Effects of Environmental Pollution on the Urban Scale

Economic growth has caused environmental problems that have affected the size of cities in recent years. Some cities are expanding, while others are shrinking. Taking residents' health into consideration, this article examines the heterogeneous effects of environmental pollution on an urban scale. In this study, it is found that environmental pollution exerts an important and heterogeneous effect on the urban scale. That is, increasing environmental pollution will exert opposite effects on the urban population scale and land scale, although the statistical significance of these influences varies among different pollutants (i.e., H1 is supported). The findings related to the heterogeneous impacts of pollution on the urban scale are plausible.

Environmental pollution has a *crowding-out* effect on urban residents; that is, the residents leave when the environmental problems become severe, thus reducing the urban population. In contrast, pollution has a significant effect on the expansion of urban land scale. Industrial pollution, including wastewater, SO_2 emissions, and smog, is primarily the result of secondary industry; therefore, the higher industrial pollution emissions correspond to the larger percentage of secondary industry [56]. Due to lower production costs, industrial plants are generally located on the outskirts of cities. As secondary industry develops, more urban land will be required, resulting in the expansion of the urban area. In this regard, increased pollution in urban areas can crowd out the urban population and explain urban land expansion.

These findings provide two insights: (1) At the macro-level, the *crowding-out* effect is aligned with either the positive contribution of pollution to emigration or the negative contribution of pollution to urbanization, as stated in previous research, including [13], and [56–60]; and (2) although the observed *expansionary* effect of pollution on the urban land scale is significant, this effect has rarely been studied. Such casual findings offer support to and extend to the pollution–landscape correlations analyzed by [18] to some degree. This research meets expectations and provides a better understanding of the connection between environmental pollution and urban sprawl.

5.2. Mediating Role of Residents' Health

Residents' health has been selected as the mediating variable to explore how environmental pollution affects the urban scale. Based on the above empirical findings, the effectiveness of the two analyzed mechanisms differs. It is highlighted that the scale of urban residents' healthcare expenditure has evident and crucial mediating effects on the nexus between environmental pollution and urban scale. In China, land expansion relies heavily on urban planning and government intervention, while population migration is relatively more flexible, based on residents' intentions and decisions. In the process of urbanization, land expansion is often rigid and relatively controllable, while the growth or loss of population usually raises concerns, particularly among local governments. Environmental pollution affects the physical and mental health of residents, which may accelerate the outward migration of residents from polluted areas. In addition to affecting the physical health of residents, it also increases the incidence of various diseases. When facing a higher risk of morbidity, moving to cities with better environments is a possible option. Furthermore, the existence of environmental pollution increases residents' living and health costs, which imposes an economic burden and may force residents to emigrate. To deal with the negative externalities that environmental pollution might bring to their lives and health, residents will take preventive or mitigation measures to avoid and reduce the relevant adverse effects. This study offers evidence that greater expenditures on urban residents' healthcare support urban land expansion and offset the negative impact of pollution on urban population growth. This supports both the critical and extensive thinking of Wu et al. [56], who considered healthcare costs as a part of income and investigated the pressure faced by individuals and concluded that increasing pollution leads to higher costs and further inhibits urbanization. In terms of residents' medical expenses, the individual does not need to cover all these costs because health insurance provided by the government can cover a portion of the expense. Thus, when the medical needs of the residents can be met, certain medical expenses will not exacerbate their economic burden and will lead to their exit from the city. Rather, environmental pollution is tolerable to a certain extent if residents are provided with adequate medical resources and do not suffer serious health consequences. Therefore, the growing scale of and support for urban residents' healthcare expenditure is conducive to realizing the coordinated promotion of both population urbanization and land urbanization.

Unsurprisingly, different pollutants have different effects on human health. The study found that air pollution has the most obvious and deadly negative effects on residents' health status. However, other industrial pollutants have relatively more indirect or chronic effects on residents' health; therefore, they do not directly affect residents' out-migration. The aggravation of environmental pollution leads to the deterioration of people's health conditions and further increases in medical expenditures, which has also been reported by Cui et al. [70]. With serious urban environmental pollution, residents will increase their expenditures on preventive measures and medical treatment, health protection, and disease treatment. To a certain extent, this can alleviate the population outflow caused by urban pollution.

6. Conclusions

Using city-level panel data from China, this study examines the impact of environmental pollution on the urban scale using various measures of pollution and the urban scale. This paper concludes that increasing pollution will exert opposite effects on the urban population scale and urban land scale. That is, increased pollution will reduce the size of the urban population but increase the scale of built-up land within cities. Through the mediating effect of residents' health, urban mortality rates, and particularly expenditures on health care can mitigate the effects of environmental pollution. That is, increasing pollution results in a decline in the health level of urban residents and an increase in the health costs of residents, which can further help identify the impact of pollution on the city scale.

Correspondingly, this study has three policy implications. (1) The government needs to improve local health services and fiscal support for residents' healthcare costs. Accordingly, more local fiscal expenditures on medical and healthcare are recommended. Importantly, the improved or additional provision of high-quality public health services and facilities results in better economic availability, leading to the mitigation of the negative effects of environmental pollution to a certain extent. (2) Local governments need to consider pollution control and environmental protection while developing the economy; otherwise, the attractiveness of cities will be reduced. More local fiscal expenditures on environmental protection and investments in pollution control are recommended. In environmental governance, special attention should be paid to the control of pollutants that have the greatest impact on human health (such as $PM_{2.5}$ and industrial sulfur dioxide in China), and the enforcement of laws and regulations should be intensified. (3) Regarding urban development, strict land-use control is needed to manage or even avoid urban sprawl caused by environmental pollution. This is of great practical importance for the realization of high-quality development and new-type urbanization in China.

This study inevitably has some limitations. First, it focused on data from 290 Chinese cities. The relationship between pollution and urban scale in more cities and other countries deserves further investigation. Second, only the direct impact of environmental pollution on the mortality rate was verified to be statistically significant in the present study, and further investigations into its indirect or partial mediating effect are needed. In this respect, the detailed effect of this mechanism is not completely clear, which requires further research. Moreover, to capture more dynamic patterns and impacts beyond the urban scale, data for either inflow and outflow of urban population or transaction and transfer of city land are worthy of further relevant discussion. Similarly, the proxies for pollution could be extended beyond the analyzed air pollutants. In summary, the limitations of the present study are mainly found in data coverage, variable measurement, and mechanism identification, among others. Correspondingly, further research could focus on the dynamic analysis of the effects of urban scale on other pollutants and further explore the mechanisms of the nexus between environmental pollution and urban scale.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152215984/s1. Ref. [90] is cited in Supplementary Materials.

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References

1. Sun, P.J.; Song, W.; Xiu, C.L.; Liang, Z.M. Non-coordination in China's Urbanization: Assessment and Affecting Factors. *Chin. Geogr. Sci.* **2013**, *23*, 729–739. [CrossRef]
2. Han, X.; Wu, P.L.; Dong, W.L. An analysis on interaction mechanism of urbanization and industrial structure evolution in Shandong, China. *Procedia Env. Sci.* **2012**, *13*, 1291–1300. [CrossRef]
3. National Bureau of Statistics of China. *2022 China Statistical Yearbook*; China Statistics Press: Beijing, China, 2023. Available online: http://www.stats.gov.cn/sj/ndsj/2022/indexch.htm. (accessed on 10 May 2023).
4. Ebenstein, A.; Fan, M.Y.; Greenstone, M.; He, G.J.; Yin, P.; Zhou, M.G. Growth, Pollution, and Life Expectancy: China from 1991–2012. *Am. Econ. Rev.* **2015**, *105*, 226–231. [CrossRef]
5. Yazdi, S.K.; Khanalizadeh, B. Air pollution, economic growth and health care expenditure. *Econ. Res.* **2017**, *30*, 1181–1190. [CrossRef]
6. Chen, F.L.; Chen, Z.F. Cost of economic growth: Air pollution and health expenditure. *Sci. Total Environ.* **2021**, *755*, 142543. [CrossRef]
7. Lu, Z.N.; Chen, H.Y.; Hao, Y.; Wang, J.Y.; Song, X.J.; Mok, T.M. The dynamic relationship between environmental pollution, economic development and public health: Evidence from China. *J. Clean. Prod.* **2017**, *166*, 134–147. [CrossRef]
8. Global Burden of Disease and Risk Factors. GBD 2010: Understanding disease, injury, and risk. *Lancet* **2012**, *380*, 2053–2054. [CrossRef] [PubMed]
9. Shukla, V.; Parikh, K. The environmental consequences of urban growth: Cross-national perspectives on economic development, air pollution, and city size. *Urban Geogr.* **1992**, *13*, 422–449. [CrossRef]
10. Huang, Z.H.; Du, X.J. Urban Land Expansion and Air Pollution: Evidence from China. *J. Urban Plan. Dev.* **2018**, *144*, 05018017. [CrossRef]
11. Liang, L.W.; Wang, Z.B.; Li, J.X. The effect of urbanization on environmental pollution in rapidly developing urban agglomerations. *J. Clean. Prod.* **2019**, *237*, 117649. [CrossRef]
12. National Bureau of Statistics of China. *2021 China City Statistical Yearbook*; China Statistics Press: Beijing, China, 2022.
13. Cao, B.R.; Fu, K.P.; Tao, J.; Wang, S.H. GMM-based research on environmental pollution and population migration in Anhui province, China. *Ecol. Indic.* **2015**, *51*, 159–164. [CrossRef]
14. Yu, Z.P.; Yan, T.H.; Liu, X.R.; Bao, A.Z. Urban land expansion, fiscal decentralization and haze pollution: Evidence from 281 prefecture-level cities in China. *J. Environ. Manag.* **2022**, *323*, 116198. [CrossRef]
15. Lin, S.F.; Wang, S.Y.; Marinova, D.; Zhao, D.T.; Hong, J. Impacts of urbanization and real economic development on CO_2 emissions in non-high income countries: Empirical research based on the extended STIRPAT model. *J. Clean. Prod.* **2017**, *166*, 952–966. [CrossRef]
16. Nosheen, M.; Abbasi, M.A.; Iqbal, J. Analyzing extended STIRPAT model of urbanization and CO_2 emissions in Asian countries. *Environ. Sci. Pollut. Res.* **2020**, *27*, 45911–45924. [CrossRef]
17. Akinsola, F.A.; Ologundudu, M.M.; Akinsola, M.O.; Odhiambo, N.M. Industrial development, urbanization and pollution nexus in Africa. *Heliyon* **2022**, *8*, e11299. [CrossRef] [PubMed]

18. Liu, Y.P.; Wu, J.G.; Yu, D.Y.; Ma, Q. The relationship between urban form and air pollution depends on seasonality and city size. *Environ. Sci. Pollut. Res.* **2018**, *25*, 15554–15567. [CrossRef]
19. Wang, L.; Jia, Y.H.; Li, X.H.; Gong, P. Analysing the Driving Forces and Environmental Effects of Urban Expansion by Mapping the Speed and Acceleration of Built-Up Areas in China between 1978 and 2017. *Remote Sens.* **2020**, *12*, 3929. [CrossRef]
20. Shen, J.F. Rural Development and Rural to Urban Migration in China 1978~1990. *Geoforum* **1995**, *26*, 395–409. [CrossRef] [PubMed]
21. Marshall, J.D. Urban land area and population growth: A new scaling relationship for metropolitan expansion. *Urban Stud.* **2007**, *44*, 1889–1904. [CrossRef]
22. Lamsal, L.N.; Martin, R.V.; Parrish, D.D.; Krotkov, N.A. Scaling Relationship for NO_2 Pollution and Urban Population Size: A Satellite Perspective. *Environ. Sci. Technol.* **2013**, *47*, 7855–7861. [CrossRef]
23. Yao, X.; Pan, S.Y.; Sun, C.W. City Size, Spatial Agglomeration and Electricity Intensity in China. *Econ. Res. J.* **2017**, *11*, 165–177.
24. Aburas, M.M.; Ho, Y.M.; Ramli, M.F.; Ash'aari, Z.H. Monitoring and assessment of urban growth patterns using spatio-temporal built-up area analysis. *Environ. Monit. Assess.* **2018**, *190*, 156. [CrossRef] [PubMed]
25. Li, C.; Gibson, J. City scale and productivity in China. *Econ. Lett.* **2015**, *131*, 86–90. [CrossRef]
26. Mao, D.F.; Peng, F.; Liu, H. Urban Expansion, Fiscal Decentralization and Environmental Pollution—An Empirical Analysis Based on the Panel Data of 263 Prefecture level Cities. *J. Zhongnan Univ. Econ. Law* **2016**, *218*, 42–53.
27. Córdoba, J.C. On the distribution of city sizes. *J. Urban Econ.* **2008**, *63*, 177–197. [CrossRef]
28. Desmet, K.; Rossi-Hansberg, E. Urban Accounting and Welfare. *Am. Econ. Rev.* **2013**, *103*, 2296–2327. [CrossRef]
29. Tsekeris, T.; Geroliminis, N. City size, network structure and traffic congestion. *J. Urban Econ.* **2013**, *76*, 1–14. [CrossRef]
30. Liu, X.Y.; Li, S.L. Housing Price, Migration Friction, and City-size Distribution in China: Theory Model and Structural Estimation. *Econ. Res. J.* **2017**, *7*, 65–78.
31. Han, F.; Li, Y.S. Industrial Agglomeration, Public Service Supply and Urban Expansion. *Econ. Res. J.* **2019**, *11*, 149–164.
32. Li, L.X.; Shen, G.J. Financial Development and City Size–Theory and Evidence from China. *China Econ. Q.* **2019**, *18*, 855–876. [CrossRef]
33. Chen, S.Y.; Liu, C.L.; Feng, B. Capital Allocation Efficiency, City-Size Distribution and Social Welfare Analysis. *Econ. Res. J.* **2019**, *2*, 133–147.
34. Braimoh, A.K.; Onishi, T. Spatial determinants of urban land use change in Lagos, Nigeria. *Land Use Policy* **2007**, *24*, 502–515. [CrossRef]
35. Seto, K.C.; Fragkias, M.; Güneralp, B.; Reilly, M.K. A Meta-Analysis of Global Urban Land Expansion. *PLoS ONE* **2011**, *6*, e23777. [CrossRef]
36. Wu, K.Y.; Zhang, H. Land use dynamics, built-up land expansion patterns, and driving forces analysis of the fast-growing Hangzhou metropolitan area, eastern China (1978–2008). *Appl. Geogr.* **2012**, *34*, 137–145. [CrossRef]
37. Fuglsang, M.; Münier, B.; Hansen, H.S. Modelling land-use effects of future urbanization using cellular automata: An Eastern Danish case. *Environ. Model. Softw.* **2013**, *50*, 1–11. [CrossRef]
38. Huang, Z.J.; Wei, Y.H.D.; He, C.F.; Li, H. Urban land expansion under economic transition in China: A multilevel modeling analysis. *Habitat Int.* **2015**, *47*, 69–82. [CrossRef]
39. Zhong, T.Y.; Chen, Y.Q.; Huang, X.J. Impact of land revenue on the urban land growth toward decreasing population density in Jiangsu Province, China. *Habitat Int.* **2016**, *58*, 34–41. [CrossRef]
40. Colsaet, A.; Laurans, Y.; Levrel, H. What drives land take and urban land expansion? A systematic review. *Land Use Policy* **2018**, *79*, 339–349. [CrossRef]
41. Song, S.F.; Zhang, K.H.L. Urbanisation and City Size Distribution in China. *Urban Stud.* **2002**, *39*, 2317–2327. [CrossRef]
42. Capello, R.; Camagni, R. Beyond Optimal City Size: An Evaluation of Alternative Urban Growth Patterns. *Urban Stud.* **2000**, *37*, 1479–1496. [CrossRef]
43. Mehmood, K.; Ahmad, H.R.; Abbas, R.; Saifullah; Murtaza, G. Heavy metals in urban and peri-urban soils of a heavily-populated and industrialized city: Assessment of ecological risks and human health repercussions. *Hum. Ecol. Risk Assess. Int. J.* **2020**, *26*, 1705–1722. [CrossRef]
44. Ravina, M.; Panepinto, D.; Zanetti, M. District heating networks: An inter-comparison of environmental indicators. *Environ. Sci. Pollut. Res.* **2021**, *28*, 33809–33827. [CrossRef] [PubMed]
45. York, R.; Rosa, E.A.; Dietz, T. STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* **2003**, *46*, 351–365. [CrossRef]
46. Xu, F.J.; Huang, Q.X.; Yue, H.B.; He, C.Y.; Wang, C.B.; Zhang, H. Reexamining the relationship between urbanization and pollutant emissions in China based on the STIRPAT model. *J. Environ. Manag.* **2020**, *273*, 111134. [CrossRef] [PubMed]
47. Voumik, L.C.; Sultana, T. Impact of urbanization, industrialization, electrification and renewable energy on the environment in BRICS: Fresh evidence from novel CS-ARDL model. *Heliyon* **2022**, *8*, e11457. [CrossRef]
48. Oke, T.R. City size and the urban heat island. *Atmos. Environ.* **1973**, *7*, 769–779. [CrossRef]
49. Salahuddin, M.; Gow, J.; Ali, M.D.; Hossain, M.R.; Al-Azami, K.S.; Akbar, D.; Gedikli, A. Urbanization-globalization-CO_2 emissions nexus revisited: Empirical evidence from South Africa. *Heliyon* **2019**, *5*, e01974. [CrossRef] [PubMed]
50. Liu, X.R.; Sun, T.; Feng, Q. Dynamic spatial spillover effect of urbanization on environmental pollution in China considering the inertia characteristics of environmental pollution. *Sustain. Cities Soc.* **2020**, *53*, 101903. [CrossRef]

51. Wang, S.J.; Gao, S.; Li, S.J.; Feng, K.S. Strategizing the relation between urbanization and air pollution: Empirical evidence from global countries. *J. Clean. Prod.* **2020**, *243*, 118615. [CrossRef]
52. Hien, P.D.; Men, N.T.; Tan, P.M.; Hangartner, M. Impact of urban expansion on the air pollution landscape: A case study of Hanoi, Vietnam. *Sci. Total Environ.* **2020**, *702*, 134635. [CrossRef] [PubMed]
53. Zhou, L.; Yuan, B.; Mu, H.W.; Dang, X.W.; Wang, S.H. Coupling relationship between construction land expansion and $PM_{2.5}$ in China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 33669–33681. [CrossRef]
54. Shahbaz, M.; Loganathan, N.; Muzaffar, A.T.; Ahmed, K.; Jabran, M.A. How urbanization affects CO_2 emissions in Malaysia? The application of STIRPAT model. *Renew. Sustain. Energy Rev.* **2016**, *57*, 83–93. [CrossRef]
55. Duan, X.L.; Li, X.; Tan, W.F.; Xiao, R. Decoupling relationship analysis between urbanization and carbon emissions in 33 African countries. *Heliyon* **2022**, *8*, e10423. [CrossRef]
56. Wu, H.T.; Gai, Z.Q.; Guo, Y.X.; Li, Y.W.; Hao, Y.; Lu, Z.N. Does environmental pollution inhibit urbanization in China? A new perspective through residents' medical and health costs. *Environ. Res.* **2020**, *182*, 109128. [CrossRef]
57. Aunan, K.; Wang, S.X. Internal migration and urbanization in China: Impacts on population exposure to household air pollution (2000–2010). *Sci. Total Environ.* **2014**, *481*, 186–195. [CrossRef]
58. Chen, S.; Oliva, P.; Zhang, P. The Effect of Air Pollution on Migration: Evidence from China. *NBER Work. Pap.* **2017**, *156*, 24036. [CrossRef]
59. Germani, A.R.; Scaramozzino, P.; Castaldo, A.; Talamo, G. Does air pollution influence internal migration? An empirical investigation on Italian provinces. *Environ. Sci. Policy* **2021**, *120*, 11–20. [CrossRef]
60. Guo, Q.B.; Wang, Y.; Zhang, Y.; Yi, M.; Zhang, T. Environmental migration effects of air pollution: Micro-level evidence from China. *Environ. Pollut.* **2022**, *292*, 118263. [CrossRef] [PubMed]
61. Liu, X.X.; Dong, X.Y.; Li, S.; Ding, Y.T.; Zhang, M. Air pollution and high human capital population migration: An empirical study based on 35 major cities in China. *Sustain. Prod. Consum.* **2021**, *27*, 643–652. [CrossRef]
62. Zhao, Z.H.; Lao, X.; Gu, H.Y.; Yu, H.C.; Lei, P. How does air pollution affect urban settlement of the floating population in China? New evidence from a push-pull migration analysis. *BMC Public Health* **2021**, *21*, 1696. [CrossRef]
63. Kampa, M.; Castanas, E. Human health effects of air pollution. *Environ. Pollut.* **2008**, *151*, 362–367. [CrossRef]
64. Beverland, I.J.; Cohen, G.R.; Heal, M.R.; Carder, M.; Yap, C.; Robertson, C.; Hart, C.L.; Agius, R.M. A Comparison of Short-term and Long-term Air Pollution Exposure Associations with Mortality in Two Cohorts in Scotland. *Environ. Health Perspect.* **2012**, *120*, 1280–1285. [CrossRef]
65. Moradi, M.; Mokhtari, A.; Mohammadi, M.J.; Hadei, M.; Vosoughi, M. Estimation of long-term and short-term health effects attributed to $PM_{2.5}$ standard pollutants in the air of Ardabil (using Air Q + model). *Environ. Sci. Pollut.* **2022**, *29*, 21508–21516. [CrossRef]
66. Brunekreef, B.; Holgate, S.T. Air pollution and health. *Lancet* **2002**, *360*, 1233–1242. [CrossRef]
67. Qi, Y.; Lu, L.Y. Pollution, Health and Inequality—Crossing the Trap of 'Environmental Health Poverty'. *J. Manag. World* **2015**, *9*, 32–51.
68. Mehmood, K.; Bao, Y.S.; Abbas, R.; Saifullah; Petropoulos, G.P.; Ahmad, H.R.; Abrar, M.M.; Mustafa, A.; Abdalla, A.; Lasaridi, K.; et al. Pollution characteristics and human health risk assessments of toxic metals and particle pollutants via soil and air using geoinformation in urbanized city of Pakistan. *Environ. Sci. Pollut. Res.* **2021**, *28*, 58206–58220. [CrossRef]
69. Bai, R.Q.; Lam, J.C.K.; Li, V.O.K. A review on health cost accounting of air pollution in China. *Environ. Int.* **2018**, *120*, 279–294. [CrossRef] [PubMed]
70. Cui, E.H.; Jiang, S.Z.; Jia, S.B. Research on the Impact of Environmental Pollution, Commercial Health Insurance to Health Costs: Based on the Empirical Analysis of Provincial Panel Data. *Nankai Econ. Stud.* **2016**, *6*, 140–150. [CrossRef]
71. Cao, C.H.; Han, L.Y. The Assessment on the Social Health Costs Caused by Fog and Haze. *Stat. Res.* **2015**, *32*, 19–23. [CrossRef]
72. Miraglia, S.G.E.K.; Saldiva, P.H.N.; Böhm, G.M. An Evaluation of Air Pollution Health Impacts and Costs in São Paulo, Brazil. *Env. Manag.* **2005**, *35*, 667–676. [CrossRef]
73. Matus, K.; Nam, K.M.; Selin, N.E.; Lamsal, L.N.; Reilly, J.M.; Paltsev, S. Health damages from air pollution in China. *Glob. Environ. Change* **2012**, *22*, 55–66. [CrossRef]
74. Jakubiak-Lasocka, J.; Lasocki, J.; Siekmeier, R.; Chłopek, Z. *Impact of Traffic-Related Air Pollution on Health. Environment Exposure to Pollutants*; Springer International Publishing: Cham, Switzerland, 2014; pp. 21–29. [CrossRef]
75. Liao, L.P.; Du, M.Z.; Chen, Z.F. Air pollution, health care use and medical costs: Evidence from China. *Energy Econ.* **2021**, *95*, 105132. [CrossRef]
76. Li, M.; Li, C.; Zhang, M. Exploring the spatial spillover effects of industrialization and urbanization factors on pollutants emissions in China's Huang-Huai-Hai region. *J. Clean. Prod.* **2018**, *195*, 154–162. [CrossRef]
77. Hao, Y.; Zheng, S.Q.; Zhao, M.Y.; Wu, H.T.; Guo, Y.X.; Li, Y.W. Reexamining the relationships among urbanization, industrial structure, and environmental pollution in China—New evidence using the dynamic threshold panel model. *Energy Rep.* **2020**, *6*, 28–39. [CrossRef]
78. Han, X.Y.; Cao, T.Y. Urbanization level, industrial structure adjustment and spatial effect of urban haze pollution: Evidence from China's Yangtze River Delta urban agglomeration. *Atmos. Pollut. Res.* **2022**, *13*, 101427. [CrossRef]
79. Guo, J.; Xu, Y.Z.; Pu, Z.N. Urbanization and Its Effects on Industrial Pollutant Emissions: An Empirical Study of a Chinese Case with the Spatial Panel Model. *Sustainability* **2016**, *8*, 812. [CrossRef]

80. Liu, K.; Lin, B.Q. Research on influencing factors of environmental pollution in China: A spatial econometric analysis. *J. Clean. Prod.* **2019**, *206*, 356–364. [CrossRef]
81. He, L.; Zhang, X.L.; Yan, Y.X. Heterogeneity of the Environmental Kuznets Curve across Chinese cities: How to dance with 'shackles'? *Ecol. Indic.* **2021**, *130*, 108128. [CrossRef]
82. Weng, Q.H.; Yang, S.H. Urban Air Pollution Patterns, Land Use, and Thermal Landscape: An Examination of the Linkage Using GIS. *Environ. Monit. Assess.* **2006**, *117*, 463–489. [CrossRef] [PubMed]
83. Bozzo, S.R.; Novak, K.M.; Galdos, F.; Hakoopian, R.; Hamilton, L.D. Mortality, migration, income and air pollution: A comparative study. *Soc. Sci. Med. Part D Med. Geogr.* **1979**, *13*, 95–109. [CrossRef] [PubMed]
84. Van Donkelaar, A.; Martin, R.V.; Brauer, M.; Boys, B.L. Use of Satellite observations for long-term exposure assessment of global concentrations of fine particulate matter. *Environ. Health Perspect.* **2015**, *123*, 135–143. [CrossRef] [PubMed]
85. Cui, Y.; Feng, P.; Jin, J.L.; Liu, L. Water Resources Carrying Capacity Evaluation and Diagnosis Based on Set Pair Analysis and Improved the Entropy Weight Method. *Entropy* **2018**, *20*, 359. [CrossRef] [PubMed]
86. Wu, R.M.X.; Zhang, Z.W.; Yan, W.J.; Fan, J.F.; Guo, J.W.; Liu, B.; Gide, E.; Soar, J.; Shen, B.; Fazal-e-Hasan, S.; et al. A comparative analysis of the principal component analysis and entropy weight methods to establish the indexing measurement. *PLoS ONE* **2022**, *17*, e0262261. [CrossRef] [PubMed]
87. Wang, Q.S.; Yuan, X.L.; Zhang, J.; Gao, Y.; Hong, J.L.; Zuo, J.; Liu, W. Assessment of the Sustainable Development Capacity with the Entropy Weight Coefficient Method. *Sustainability* **2015**, *7*, 13542–13563. [CrossRef]
88. Li, Y.J.; Zhang, Q.; Wang, L.Z.; Liang, L. Regional environmental efficiency in China: An empirical analysis based on entropy weight method and non-parametric models. *J. Clean. Prod.* **2020**, *276*, 124147. [CrossRef]
89. Zeng, W.S.; Tang, S.Z. Bias Correction in Logarithmic Regression and Comparison with Weighted Regression for Nonlinear Models. *Nat. Preced.* **2011**, 1–11. [CrossRef]
90. Tamura, R.; Kobayashi, K.; Takano, Y.; Miyashiro, R.; Nakata, K.; Matsui, T. Mixed integer quadratic optimization formulations for eliminating multicollinearity based on variance inflation factor. *J. Glob. Optim.* **2019**, *73*, 431–446. [CrossRef]