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Characterizing the Influences of Economic Development, Energy Consumption, Urbanization, Industrialization, and Vehicles Amount on $PM_{2.5}$ Concentrations of China

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Abstract: The speeding-up of economic development and industrialization processes in China have brought about serious atmospheric pollution issues, especially in terms of particulate matter harmful to health. However, impact mechanisms of socio-economic forces on $PM_{2.5}$ (the particle matter with diameter less than 2.5 μm) have rarely been further investigated. This paper selected GDP (gross domestic product) per capita, energy consumption, urbanization process, industrialization structure, and the amount of possession of civil vehicles as the significant factors, and researched the relationship between these factors and $PM_{2.5}$ concentrations from 1998 to 2016, employing auto-regressive distributed lag (ARDL) methodology and environmental Kuznets curve (EKC) theory. Empirical results illustrated that a long-term equilibrium nexus exists among these variables. Granger causality results indicate that bi-directional causality exist between $PM_{2.5}$ concentrations and GDP per capita, the squared component of GDP per capita, energy consumption and urbanization process. An inverse U-shape nexus exists between $PM_{2.5}$ concentrations and GDP per capita. When the real GDP per capita reaches 5942.44 dollars, $PM_{2.5}$ concentrations achieve the peak. Results indicate that Chinese governments should explore a novel pathway to resolve the close relationship between socio-economic factors and $PM_{2.5}$, such as accelerating the adjustment of economic development mode, converting the critical industrial development driving forces, and adjusting the economic structure.

Keywords: $PM_{2.5}$ concentrations; GDP per capita; Energy consumption; Urbanization process; Environmental Kuznets curve; Auto-regressive distributed lag methodology; China

1. Introduction

The speeding-up of economic development and urbanization processes in China, beginning from reforming and opening up, have not only improved domestic people's living standards, but also brought about critical environmental pollution and resources depletion [1,2], especially the air pollution including haze and fog weather, which has become a frequently occurring and pressing matter in recent years [3,4]. From 2012 spring, many regions in the north and east of China have suffered from serious haze and fog weather. Taking Beijing, Tianjin, and Hebei as examples, according to the data on China air quality on-line monitoring platforms [5], for about half of the year from 2013–2017, these three regions were under haze and fog, and the air quality for half of the year was not up to standard. The primary constituent of such haze and fog pollutants is particle matter, of which the diameter is less than 2.5 μm ($PM_{2.5}$). Since $PM_{2.5}$ can easily be inhaled into the lungs and can persist in the atmosphere and move to other regions blown by wind, $PM_{2.5}$ has caused an enormous threat to human health, as well as exerted a profound influence on the global climate [6,7]. In 2014, the annual average of $PM_{2.5}$ concentrations of Hebei, Beijing, Tianjin, Henan, Hubei, and Jiangsu were 91.8 $\mu g/m^3$, 84.5 $\mu g/m^3$, 85.8 $\mu g/m^3$, 80.1 $\mu g/m^3$, 84.1 $\mu g/m^3$, and 63.3 $\mu g/m^3$ [5]. According to the 'Technical Regulation on Ambient Air Quality Index' of national environmental protection standard of China in 2012 [8] and Air Quality Guidelines issued by World Health Organization (WHO) in 2005 [9], the standards of the annual average $PM_{2.5}$ concentrations set in the above two documents are 35 $\mu g/m^3$ and 10 $\mu g/m^3$, respectively. By aiming to reduce $PM_{2.5}$ pollution, all provincial governments actively implemented industrial restructuring, increasing the use of clean energy, and traffic pollution controlling to achieve the 'transition period' standard stipulated by WHO that the average annual $PM_{2.5}$ concentration decreases to 35 $\mu g/m^3$ in 2030. In order to realize this goal, it is significant to explore the impacts of anthropogenic driving forces on $PM_{2.5}$ [10–12]. However, currently few studies quantify the influences of socio-economic forces containing economic development, industrial progress, energy consumption, and urbanization on $PM_{2.5}$ demonstrating that the relationships among these socio-economic forces and $PM_{2.5}$ of China are poorly comprehended [13]. Better understanding the complicated relationships among these variables is significant for policy makers in order to draw up effective policies to curb atmospheric pollution.

Since China began to monitor $PM_{2.5}$ concentrations data in real time in most regions from 2013, the lack of large-scale and long-range data for $PM_{2.5}$ concentrations has restricted the studies on investigating the relationships among socio-economic forces and $PM_{2.5}$ concentrations. Estimating large scale $PM_{2.5}$ concentrations via remote sensing is an effective approach to solve this issue [14]. Through integrating the data of satellite $PM_{2.5}$ concentrations and significant socio-economic factors, the long-run nexus among $PM_{2.5}$ concentrations and significant socio-economic forces are examined, for the first time to our best knowledge, employing the auto-regressive distributed lag (ARDL) methodological framework, and the environmental Kuznets curve (EKC) nexus between $PM_{2.5}$ concentrations and GDP per capita is also tested from 1998 to 2016. By further analyzing the complicated nexus between $PM_{2.5}$ concentrations and socio-economic forces, policy implications based on empirical analysis results are obtained, which can provide valuable references for policy makers.

The remaining sections of this paper are divided into six primary parts. Section 2 summarizes the previous literature on EKC and $PM_{2.5}$ concentrations. The following section explains the selection of explanatory variables and sources of socio-economic factors' data and $PM_{2.5}$ concentrations data. The methodological framework is elaborated in Section 4. Empirical analysis is conducted in Section 5. Section 6 discusses empirical results and puts forward several policy recommendations. Section 7 summarizes conclusions.

2. Literature Review

A large amount of research on the nexus between economic progress and environmental pollution has come forth since the 1990s. Some empirical studies employed EKC to describe the inverse U-shape relevance between environmental pollution and economic progress, which is deemed as an empirical hypothesis proposed by Grossman and Krueger [15,16]. Generally, in the earlier phase of economic growth, the pollution increased, then after reaching the turning point, the pollution began to reduce and the environmental quality started to improve with the growth of economy. Since the 1990s, many studies have employed EKC to research the existence of inverse U-shape nexus between economic progress and carbon dioxide (CO_2) emissions [17–23], between economic growth and sulfur oxide (SO_2) emissions [24–26], and between economic growth and nitrous oxides (NO_x) emissions [27,28]. Additionally, the EKC hypothesis was also employed in studies for hazardous waste, water pollution, and particulate matter [29–31]. Kasman and Duman [17] researched the causality between CO_2 emissions, energy consumption, economic development, urbanization process, and trade openness based on panel data model for new European union members from 1992–2010. The primary results supported the EKC hypothesis that there exists an inverted U-shape nexus between the environment and people's income for selected countries. Wang et al. [22] utilized a semi-parametric panel regression model along with the STIRPAT approach to research the complicated nexus among industrial CO_2 emissions, economic progress, and urbanization rate in China. Results proved that an inverted U-shape nexus between CO_2 emissions and economic growth exists in the electricity and heat generation sector. Huang [26] established the panel spatial Durbin models researching on the nexus among SO_2 emissions, gross regional product (GRP) per capita, investment, and economic structure of China. Results illustrated that an N-shape nexus exists between SO_2 emissions and GDP per capita. Although the number of empirical studies employing EKC is growing rapidly, the investigations on the nexus between $PM_{2.5}$ concentrations and socio-economic factors are still rare. Xu et al. [32] explored the critical driving forces of $PM_{2.5}$ from a regional perspective using Chinese provincial data based on co-integration analysis. Yu et al. [33] empirically analyzed the socio-economic forces of urban $PM_{2.5}$ emissions for China according to the data of $PM_{2.5}$ of 73 cities in China in 2013 and verified the inverse U-shape EKC between $PM_{2.5}$ and GDP per capita. Li et al. [12] investigated the primary anthropogenic driving forces contributing to making $PM_{2.5}$ concentrations increase in China, integrating the panel data approach and econometric models.

The reasons for the shortage of studies investigating the contributions of various socio-economic factors to $PM_{2.5}$ are twofold. First, compared with traditional atmospheric pollutants such as SO_2, CO_2, and NO_x, $PM_{2.5}$ is not a threatening environmental problem in developed countries which have finished their industrialization process and technologies have achieved a high level, therefore the public attention on $PM_{2.5}$ is not remarkable. Second, although $PM_{2.5}$ greatly threatens the environment and humans' health in developing countries, governments only began collecting data of $PM_{2.5}$ in recent years, therefore the large scale and long-term data of $PM_{2.5}$ concentrations are unavailable. Seeing that China is frequently threatened by haze and fog, of which the primary component is $PM_{2.5}$, investigating the relationship between significant socio-economic factors and $PM_{2.5}$ concentrations is of great importance for policy makers. Therefore, $PM_{2.5}$ is selected as the primary research object in this paper.

Previously, spatial panel data model and co-integration theory were always employed to investigate the relationship between atmospheric pollutants and their driving forces. Magazzino's research on the nexus among economic progress, energy consumption, and CO_2 emissions for six ASEAN (Association of South East Asian Nations) countries from 1971 to 2007 [34] and 19 APEC (Asia-Pacific Economic Cooperation) countries from 1960 to 2013 [35], was based on the panel VAR (vector auto-regression) technique. Results implied that a long-term equilibrium nexus exists between these variables. Guo et al. [36] established a novel method on the basis of vector auto-regression researching the nexus among SO_2 emissions, freight turnover, GDP, and urban population of Beijing. Results indicated that the expansion of logistic services exerts the greatest influence on air pollution. Wang et al. [37] explored the influences of democracy, urbanization process, and political globalization on $PM_{2.5}$ concentrations of G20 countries, based on panel quantile regression. Results illustrated that the impact of democracy on $PM_{2.5}$ concentrations is significant and positive for countries with higher emissions. Saidi [38] investigated the causality nexus among CO_2 emissions, energy consumption, and economic progress for three North-African countries based on the panel co-integration model from 1980–2012. José [39] investigated the relationships among primary energy consumption and economic development of Portugal, Greece, Spain, Italy, and Turkey based on an ARDL bounds examination method. Abdul and Syed [40] explored the long-term nexus among CO_2 emissions, residents' income, energy consumption, and foreign trade of China, utilizing the EKC theory and ARDL methodology based on the data from 1975 to 2005. Results demonstrated that CO_2 emissions are primarily determined by residents' income and energy consumption. For traditional co-integration theory, they need to test for the stability of time series and make them stable by differencing which would interfere with long-term analysis. Since ARDL methodology can be utilized in spite of whether the time series is stable at level or after first differenced form and is suitable for energy related problems [39,40], this investigation, for the first time to our best knowledge, utilized ARDL methodology to analyze the long-term equilibrium nexus between $PM_{2.5}$ concentrations and significant socio-economic driving forces on the basis of the general-to-specific simulating technology [41–44].

The primary contributions of this paper contain: (1) through employing satellite $PM_{2.5}$ concentrations data, the EKC nexus of $PM_{2.5}$ concentrations and economic progress of China is tested for the first time from country level; (2) the long-term relationship among $PM_{2.5}$ concentrations and significant socio-economic forces containing economic development, industrial process, energy consumption, urbanization process, and vehicles amount are examined from 1998 to 2016 utilizing ARDL methodological framework; (3) effective and practicable policy implications are obtained through further analyzing the complicated nexus of $PM_{2.5}$ concentrations and socio-economic forces which can provide valuable references for policy makers.

3. Variables Selection and Data Sources

Annual $PM_{2.5}$ concentrations data for China in the scope of 1998–2016 are collected from remote sensing data monitored by Aaron van Donkelaar Professor from Dalhousie University of Canada. Ground–level $PM_{2.5}$ data are estimated through integrating Aerosol Optical Depth (AOD) and then correct to ground-based observations throughout the world of $PM_{2.5}$ data employing Geographically Weighted Regression (GWR), elaborated in References [41–43]. According to the statistics, the tendency of $PM_{2.5}$ concentrations in China during the period of 1998–2016 is displayed in Figure 1. It can be seen that from 2001, the annual $PM_{2.5}$ concentrations are all more than 35 $\mu g/m^3$. In 2007, it arrived at the peak with 50.1 $\mu g/m^3$. In order to achieve the 'transition period' standard set by WHO that the average annual $PM_{2.5}$ concentrations decrease to 35 $\mu g/m^3$ in 2030, considering the current emissions level of $PM_{2.5}$, we need to investigate the driving factors of $PM_{2.5}$ and the contributions of them to $PM_{2.5}$; this analysis will, therefore, enable us to formulate effective policies to curb the increase of $PM_{2.5}$.

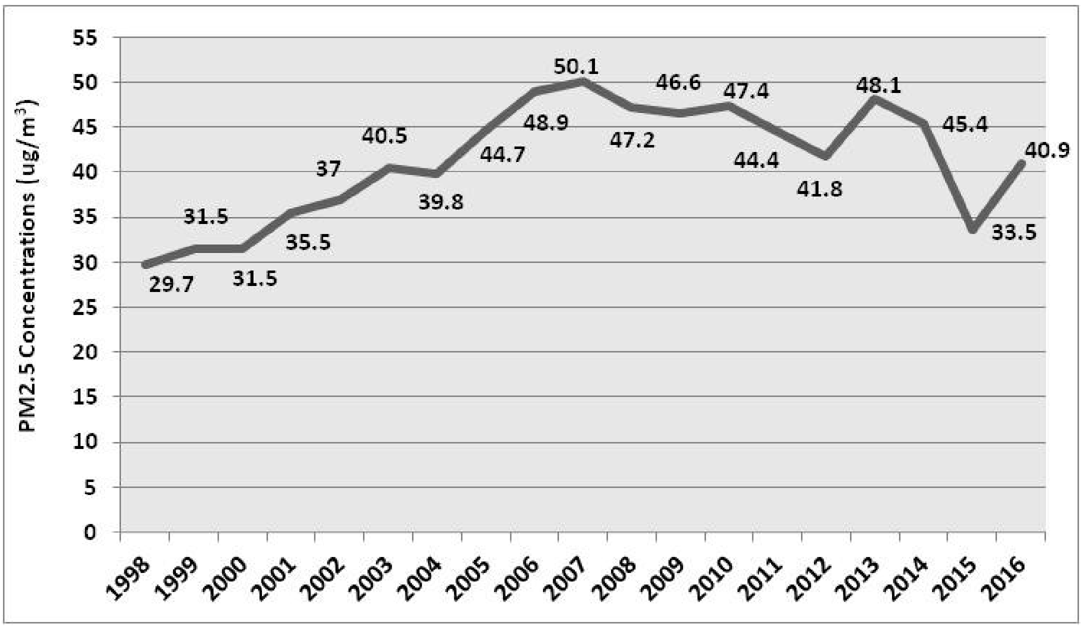

Figure 1. The tendency of annual $PM_{2.5}$ concentrations in China. (Data source: remote sensing data monitored by Aaron van Donkelaar Professor from Dalhousie University of Canada [41–43]).

The significant driving forces of $PM_{2.5}$ concentrations are selected as explanatory variables based on grey correlation degree analysis. The fundamental theory of grey correlation degree analysis can be referred to in the literature [44]. Some social-economic factors are employed to analyze the correlation degree with $PM_{2.5}$ concentrations and the factors with relatively high correlation degree (higher than

0.80) are selected as the significant variables affecting $PM_{2.5}$ concentrations utilized to establish the ARDL model in order to analyze the long-term equilibrium nexus between $PM_{2.5}$ concentrations and these factors. Results of grey correlation degree are illustrated in Table 1. As indicated in Table 1, GDP per capita, total energy consumption amount, the proportion of population amount of urban areas in the total population, the proportion of secondary industry added value in GDP, and the amount of possession of civil vehicles are highly correlated with $PM_{2.5}$ concentrations. Therefore, this paper has chosen GDP per capita, total energy consumption amount, urbanization process represented by the proportion of population amount of urban areas in the total population, industrial process represented by the proportion of secondary industry added value in GDP, and the amount of possession of civil vehicles as independent variables, the data of which were collected from China Statistic Year Book [45].

Table 1. Results of grey correlation degree between $PM_{2.5}$ concentrations and several social-economic factors of China.

	Comparison Sequence	Correlation Degree
Economic progress	Gross domestic product	0.7923
	GDP per capita	0.8534
Economic structure	The proportion of secondary industry added value in GDP	0.8677
	The proportion of tertiary industry added value in GDP	0.6125
Urbanization process	The proportion of population amount of urban areas in the total population	0.8192
Energy consumption	Total energy consumption amount	0.8235
	Energy consumption efficiency	0.7561
Vehicles amount	The amount of possession of civil vehicles	0.8022

For GDP per capita, in accordance with the research results in previous studies on the influences of socio-economic forces on environmental pollutions, we can discover that the emissions or concentrations of pollutions are highly correlated with the average income [22,23,26,31]. Considering the reality that the haze and fog weather has occurred in several developed countries during the industrialization process, it is very likely that the emergence of such weather is an inevitable phase for China to undergo through the development of the economy. If this hypothesis is verified, the nexus between GDP per capita and $PM_{2.5}$ should also be an inverse U-shape. To examine this hypothesis, GDP per capita is taken as a critical factor, and the squared component of GDP per capita is also employed to testify whether there exists a nonlinear nexus between $PM_{2.5}$ concentrations and GDP per capita. The data of GDP per capita from 1998 to 2016 are converted into the constant price, taking the year 2000 as the basic period.

For the industrialization process, since the secondary industry contains energy intensive industries and pollutant emissions intensive industries, it greatly contributes different pollutants discharging which significantly threaten the environmental quality. Hence, relative scale of secondary industry exerts critical impact on atmospheric quality. Thus, we employ the proportion of secondary industry added value in GDP to represent economic structure and this is deemed as an independent variable.

For the amount of possession of civil vehicles, scientific studies have verified that the vehicle exhaust emits organic hydrocarbons, black carbon, NO_x, as well as various kinds of pollutants that are the primary resources of $PM_{2.5}$ [46]. Thus, the number of vehicles can exert great influence on $PM_{2.5}$ concentrations. Therefore, the amount of possession of civil vehicles is also employed as an independent variable.

For energy consumption, the consuming of energy, especially the combustion of fossil fuel energy, has a significant influence on the environment. The emissions of smoke, fog, sulfide, and NO_x primarily originated from the use of energy are the major components of $PM_{2.5}$. Therefore, the total amount of energy consumption is also treated as an independent variable.

For the urbanization process, urbanization has been shown to have a great impact on the eco-environment [47]. The existing literature has discovered that greenhouse gas emissions and $PM_{2.5}$ concentrations will increase with the rapid process of urbanization [31,48–50]. Therefore, this research also treats the urbanization process as an independent variable, which is represented by the share of population in urban areas in the total population.

Table 2 lists the detailed description of $PM_{2.5}$ concentrations and five explanatory variables.

Table 2. Detailed description of dependent variable and explanatory variables.

Variables	Representation in the Established Model	Measurement Unit	Minimum	Maximum	Average	Standard Deviation	Data Source
$PM_{2.5}$ concentrations	$PM_{2.5}$	μg/m^3	29.70	50.10	41.29	6.51	Remote sensing data monitored by Aaron van Donkelaar Professor from Dalhousie University of Canada [41–43].
GDP per capita	*GDP*	yuan per person	6860.00	53,935.00	24,625.68	16,188.43	China Statistic Year Book [45]
Energy consumption	*EC*	10^4 ton	136,184.00	436,000.00	292,140.69	110,030.32	
The share of population amount of urban areas in the total population	*ur*	%	33.35%	57.35%	45.67%	7.52%	
The proportion of secondary industry added value in GDP	*is*	%	39.88%	47.56%	45.14%	2.00%	
The amount of possession of civil vehicles	*ve*	10^4 cars	1319.30	18,574.54	6638.27	5524.94	

4. Methodological Framework

4.1. Basic Theory of EKC

Grossman and Krueger [15,16] firstly analyzed the complicated relationship between the scale of an economy and the pollutants intensity, discovering that pollutant intensity rises at the early phase of an economy's development and then decreases after achieving the turning point. According to the selected significant socio-economic factors influencing $PM_{2.5}$ concentrations, the basic form of EKC model can be expressed as:

$$\ln PM_{2.5t} = \beta_0 + \beta_1 \ln GDP_t + \beta_2 (\ln GDP_t)^2 + \beta_3 \ln EC_t + \beta_4 \ln ur_t + \beta_5 \ln is_t + \beta_6 \ln ve_t + \varepsilon_t \quad (1)$$

where $PM_{2.5t}$ represents the amount of $PM_{2.5}$ concentrations, GDP_t indicates GDP per capita, EC_t demonstrates the total energy consumption amount, ur_t illustrates the urbanization process, is_t implies the industrial process, ve_t means the amount of possession of civil vehicles, ε_t is a random error component, and β_i is the coefficient of each variable representing the contribution of corresponding socio-economic factor to $PM_{2.5}$ concentrations.

Previous literature supporting the inverted U-shape relationship found that $\beta_1 > 0$ and $\beta_2 < 0$, and when GDP per capita achieves $e^{-\beta_1/2\beta_2}$, the pollutants amount reaches the peak.

4.2. Basic Theory of ARDL

Problems of spurious regression may emerge if time series data are utilized in non-stationary form. One of the common used solutions is to make the sequence stable through differencing. However, differencing the sequence would restrict the long-term analysis. At the aim of evading such a problem, many techniques are employed to test the existence of long-run equilibrium nexus among various time series. This paper employed the ARDL model, put forward by Pesaran et al. [51–54], to establish the long-run equilibrium nexus among the selected variables, combining with the EKC theory. For ARDL, the significant advantage is that it can be used whether or not the time series is stable at level or after first differenced form. The other merit is that this method utilizes sufficient lags number to trap the data producing procedure in a general-to-particular simulating structure. Additionally, the ARDL model applied to a small sample performs superior to Johensen and Juselius' co-integration approach [54]. Moreover, the error correction model (ECM) could also be generated from the ARDL methodology via simple linear conversion.

The ARDL approach should start with examining for the stability of the data series to evade spurious regression. Although the ARDL approach can be employed with or without data series stability at level or after first differenced into consideration, Ouattara [55] discovered that if the data series are stable after second differenced, the computed F-statistics calculated by Pesaran et al. [54] will be ineffective, as the bound test is conducted on the basis of the hypothesis that the data series are stable at level or first differenced form. Considering this, the ARDL framework should start with unit root examinations to guarantee that none of the data series is stable after the second differenced or beyond.

Secondly, the optimal lags order should be selected of every variable. The ARDL approach evaluates $(p+1)^k$ regressions, of which p represents the maximum lags length and k means the number of variables in the equation. The optimal lags order generally selected by Schawrtz–Bayesian criteria (SBC) and Akaike's information criteria (AIC).

After selecting optimal lags order, the long-term relationship among chosen socio-economic factors and $PM_{2.5}$ concentrations can be established by F-tests and coefficients are estimated to analyze the devotions of various variables to $PM_{2.5}$ concentrations. ARDL formula of Equation (1) can be elaborated as:

$$\begin{aligned}\Delta \ln PM_{2.5t} = \; & \beta_0 + \sum_{i=1}^{p} \delta_i \Delta \ln PM_{2.5t-i} + \sum_{i=1}^{p} \phi_i \Delta \ln GDP_{t-i} + \sum_{i=1}^{p} w_i \Delta (\ln GDP_{t-i})^2 \\ & + \sum_{i=1}^{p} \theta_i \Delta \ln EC_{t-i} + \sum_{i=1}^{p} \xi_i \Delta \ln ur_{t-i} + \sum_{i=1}^{p} \omega_i \Delta \ln is_{t-i} + \sum_{i=1}^{p} \eta_i \Delta \ln ve_{t-i} \\ & + \lambda_1 \ln PM_{2.5t-1} + \lambda_2 \ln GDP_{t-1} + \lambda_3 (\ln GDP_{t-1})^2 + \lambda_4 \ln EC_{t-1} \\ & + \lambda_5 \ln ur_{t-1} + \lambda_6 \ln is_{t-1} + \lambda_7 \ln ve_{t-1} + U_t\end{aligned} \tag{2}$$

where U_t is the white noise, λ_i corresponds to the long-term nexus, and the components with sum signs indicate the error correction dynamics.

F-tests are utilized to test whether the long-run nexus exists among various variables. The null hypothesis is $H_0 : \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0$, which indicates that no long-term nexus exists, while the opposite hypothesis is $H_1 : \lambda_1 \neq 0, \lambda_2 \neq 0, \lambda_3 \neq 0, \lambda_4 \neq 0, \lambda_5 \neq 0, \lambda_6 \neq 0, \lambda_7 \neq 0$. The *F*-statistics value is compared with two significant values suggested in Reference [54]. One supposed that all data series are stable at level and the other presumed that they are stable after first differenced. If the computed *F*-statistics is more than the upper threshold value, H_0 should be rejected despite of whether data series are stable at level or after first differenced. If the computed *F*-statistics is less than the bottom value, H_0 should be accepted. If the computed *F*-statistics is in the scope of the upper and bottom critical values, the examination is of no consequence.

At the aim of guaranteeing the validity of the established model, the diagnostic examinations are carried out, which contain examining the serial correlation, normality, functional form and heteroskedasticity related to the selected method [56].

The research route of our paper is illustrated in Figure 2.

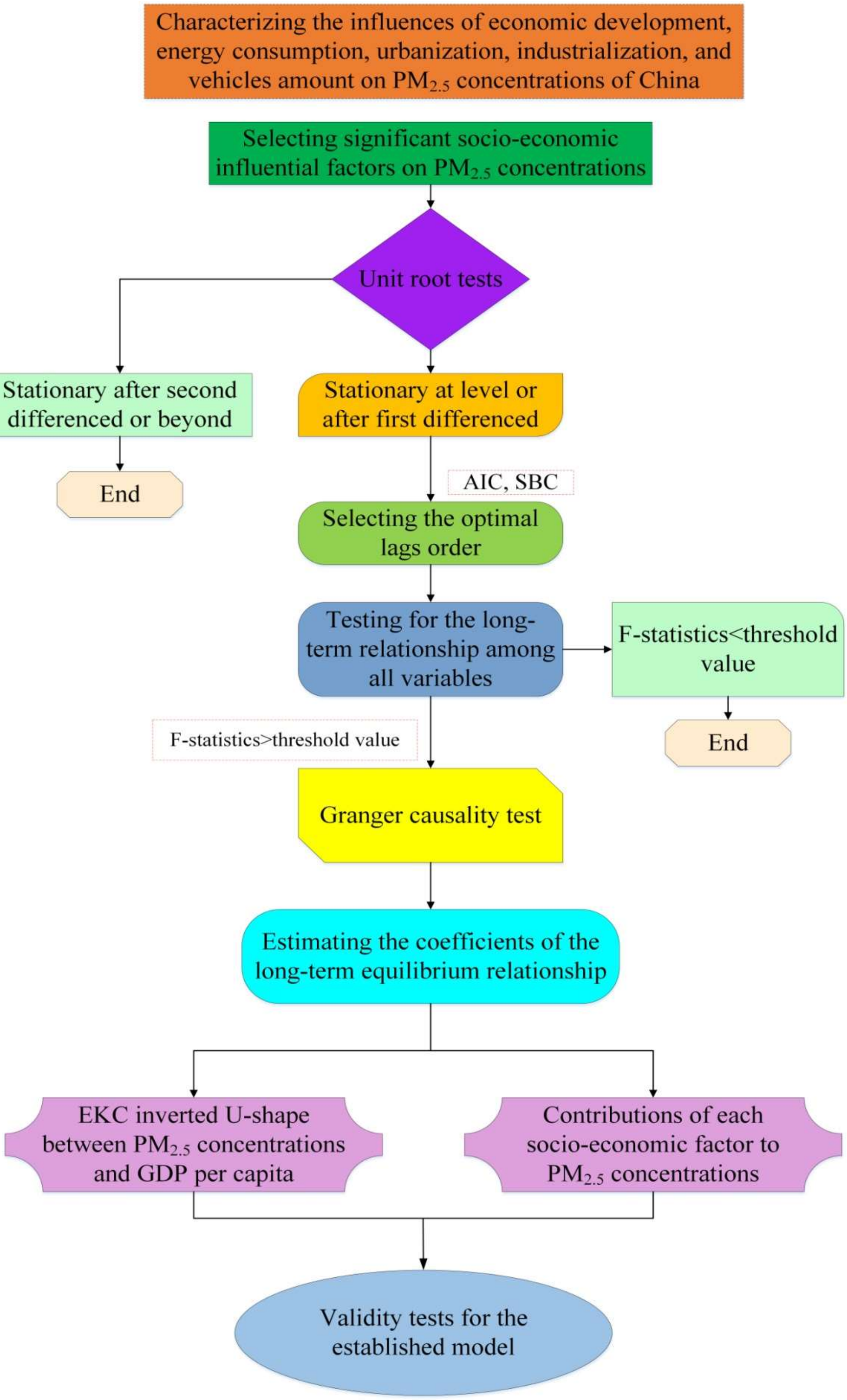

Figure 2. Research framework for characterizing the influences of economic development, energy consumption, urbanization, industrialization, and vehicles amount on $PM_{2.5}$ concentrations of China.

5. Empirical Analysis

Our research focuses on exploring the long-term nexus of $PM_{2.5}$ concentrations and significant socio-economic factors of China. The ARDL method is employed to examine the co-integration relationship among all of the variables taken into account. Considering the critical steps required by the ARDL approach, the empirical analysis is conducted as follows:

- **Step 1**: Examining the stability of all variables to prevent spurious regression.

Since the bound test of the ARDL approach assumed that the variables should be stable at level or after first differenced, we need to carry out unit root test to guarantee that none of the variables are stable after second differenced or beyond to ensure the validity of *F*-statistics. To verify this, we utilized the traditional Augmented Dickey Fuller (ADF) test for unit root examination. The examination results are shown in Table 3. As the results illustrated, none of the variables is stationary after second differenced or beyond. All variables are unstable at level at 10% significance level, but all data series are stationary after first differenced at 10% significance level. Therefore, all the selected variables satisfy the basic assumption of ARDL approach.

Table 3. Unit root examination results of all variables.

Form	Variables	*t*-Statistics	*P*-Value	Conclusions
Level	$\ln PM_{2.5}$	−2.255240	0.1955	Unstable
	$\ln GDP$	−1.964302	0.5726	Unstable
	$(\ln GDP)^2$	−2.122801	0.4934	Unstable
	$\ln EC$	−1.769321	0.3867	Unstable
	$\ln ur$	−1.655064	0.4347	Unstable
	$\ln is$	0.751522	0.9992	Unstable
	$\ln ve$	−0.674718	0.8278	Unstable
First differenced	$\Delta\ln PM_{2.5}$	−6.662052	0.0004	Stable
	$\Delta\ln GDP$	−3.084791	0.0497	Stable
	$\Delta(\ln GDP)^2$	−3.180230	0.0478	Stable
	$\Delta\ln EC$	−2.699950	0.0944	Stable
	$\Delta\ln ur$	−9.215506	0.0000	Stable
	$\Delta\ln is$	−3.484361	0.0735	Stable
	$\Delta\ln ve$	−3.945974	0.0095	Stable

- **Step 2**: Selecting the optimum lags order.

After identifying that all data series are stable after first differenced, the ARDL co-integration procedure should step to choose the optimum lags length. At this step, AIC and SBC statistics are applied to choose the optimum lags order of ARDL approach. The results are illustrated in Table 4. We need to choose a high enough lags order to guarantee that the optimum lags order cannot be higher than it. We set the maximum lag length to be 3, and according to the results of AIC and SBC criteria, the optimum lag length should be 1.

Table 4. Testing results for selecting the optimum lag order.

Order	AIC	SBC
0	−20.46536	−20.11910
1	−38.95490 *	−36.18486 *
2	−25.42735	−28.57295
3	−22.38471	−25.41761

Note: * illustrates the optimum lag order chosen by the criterion.

- **Step 3**: Testing for the long-term relationship among all variables by *F*-statistics.

Based on the above two steps, the long-term nexus among all variables should be examined employing bounds test. Equation (2) will be estimated employing ordinary least square (OLS) approach and the *F*-statistics for the joint indication of lag levels for data series will be calculated. The calculated *F*-statistics for lag 1 order is 5.569. Critical values can be referred to the literature [44] which is 5.06 at 1% significance level. Therefore, it is confirmed that a strong long-term equilibrium nexus exists among all variables.

- **Step 4**: Examining the Granger causality nexus among all variables.

Before estimating the long-term relationship among all variables, we need to verify whether there exists a causality nexus between the dependent variable $PM_{2.5}$ concentrations and each of the independent variables. This research employed the Granger Causality examination approach to test the causality nexus between variables. The results are displayed as Table 5. It is found that there exists bi-directional causality nexus between $PM_{2.5}$ concentrations and GDP per capita, $PM_{2.5}$ concentrations and the squared component of GDP per capita, $PM_{2.5}$ concentrations and total energy consumption as well as $PM_{2.5}$ concentrations and urbanization process. This indicates that the changes of GDP per capita, total energy consumption and urbanization process will have great influences on $PM_{2.5}$ concentrations, and the change of $PM_{2.5}$ concentrations will also have great impacts on these socio-economic factors. The increase of GDP per capita, total energy consumption, and urbanization rate will bring about the increase of $PM_{2.5}$ concentrations, and the decrease of $PM_{2.5}$ concentrations will conversely lead to the decrease of GDP per capita, total energy consumption, and urbanization rate. There exists uni-directional causal nexus between $PM_{2.5}$ concentrations and industrialization process as well as $PM_{2.5}$ concentrations and the amount of possession of civil vehicles. Additionally, the uni-directional causal nexus all run from the socio-economic factors to $PM_{2.5}$ concentrations, which demonstrate that the variety of these socio-economic factors will shock the amount of $PM_{2.5}$ concentrations, while the change of $PM_{2.5}$ concentrations will take no effect on these socio-economic factors. That indicates the increase of the ratio of secondary industry added value in GDP and the amount of possession of civil vehicles will result in the increase of $PM_{2.5}$ concentrations, while if the increase of $PM_{2.5}$ concentrations is controlled, it will have no impacts on the development of industrialization process and the increase of the amount of possession of civil vehicles.

Table 5. Granger Causality examination results.

Null Hypothesis	*F*-statistics	*P*-value	Conclusion
lnGDP does not Granger cause ln$PM_{2.5}$	4.509638	0.0337	Reject
ln$PM_{2.5}$ does not Granger cause lnGDP	3.714609	0.0750	Reject
$(\ln GDP)^2$ does not Granger cause ln$PM_{2.5}$	4.763327	0.0291	Reject
ln$PM_{2.5}$ does not Granger cause $(\ln GDP)^2$	0.393601	0.6896	Reject
lnEC does not Granger cause ln$PM_{2.5}$	3.544326	0.0817	Reject
ln$PM_{2.5}$ does not Granger cause lnEC	3.296452	0.0885	Reject
lnur does not Granger cause ln$PM_{2.5}$	5.784270	0.0162	Reject
ln$PM_{2.5}$ does not Granger cause lnur	5.824954	0.0158	Reject
lnis does not Granger cause ln$PM_{2.5}$	4.854508	0.0276	Reject

Table 5. *Cont.*

Null Hypothesis	*F*-statistics	*P*-value	Conclusion
$\ln PM_{2.5}$ does not Granger cause $\ln is$	0.497810	0.4805	Accept
$\ln ve$ does not Granger cause $\ln PM_{2.5}$	4.273168	0.0387	Reject
$\ln PM_{2.5}$ does not Granger cause $\ln ve$	2.043105	0.1529	Accept

- **Step 5**: Estimating the coefficients of the long-term equilibrium relationship.

Based on the ARDL co-integration approach, the long-term equilibrium relationship in Equation (2) can be estimated. The AIC and SBC criterion, Hannan Quinn criterion are employed to find the coefficients of the variables at level. Since SBC is a parsimonious method selecting the least possible lag order and minimizing the loss of freedom degree, here we illustrate the results of the model selected by SBC. The coefficients are displayed in Table 6. As the results demonstrated, the coefficients for GDP per capita in constant price, total energy consumption, urbanization process, industrialization process, and the amount of possession of civil vehicles are all positive and significant at 5% significance level according to *t*-statistics and *P*-values. Based on the coefficients, 1% increases of GDP per capita in the constant price, total energy consumption, urbanization process, industrialization process, and the amount of possession of civil vehicles will lead to 0.762%, 0.745%, 0.597%, 0.501%, and 0.468% increases of $PM_{2.5}$ concentrations, respectively. Therefore, GDP per capita makes the greatest contributions to $PM_{2.5}$, followed with total energy consumption, urbanization, industrialization process, and the amount of possession of civil vehicles.

The coefficient of the squared component of GDP per capita in constant price is negative and significant, which verifies the hypothesis of EKC that there exists an inverse U-shape between $PM_{2.5}$ concentrations and GDP per capita. According to the coefficients of $\ln GDP$ and $(\ln GDP)^2$, we can estimate the turning point of GDP per capita in constant price when $PM_{2.5}$ concentrations achieve the peak, which turned out to be 39,471.47 yuan (based on the exchange rate between RMB yuan and dollar listed in the China Statistic Year Book [45] in 2017, we transfer 39,471.47 yuan to 5942.44 dollar). Compared with the highest value of GDP per capita in constant price 30,933.12 yuan in 2016, based on the EKC assumption, the $PM_{2.5}$ concentrations will still increase until the GDP per capita in constant price reaches the inflection point, and then $PM_{2.5}$ concentrations will decrease with the growth of economy.

Table 6. The coefficients estimation results of auto-regressive distributed lag (ARDL) model.

Dependent Variable: $PM_{2.5}$ Concentrations			
Independent variables	Coefficients	*t*-Statistics	*P*-Values
$\ln GDP$	0.762	−3.38126	0.0432
$(\ln GDP)^2$	−0.036	−3.36582	0.0464
$\ln EC$	0.745	−4.59122	0.0312
$\ln ur$	0.597	3.51175	0.0397
$\ln is$	0.501	−4.12643	0.0212
$\ln ve$	0.468	−3.92563	0.0297

- **Step 6**: Estimating the coefficients of error correction terms.

The above coefficients are for the long-term equilibrium relationship in Equation (2), considering that the ARDL methodology can also analyze ECM, hence this step analyzes the coefficients of error correction terms (which are the components with sum signs) in Equation (2). Results of the ECM estimation are illustrated in Table 7. As indicated in Table 7, all of the error correction components are significant at 1% significance level. The coefficient of ECM_{t-1} is also significant and correct with negative value, which demonstrates that approximately 19.87% imbalance in $PM_{2.5}$ concentrations of previous years' variation adjust back to the long-term equilibrium of current years. The value of R^2 illustrates the ECM is relatively good regression.

Table 7. ECM estimation results of ARDL model.

Error correction Terms	Coefficients	*t*-Statistics
$\Delta \ln PM_{2.5}$	0.6433	4.6787 *
$\Delta \ln GDP$	0.7821	3.8923 *
$\Delta (\ln GDP)^2$	−0.2387	3.4032 *
$\Delta \ln EC$	0.4365	4.0188 *
$\Delta \ln ur$	0.3379	3.7265 *
$\Delta \ln is$	0.2028	3.6912 *
$\Delta \ln ve$	0.1615	3.5842 *
$\Delta Intercept$	−4.3029	3.8849 *
$ecm(-1)$	−0.1987	3.4308 *
R-squared:	0.8897	

Note: * demonstrates 1% significance level.

- **Step 7**: Examining the validity of the established model.

With the aim of verifying the validity of the established model, the diagnostic examinations including functional form, serial correlation, heteroskedasticity, and normality tests are conducted. Results of them are indicated in Table 8. The results of all the diagnostic examinations demonstrate that there exist no serial correlation and heteroskedasticity. Additionally, the established model passed through the examinations of normality and functional form specification. Therefore, the established model has shown validity.

Table 8. Validity testing results for the established model.

Diagnostic Tests	Test-Statistics	*P*-Values
Serial correlation	0.0203	0.821
Functional form	2.2326	0.256
Normality	1.4314	0.371
Heteroskedasticity	0.0123	0.898

6. Discussion and Policy Implications

Previous literature has illustrated that the increase of $PM_{2.5}$ has been greatly influenced by socio-economic factors [10]. On the purpose of discovering and better understanding the relationship between socio-economic factors and $PM_{2.5}$, this paper selected GDP per capita, total energy consumption, urbanization process, industrialization process, and the amount of possession of civil vehicles as the most significant socio-economic factors which have great influences on $PM_{2.5}$ concentrations based on grey correlation degree analysis results, and we assumed that the selected socio-economic factors can reflect the overall development trend and conditions for China's socio-economic development. The empirical results have verified our assumption that these selected variables have high relativity with $PM_{2.5}$ concentrations and make great contributions to $PM_{2.5}$ concentrations increase.

From the results of long-term causality relationships between each independent variable and $PM_{2.5}$ concentrations, we can conclude that if the development pattern of China remains unchanged, the control of $PM_{2.5}$ concentrations will bring undesirable effects on economic development, energy consumption, and urbanization process, as there exist bi-directional causal nexus between these variables and $PM_{2.5}$ concentrations. Contrarily, under present development pattern, the growth of economic development and the increase of energy consumption and urbanization process will result in the ascending of $PM_{2.5}$ concentrations. Thus, policy makers should carefully balance the relationship between $PM_{2.5}$ concentrations reduction and the increase of economic progress, energy consuming, and urbanization process when formulating policies to restrict $PM_{2.5}$ concentrations under present development pattern.

For economic development, currently, economic growth is deemed as the most significant mission both for central and provincial governments. Chinese 13th Five Year Plan, as the critical document proposing development goals covering various economic, social, and environmental aspects in the period of 2016–2020, set an annual average growth ratio of 6.5% as the minimum requirement for economic growth [57]. According to the empirical results, GDP per capita makes the greatest contribution to $PM_{2.5}$ concentrations and a bi-directional causal nexus exists between economic development and $PM_{2.5}$ concentrations. Hence, the close nexus between $PM_{2.5}$ concentrations and economic development demonstrates that a novel pathway is urgently required to decrease the impacts of economic development on $PM_{2.5}$ concentrations. Therefore, under the current situation, accelerating the adjustment of economic development mode transformed from the original rough mode consuming large amounts of energy and resources with insufficient economic growth and increased pollutants emissions to novel intensive mode depending on high level technologies with rapid economic growth and decreased pollutants emissions, is indispensable. Such conversion of economic development mode will greatly contribute to economic growth and pollutants reduction which can guarantee the sustainable development of China's society and economy. Although the transformation of economic mode needs investment and time, it is an integral step to synchronously decrease $PM_{2.5}$ concentrations and guarantee the growth of economy.

For energy consuming and industrialization process, in accordance with the results of the Granger causality examination and coefficients of the established model, the present industrial development mode highly relies on energy intensive industries which results in large amount resources consuming and pollutants emissions. From the early 1990s, the economic development of China has been greatly prompted by heavy industries, especially the chemical industry and metal manufacturing industry [58]. However, considering the serious overcapacity problem of heavy industries and the significance of sustainable development, the development of China's economy will not depend on heavy industries in the predictable future and the industrial development mode need to be transformed. Although central governments and provincial governments have made great efforts to alter the industrial development mode, it is a tough and long way to realize industrial development conversion. The strategies below may help to accelerate the conversion process which will contribute to reducing $PM_{2.5}$ concentrations and promote sustainable development of industrial sectors: (1) the critical industrial development driving forces should be transformed from traditional energy consumption and resources to technological progress and innovation; (2) the backward generation capacity and heavy pollution enterprises should be eliminated gradually; (3) the economic structure should be adjusted by promoting the development of tertiary industries; (4) local governments should improve $PM_{2.5}$ emissions criterion appropriately considering the level of technological development and the ability of enterprises to control pollution which is a more direct strategy to decrease $PM_{2.5}$ concentrations.

For urbanization process, the empirical results indicate that there exists a bi-directional causality between $PM_{2.5}$ concentrations and urbanization process, moreover, according to the coefficients in the established model, the contribution of urbanization process to $PM_{2.5}$ concentrations ranks the third. Hence, the deceleration of urbanization process may benefit for decreasing $PM_{2.5}$ concentrations. However, since a high goal for achieving 60% urbanization rate in 2020 was set in the New-Type Urbanization Plan [59] issued by central government, the urbanization process cannot be decelerated. Seeing that cities with high urbanization rate always have high $PM_{2.5}$ concentrations [12], population mitigation into more intensive population urban regions should be restricted which is probably an effective measure to control $PM_{2.5}$ concentrations.

For the amount of possession of civil vehicles, Granger causality examination results and coefficients in the established model demonstrate that the amount of possession of civil vehicles is a significant factor of $PM_{2.5}$ concentrations. The increase of the number of vehicles brings about not only the increase of $PM_{2.5}$ concentrations, but also severe traffic pressures, especially in megacities such as Beijing and Shanghai. Therefore, governments should continue to promote the popularity of electric vehicles and restricting the successful rate for petrol car licenses.

7. Conclusions

Although the Chinese economy experienced rapid development, the mode of it was extensive, which heavily depended on energy and resources consuming and emitted large amounts of pollutants, especially atmospheric pollutant such as $PM_{2.5}$, which has attracted more attention from the public due to its hazardous effects on human health. Since the increase of $PM_{2.5}$ concentrations results from several socio-economic influential factors, this paper has aimed at exploring the relationship among significant socio-economic forces and $PM_{2.5}$ concentrations so that effective strategies can be formulated to restrict $PM_{2.5}$. GDP per capita, total energy consumption amount, urbanization process, industrialization structure, and the amount of possession of civil vehicles were selected as the independent variables which reflect the socio-economic development of China. The data of all variables from 1998–2016 were collected to establish the long-term equilibrium relationship based on ARDL method. According to the Granger causality test results, bi-directional causality nexus exist between $PM_{2.5}$ concentrations and GDP per capita, $PM_{2.5}$ concentrations and the squared component of GDP per capita, $PM_{2.5}$ concentrations and total energy consumption as well as $PM_{2.5}$ concentrations and urbanization process, and uni-directional causal nexus exist between $PM_{2.5}$ concentrations and industrialization process as well as $PM_{2.5}$ concentrations and the amount of possession of civil vehicles both of which run from the socio-economic factors to $PM_{2.5}$ concentrations. Through estimating the coefficients in the long-run equilibrium nexus, we can obtain that an inverse U-shape nexus exists between $PM_{2.5}$ concentrations and GDP per capita which verified EKC assumption and when the real GDP per capita reaches 39,471.47 yuan (5942.44 dollar), $PM_{2.5}$ concentrations will achieve the peak. Based on the estimated coefficients, GDP per capita makes the greatest contributions to $PM_{2.5}$ concentrations, followed by total energy consumption, urbanization, industrialization process, and the amount of possession of civil vehicles.

According to the empirical analysis, policy implications aimed at reducing $PM_{2.5}$ concentrations and promoting the sustainable development of China's society and economy are put forward based on the Granger causality relationship between various variables and $PM_{2.5}$ concentrations as well as the contribution of different independent variables to $PM_{2.5}$ concentrations. For GDP per capita, accelerating the adjustment of economic progress mode transformed from the original rough mode to novel intensive mode is an integral step to synchronously decrease $PM_{2.5}$ concentrations and guarantee the growth of economy. For energy consumption and industrialization process, strategies below will help to accelerate the industrial conversion process to reduce $PM_{2.5}$ concentrations: (1) the critical industrial development driving forces should be transformed from traditional energy consumption and resources to technological progress and innovation; (2) the backward generation capacity and heavy pollution enterprises should be eliminated gradually; (3) the economic structure should be adjusted by promoting the development of tertiary industries; (4) local governments should improve $PM_{2.5}$ emissions criterion appropriately. For the urbanization process, population mitigation into more intensive population urban regions should be restricted. For the amount of possession of civil vehicles, governments should continue to promoting the popularity of electric vehicles and restricting the successful rate for petrol car licenses.

Above all, this paper is an initial study to investigate the nexus between social and economic forces and $PM_{2.5}$ concentrations of China from a macro view. The purpose of this research is to encourage researchers to further explore the reasons for severe atmospheric pollution in China and provide validity and practicable policy recommendations for policy makers. Considering the data availability, in future research, panel data model analysis can be conducted to analyze the influences of various socio-economic forces on $PM_{2.5}$ with regard to various provinces or regions in China as well as for developing countries based on high resolution data sources. Additionally, in terms of spatial spillover effects of $PM_{2.5}$ concentrations, appropriate models should be established to be applied in researching the nexus between $PM_{2.5}$ concentrations and influencing factors of various regions, such as Spatial Autoregressive Model. Meaning, then, that pertinent policy implications can be put forward considering the actual situation of different regions.

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