The Relationship between Population Density and Sulfur Dioxide Emissions in China Based on the Perspective of System Theory

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***Abstract*—Whether the growth of urban population will bring more serious sulfur dioxide pollution is a problem that has drawn experts and governors' attention. This article analyzes the relationship between urban population density, industrial structure, and sulfur dioxide pollution from the perspective of system theory. The results show that the growth rate of sulfur dioxide emissions is much smaller than the growth rate of population density; after controlling the two-way fixed effect, there is no direct correlation between population density and sulfur dioxide emissions. This paper further finds that the tertiary industry is a mediation channel for population density to affect sulfur dioxide emissions. The increase in population density will promote the development of environmentally friendly tertiary industries, thereby reducing sulfur dioxide emissions. Therefore, simply restricting urban population growth cannot well solve the air pollution problem caused by sulfur dioxide emissions. Instead, the government should promote population agglomeration, play the important role of scale effect and the improve of industrial structure.**

***Keywords*—population density, sulfur dioxide, industrial structure, system theory**

I. Introduction

With the rapid urbanization and industrialization, China's economy has achieved rapid growth for more than 30 years. From 1978 to 2020, GDP increased from 370 billion yuan to 101.6 trillion yuan, an increase of nearly 275 times. But at the same time, air pollution has become a serious problem in the development of Chinese cities. According to the data of the 2023 China Ecological Environment Communique, of the 337 cities at the prefecture level and above (hereinafter referred to as 337 cities), 203 cities have reached the standard of environmental air quality, accounting for less than 60% of the total cities. Whether Air Pollution Index (API) or Air Quality Index (AQI), sulfur dioxide is included in the monitoring list of air pollutants. This indicates that sulfur dioxide plays a relatively important role in air pollutants. Moreover, At the same time, the data show that industrial emissions are the main source of sulfur dioxide in China (Ying *et al.*, 2016). The study found that rising sulfur dioxide emissions endanger public health, not only increase the number of deaths from respiratory and lung cancer, but also incur huge medical costs (Shuo, 2014).

In this case, some people think that the sharp increase of urban population will bring a lot of environmental pollution problems, which will bring adverse effects to the lives of residents and restrict the sustainable development of cities (Yu and Wang, 2014). Therefore, the view is that urban pollution can be controlled by controlling the population. In policy practice, big cities have taken the lead, such as Beijing and Shanghai, which want to limit their populations to 23 million and 25 million, respectively. However, with the high quality development of China's economy and the continuous progress of urbanization, more people will live in cities in the future. At the same time, with the transformation of industrial structure from heavy pollution secondary industry to environmentally friendly tertiary industry, the level of urban pollution will decline (Soumyananda, 2014). Therefore, whether to promote high quality economic development and sustainable development depends on the relationship between urban population agglomeration, industrial structure and urban pollution. In this paper, the system theory is used as the research basis, and the mediation model is used to verify the relationship between the above three.

The following structural arrangements are as follows: the second section carries on the literature review and puts forward the research hypotheses; the third section constructs the econometric model and introduces the data source; the fourth section reports the empirical results of mediation models and carries on robustness tests; the fifth section summarizes the full text and puts forward the relevant suggestions.

II. Literature Review and Research Hypothesis

A. The Relationship between Population Density and Sulfur Dioxide Emission

In Northeast China, there is a high correlation between population density and sulfur dioxide concentration (He and Yu, 2019). Based on the quantile regression analysis of more than 200 cities, Jin *et al.* (2014) found that the increase in population density will aggravate sulfur dioxide pollution. But under various pressures, cities with high population density may also take effective measures to reduce sulfur dioxide pollution. Through the dynamic panel regression of urban panel data, Yu and Zhang (2015) found that the increase of population density will reduce the convergence rate of per capita sulfur dioxide emissions, that is, the increase of urban population density is not conducive to sulfur dioxide emission reduction. Lei *et al.* (2021) used China's satellite observation data and spatial lag model from 2005 to 2017 to analyze the situation of sulfur dioxide pollution in China. They found that the increase of population density is one of the important reasons for the aggravation of sulfur dioxide pollution. In American, some studies have found that the low

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population density caused by too scattered urban layout increases commuting time, thus aggravating air pollution (Brian, 2008). In east Asia, someone find that population growth has a significant impact on the increase of air pollution in small and medium-sized cities, but the impact on large cities is not significant.

B. The Relationship between Population Density and Industrial Structure

In addition to climate, elevation and traffic factors, the industrial structure will also have a significant impact on the population density, that is, with the increase of the proportion of non-agricultural industries, the population density will also increase (Chen *et al.*, 2009). The results show that the average proportion of the secondary and tertiary industries in counties with a population density of more than 600 square kilometers is more than 90%. Through the comparison with Japan and South Korea, it is found that the difference of population density between cities is the result and manifestation of the difference of industrial structure between cities (Qing *et al.*, 2015). Population is an important support for the development of service industry. Population agglomeration helps to promote the development of the tertiary industry and thus promote the optimization of industrial structure (Yi and Lu, 2018). Based on this fact, they found that the population density is significantly related to the development of service industry, that is, the increase of urban population density promotes the development of service industry, while the decrease of urban population density will lead to the decrease of the proportion of service industry in GDP.

C. The Relationship between Industrial Structure and Sulfur Dioxide

When the heavily polluted industrial economy turns to a clean service economy, air pollution will decrease, that is, economic growth has a positive impact on air quality through the composition effect. Hui *et al.* (2015) through VAR model and time series data of the Hebei province in China, found that industrial structure upgrading will aggravate air pollution in the short term, but in the long run, industrial structure upgrading has a positive impact on air pollution. Kai *et al.* (2016) proved that the increase of the proportion of the secondary industry will aggravate the air pollution by the dynamic space panel regression. Based on the panel data of 284 prefecture-level cities for 9 years, Ji *et al.* (2016) found that before crossing the inflection point, due to factors such as local government performance assessment, the rising proportion of the secondary industry will lead to the decline of the intensity of environmental control, which is not conducive to sulfur dioxide emission reduction. Through the establishment of spatial econometrics models for provincial panel data, Zhong and Ye (2017) found that the development of the secondary industry will lead to the increase of sulfur dioxide pollution.

In summary, the following assumptions are put forward in this paper:

H1. An increase in population density will not increase the sulfur dioxide emissions of city.

H2. An increase in the proportion of the tertiary industry will decrease sulfur dioxide emissions.

III. Materials and Methods

A. Data Sources and Sample Selection

According to the China Urban Statistical Yearbook, this paper collects the panel data of nearly 300 cities from 2003 to 2015. The data, which include most of the 31 provinces, municipalities and autonomous regions excluding Hong Kong, Macao and Taiwan, span more than a decade and account for at least 80 per cent of China's population. Therefore, the data are representative to a certain extent in terms of the number of cities, the number of people and the time span.

B. Definition of Variables

Industrial emissions are the main source of sulfur dioxide emissions and are due to the availability of data. In this paper, industrial sulfur dioxide emissions are selected as the proxy variable of carbon dioxide emissions. The population density uses the number of people per square kilometer. To eliminate the estimation deviation caused by missing variables as much as possible, a series of other variables that may affect industrial sulfur dioxide emissions are controlled in this study. These control variables include the total industrial output value above the scale, industrial electricity consumption, the actual foreign investment, the area of paving roads and the total amount of liquefied petroleum gas supply. The total industrial output value and industrial electricity consumption represent the industrial development, the actual foreign investment represents the opening to the outside world, the paving road area represents the urban traffic situation, and the total amount of gas supply represents the use of clean energy. The descriptive statistics of variables are shown in Table 1 below.

Table 1. Descriptive statistics

Variables	**Obs**	**Mean**	**SD**	**Min**	**Max**	**Units**
SO_2	3650	65334.08	80257.75	2	1364205	Tons
PD	3679	411.69	306.19	4.7	2661.54	Person / square kilometre
Me	3677	36.16	8.32	8.58	85.34	Percentage
Industry	3673	1930	3000	0	30300	100 million ¥
Power	3613	428366.2	622630.9	0	5195783	10,000 kilowatt hours
FDI	3514	56916.59	135299.5	0	2075016	10,000$
Road	3661	1246.48	1585.81	1	14248	Ten thousand square meters
LPG	3583	31029.3	81380.78	0	1087766	Tons

C. Model Construction

To test the impact of population density on sulfur dioxide emissions, this paper constructs the following model:

$$lnSO_{2it} = \beta_0 + C \cdot lnPD_{it} + \beta_k \cdot control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where i represents cities, i represents years; $lnSO_{2it}$ denotes the sulfur dioxide emissions of city i in year t; $lnPD_{it}$ denotes the population density of city i in year t; the coefficient C is the focus of our attention, which denotes the effect of population density on the sulfur dioxide emission. μ_i is the city fixed effect; γ_t is the year fixed effect; ε_{it} is the random disturbance term, β_0 is the constant term, β_k is the regression coefficient of each control variable.

To verify the mediating role of the proportion of the tertiary industry in the impact of population density on sulfur dioxide emission, we constructed a model as follows:

$$Me_{it} = \beta_0 + a \cdot lnPD_{it} + \beta_k \cdot control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

$$lnSO_{2it} = \beta_0 + C' \cdot lnPD_{it} + b \cdot Me_{it} + \beta_k \cdot control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (3)$$

where Me_{it} represents the proportion of the tertiary industry, and the rest of the variables are the same as in Model 1.

IV. Result and Discussion

A. Benchmark Regression

Table 2 presents the results of the baseline regression. The first column does not contain any control variables and the second column introduces the relevant control variables. Columns (3) and (4) gradually incorporate city fixed effects and time fixed effects, respectively. The regression results show that the regression coefficient of population density is positive and significant at the 1% level without controlling for the relevant variables and fixed effects, indicating that population density has a significant effect on SO_2 emissions. However, with the inclusion of relevant control variables and fixed effects, the regression coefficient is still positive but not significant. This indicates that population density does not have a significant effect on sulfur dioxide emissions. From the regression coefficients in column (4), it can be seen that even if population density has a significant effect on sulfur dioxide emissions, the effect is small. Therefore, H1 is accepted.

Table 2. The effect of population density to sulfur dioxide emissions

	(1)	(2)	(3)	(4)
	SO_2	SO_2	SO_2	SO_2
PD	0.195**	0.1622**	0.143*	0.0298
	(0.0222)	(0.0245)	(0.0757)	(0.060)
Control Variables	NO	YES	YES	YES
City effect	NO	NO	YES	YES
Year effect	NO	NO	NO	YES
Constant	0.325**	0.281**	0.254**	0.215***
	(0.106)	(0.115)	(0.114)	(0.106)
N	3646	3332	3332	3332
R^2	0.024	0.126	0.005	0.232

Note: ***, **, * show level of significance of parameter at 1%, 5%, and 10%, respectively.

B. Robustness Tests

To ensure the robustness of the model results in this paper, we conduct robustness tests by replacing the explanatory variables and dividing the number of people in the city by its area to obtain a new variable on population density. The results show that our benchmark regression results are robust.

The results of the robustness test are shown in Table 3, which shows that even if we adjust the explanatory variables in the model, the effect of population density on SO_2 emissions is still significantly positive, with only a slight change in the value of the regression coefficient. This finding confirms that our previous results are not due to chance in the selection of specific variables, but reflect a real and consistent relationship between population density and SO_2 emissions.

Table 3. Robustness checks

	(1)	(2)	(3)
	SO_2	SO_2	SO_2
PD	−0.0347	0.607*	−0.0273
	(0.0585)	(0.348)	(0.0584)
Control Variables	NO	YES	YES
City effect	NO	NO	YES
Year effect	NO	NO	NO
Constant	0.325**	0.281**	0.254**
	(0.106)	(0.115)	(0.114)
N	3646	3332	3332
R^2	0.024	0.126	0.005

Note: ***, **, * show level of significance of parameter at 1%, 5%, and 10%, respectively.

C. Analysis of Intermediary Mechanisms

In this section, we will verify the impact of population density on sulfur dioxide emissions from the perspective of industrial structure. The results are shown in Table 4.

In column (1), the coefficient of population density is significantly positive, indicating that population density can significantly increase the proportion of the tertiary sector. In column (2), the proportion of the tertiary sector is significantly negatively correlated with sulfur dioxide emissions at the 1% level, indicating that an increase in the tertiary sector's share can reduce the emission of sulfur dioxide in cities. This suggests that the proportion of the tertiary sector has a mediating effect, that is, the increase in urban population density helps to increase the proportion of the tertiary sector, thereby reducing the emission of sulfur dioxide in cities. The tertiary sector typically has a lower energy consumption intensity, relying on cleaner and more efficient service activities rather than heavy industrial production, thus reducing reliance on fossil fuels and related emissions. Moreover, the development of the tertiary sector has promoted the application of technological innovation, such as intelligent transportation systems and green buildings, which have improved energy efficiency and further reduced sulfur dioxide emissions. At the same time, government support for the tertiary sector and market preferences for environmental protection services have also provided momentum for the research and application of clean energy and low-carbon technologies, jointly promoting the improvement of environmental quality. Therefore, H2 is accepted.

Table 4. Mechanism checking

	(1)	(2)
	Me	SO_2
PD	1.456***	0.0298
	(0.340)	(0.0605)
Me		−0.011***
		(0.0028)
Control Variables	YES	YES
City effect	YES	YES
Year effect	YES	YES
Constant	0.325**	0.223**
	(0.106)	(0.121)
N	3646	3332
R^2	0.024	0.128

Note: ***, **, * show level of significance of parameter at 1%, 5%, and 10%, respectively.

V. Conclusion

From the perspective of system theory, this paper firstly combs the relationship between population density, industrial structure and sulfur dioxide emission, and then proves that there is an inhibitory effect among the three elements. By analyzing the data of 287 cities from 2003 to 2015, it is found that the increase of population density does not necessarily lead to the increase of sulfur dioxide emissions. More importantly, the tertiary industry is an intermediary channel for population density to reduce industrial sulfur dioxide emissions. The increase of population density will promote the development of environmentally friendly tertiary industry, reduce the proportion of heavily polluting secondary industry, and ultimately reduce industrial SO_2 emissions.

Combining relevant literature and the above conclusions, this paper puts forward the following three policy recommendations. First, the government should accelerate new urbanization, gradually liberalize restrictions on population movement, promote free movement of population, accelerate the urbanization process, and give full play to the role of industrial structure upgrading in improving the environment. Secondly, the government should promote orderly population agglomeration and give full play to the effect of economies of scale. As a useful supplement during the transformation of the industrial structure, the government should promote small-scale population agglomeration in order to fully utilize the scale effect of public transportation and other infrastructure to reduce per capita costs and pollution. Third, the government should rationally plan the urban layout and rationally distribute residential, commercial and industrial areas to avoid a disconnect between population agglomeration and urban development. On the other hand, sulfur dioxide emissions come mainly from industry. And one of the results of industrial development is the increase in the proportion of industrial sulfur dioxide high emitting enterprises. For this reason, the government should encourage high-emission industrial enterprises to upgrade production technology, install emission reduction facilities, and achieve internal optimization of industrial structure.

This study also has some limitations. First, the research time span is from 2003 to 2015. As time goes by and policies change, the current conclusions may need further updating and verification. Second, the study mainly focuses on the relationship between population density, the proportion of the tertiary industry, and sulfur dioxide emissions, without in-depth discussion of other possible influencing factors, such as technological progress and environmental policies. Future research can extend the time span and consider more influencing factors in order to achieve more comprehensive and in-depth conclusions.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yong Zhan and Xiaoyi Zhan conducted the research; Min Wu analyzed the data; all authors had approved the final version.

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