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The Potential of Green Development and $PM_{2.5}$ Emission Reduction for China's Cement Industry

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Abstract: The atmospheric dust caused by the cement industry is one of the main components of air pollutants. China is the largest producer and consumer of cement. It is challenging to balance cement needs and environmental protection. Based on the emission source data, this study examined the spatial and temporal patterns of $PM_{2.5}$ by the cement industry's contribution ($PM_{2.5Cement}$). The annual value of $PM_{2.5Cement}$ decreased from 1.40×10^6 μg/m^3 in 2010 to 0.98×10^6 μg/m^3 in 2017, which was reduced by 30.31%. I used the standard deviation ellipse and gravity center transfer method and identified that the cement industry center shifted from the east to the midwest of China, where a high-density population exists and a large portion of the population is exposed to the air pollution. The geographical detector method was used to analyze the contribution of the natural environment, green development, and socioeconomic development to $PM_{2.5Cement}$. The main driving factors were identified as the socioeconomic development and the traffic conditions in 2010, which was giving way to the regional independent innovation in 2017. The cement industry's contributions to atmospheric $PM_{2.5}$ vary spatially, suggesting that green development and optimized location for the cement industry are crucial to reducing the size of the population exposed to the pollutants.

Keywords: air pollution; cement industry; $PM_{2.5}$; geographical detector

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1. Introduction

The cement industry is considered to be one of the energy, resource, CO_2, and pollutant emission-intensive sectors; the caused dust is a main component of air pollution [1], and its particles contributed 92.5% $PM_{2.5}$ and 61.0% PM_{10} [2]. In China, with high levels of $PM_{2.5}$ pollution and a large population, the harm is extensive and far-reaching, including sickness and economic burdens [3], high risks for cancer [4], increased morbidity and mortality of respiratory [5,6], rebrovascular diseases [7], and, even worse, the impact on children [8,9]. Meanwhile, the dust emitted by the cement industry is classified as "mixed dust", including silica, SO_2, and other elements [10,11]. Silica content in the air directly determines the probability of pneumoconiosis [12]. Mahlet [13] found that 50.8% of cement factory workers suffered from chronic respiratory symptoms. Meanwhile, types of aerodynamic noise generated during the operation of equipment in the cement industry causes irreversible sensorineural hearing damage [14,15]. In addition, dust emitted by the cement industry is mostly composed of alkaline, which can easily cause the alkalization of surrounding land and affects plant growth [16]. Moreover, in the production of building materials, cement can result in high CO_2 emissions that contribute to greenhouse gases' accumulation and cause environmental pollution [17,18], reducing essential short-term health benefits.

China is the world's largest cement producer and consumer (https://www.emis.com/, accessed on 12 March 2021) making up about 60% of global production (USGS, 2015). The pollutant emissions by the cement production are far higher than the air quality control standard [19–24]. The environmental pollution by the cement industry should not be underestimated under the requirement of advocating green development [25]. From 2013 to 2017, with the implementation of the toughest-ever clean air policy in China, significant declines in fine particle ($PM_{2.5}$) concentrations occurred nationwide [26,27], but it is still far below the international standards. Linked in 2017 in mainland China, premature deaths and a loss of quality of life due to $PM_{2.5}$, approximately a total of 852,000 and 19.98 million people, respectively, represented 30% of all victims worldwide [28]. Meanwhile, more cement output was demanded for infrastructure systems due to the ongoing urbanization in China. The conflict is inevitable between industrial development and environmental pollution [29].

In response, China launched the "Pollution Prevention and Control Battle" to control atmospheric pollution by focusing on limiting pollution emissions, adjusting industrial and energy structures, improving policies and regulations, exercising strict supervision and management, and strengthening scientific research [30–32]. The polluting industries seeking the "pollution refuge" phenomenon were evident in the local government department, where underdeveloped areas in the central and western regions accommodated portions of highly polluting industries from the eastern areas through "regional competition" and "policy depression." The industrial agglomeration and pollution antagonistic zones were dominated by polluting industries; environmental risks were the greatest in these areas [33]. Therefore, it remains unknown whether $PM_{2.5}$ concentration through cement production in China was significantly reduced or whether the drop was caused by regional transfer. More importantly, it is urgent to know what the main driving factors of such transfer are that should be formulated by region and pollutant industry to improve environmental quality. In this paper, I explore the cement industry in China and its spatial distribution of $PM_{2.5}$ and target and adopt more reasonable and precise policies to reduce air pollution caused by the cement industry. My purposes were to understand (1) the temporal and spatial patterns of the cement industry and their contribution to regional air quality and (2) the main factors driving the spatiotemporal distribution of the cement industry in different regions. This study can provide a guidance for formulating corresponding policies on the cement industry's layout in different regions and promoting clean production and green development.

2. Materials and Methods

2.1. Data Sources

$PM_{2.5}$ emission inventory data of cement production and PM2.5 emission inventory data of the whole department (http://www.meicmodel.org, accessed on 1 January 2021) and the spatial distribution of the cement industry (http://www.shuini.biz, accessed on 1 January 2021) during 2010–2017 in China were collected. Here, I chose 2010 and 2017 annual data to demonstrate the differences in $PM_{2.5}$ spatial and temporal distribution prior/after the air pollution control enforcement. From 2013 to 2017, to address the severe air pollution issues and protect public health, the State Council of China promulgated the toughest-ever Air Pollution Prevention and Control Action Plan (Action Plan) [34]. The national five-year plan (2013–2017) aims to decrease the concentrations of $PM_{2.5}$ by 10% by 2017 in populated regions and metropolises, compared to before 2013 [35]. The data cover 22 provinces, 5 autonomous regions, and 4 municipalities that are directly under the Central Government. In addition, the cement industry development is affected by regional social development level, policy, and innovation ability, and the pollution emissions are affected by pollution sources, pollution path, emission reduction, environmental purification capacity, pollution diffusion, vegetation coverage, meteorological conditions, and so on. Consequently, I analyzed the factors that are potentially responsible for the spatial and temporal changes of the cement industry from three aspects: natural factors, socioeconomic factors, and green development (Table 1).

Table 1. The 14 influencing factors for three types (natural factors, social economic factors, and green development). The effect shows the positive or negative effect on $PM_{2.5Cement}$.

Type	Indicator	Factor	Unit	Effect	The Data Source
Natural factors	Annual precipitation	X1	mm	−	China Meteorological Data Network (http://data.cma.cn/, accessed on 1 June 2021)
	Mean annual temperature	X2	°C	+	
	Annual sunshine hours	X3	0.1 h	−	
	Wind speed	X4	0.1 m/s	−	
	The green area	X5	ha	−	China Urban Statistical Yearbook (2011, 2016), China Provincial Statistical Yearbook (2011, 2016), China Environmental Statistical Yearbook (2011, 2016), China Environmental Statistical Yearbook (2011, 2016), China Urban and Rural Construction Statistical Yearbook (2011, 2016)
social economic factors	Gross regional Product (GDP)	X6	$\times 10^4$ Yuan (¥)	+	
	The proportion of secondary industry in GDP	X7	%	+	
	Labor force	X8	$\times 10^4$ (pers)	+	
	The length of the road	X9	km	+	
	Industrial smoke (powder) dust emission	X10	Tons	+	
	Comprehensive utilization rate of general industrial solid waste	X11	%	−	
Green development factors	Science and technology spending	X12	$\times 10^4$ Yuan (¥)	−	
	Green patent grant	X13	-	−	http://www.cnipa.gov.cn/, accessed on 1 June 2021
	Green patent filings	X14	-	−	

Green development policy can affect the distribution and output of cement enterprises and the discharge of pollutants. In the process of transportation, cement products will also cause serious dust hazards [18]. The comprehensive utilization rate of general industrial solid waste reflects the intensity of pollutant reduction. Gross Regional Product (labeled as GDP) and the secondary industry structure reflect the quality of regional economic development. The workforce reflects the potential for regional development. Vegetation coverage and atmospheric environment regulate the potential for atmospheric purification and pollutant diffusion in the region. The government's investment in science and technology is evident; the number of green patent applications and grants reflect the government's emphasis on green technology and the ability to improve pollution prevention and control, energy conservation, and emission reduction. Considering all the above factors, six parameters of socioeconomic factors, three green development factors, and five meteorological and natural factors were selected for every province in the study (Table 1).

2.2. Methods

2.2.1. $PM_{2.5}$ by Cement Industry

The Community Multiscale Air Quality (CMAQ) modeling system used in this study was developed by the U.S. Environmental Protection Agency [36–38] for air quality management and atmospheric research. The model represents atmospheric processes including emissions from anthropogenic and biogenic sources, meteorological transport, atmospheric chemical reactions, radiation, cloud processing, and deposition. Here, I evaluate the annual $PM_{2.5Cement}$ value and the percentage of $PM_{2.5Cement}$ in the atmosphere ($PPM_{2.5Cement}$). First, I used the CMAQ model to simulate the ambient air quality based on the emission inventory of 2010 and 2017, through which the annual average concentration of $PM_{2.5}$ was predicted by summing the emission inventory ($PM_{2.5total}$). Then the cement industry was removed from the emission inventory. The average annual concentration of $PM_{2.5}$ was not included in the emission of the cement industry ($PM_{2.5no\text{-}Cement}$). The formula is as follows:

$$PM_{2.5Cement} = PM_{2.5total} - PM_{2.5no-Cement} \tag{1}$$

$$PPM_{2.5Cement} = \frac{PM_{2.5Cement}}{PM_{2.5total}} \quad (2)$$

where $PM_{2.5Cement}$ is the annual contribution value of $PM_{2.5}$ from cement production; $PM_{2.5total}$ is the annual contribution value by totaling emission inventory; $PM_{2.5no\text{-}Cement}$ is the $PM_{2.5}$ excluding cement industry emission inventory; $PPM_{2.5Cement}$ is the percentage contribution of $PM_{2.5Cement}$ to $PM_{2.5total}$. I also used the standard deviation ellipse and gravity center transfer method [39] to explore the spatiotemporal changes in the cement industry between 2010 and 2017.

2.2.2. Geographic Detector Model

I used the Geographic detector model [40] to analyze the main factors affecting $PM_{2.5Cement}$. The model includes four detectors: factor detection, interaction detection, risk detection, and ecological detection. To achieve my study objectives, I chose factor detection and interaction detection, with factor detection defined as follows: to detect spatial association of the dependent variable Y($PM_{2.5Cement}$) and independent factor X_j (j = 1,2. . . 14). Here, the independent variable X was the natural factor, socioeconomic factor, and green development factor, and the formula is as follows:

$$q = 1 - \frac{\sum_{i=1}^{L} N_{i,j}\sigma_{i,j}^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \quad (3)$$

$$SSW = \sum_{i=1}^{L} N_{i,j}\sigma_{i.j}^2, \; SST = N\sigma^2 \quad (4)$$

where q is the explanatory strength of a given independent variable X_j on the dependent variable Y($PM_{2.5Cement}$), with a range of [0,1]; L represents the number of stratum of X variable; N and $N_{i,j}$ represent the size of sample in the whole study region and the i-th stratum of the j-th variable. A large value indicates a high degree of explanation, i.e., stronger effect of the independent variable X_i on the dependent variable Y. $\sigma_{i,j}{}^2$ and σ^2 are the variances of Y value in each stratum of j-th variable and whole region, respectively; SSW is the sum of squares, and SST is the total sum of the squares. The method has no linear or non-linear relationship assumption; it can only be used to measure the actual spatial association between two variables. Interaction detection is as follows: to judge the interaction effects of two factors on the $PM_{2.5Cement}$ value (q ($Xa_1 \cap X_b$)). The relationship between the two factors can be divided into the following categories (Table 2).

Table 2. Interaction detection by the Geographic detector model.

Criterion	Interaction
q ($X_a \cap X_b$) < Min (q (X_a), q (X_b))	Nonlinear weakening
Min(q(X_a), q(X_b))< Q($X_a \cap X_b$)< Max(q(X_a), q(X_b))	One factor nonlinear attenuation
q ($X_a \cap X_b$) > Max (q (X_a), q (X_b))	Two factor enhancement
q ($X_a \cap X_b$) = q (X_a) + q (X_b)	independent
q ($X_a \cap X_b$) > q (X_a) + q (X_b)	Nonlinear enhancement

Min(q(X_a), q(X_b)): select the minimum value at q(X_a) and q(X_b); q (X_a) + q(X_b): sum of q(X_a) and q(X_b); Max(q(X_a), q(X_b)): select the maximum value between q(X_a) and q(X_b); q ($X_a \cap$ Xb): q (X_a), q(X_b) both interact.

3. Results

3.1. Spatial and Temporal Characteristics of $PM_{2.5Cement}$

The annual total $PM_{2.5Cement}$ value was 1.40×10^6 µg/m^3 in 2010 and 0.98×10^6 µg/m^3 in 2017 for the study areas, which was decreased by 30.31%. The $PPM_{2.5Cement}$ decreased from 0.24% in 2010 to 0.21% in 2017. Spatially, the high annual $PM_{2.5Cement}$ were concentrated in the east and southwest (Figure 1a), and the high $PPM_{2.5Cement}$ measures were mainly found in the central region, western and eastern provinces, and Qinghai Provinces (Figure 2a) in 2010. Interestingly in Qinghai provinces, although its $PPM_{2.5Cement}$ value was the highest (1.22%, 1.35%) in all provinces in the two years, the annual $PM_{2.5Cement}$ was only 23,463 $\mu g/m^3$ in 2010 and 20,115 $\mu g/m^3$ in 2017, and it ranked 18th in the 31 study regions (Figure 4). Then I used the annual $PM_{2.5Cement}$ value to range segmentation. In 2010, there were eight provinces with $PM_{2.5Cement}$ > 60,000 $\mu g/m^3$, including Hunan ($PM_{2.5Cement}$, 20,152.8 $\mu g/m^3$, $PPM_{2.5Cement}$, 0.56%), Anhui (17,247.2 $\mu g/m^3$, 0.55%), Jiangsu (85,846 $\mu g/m^3$, 0.40%), Zhejiang (76,522.03 $\mu g/m^3$, 0.68%), Sichuan (73,124.01 $\mu g/m^3$, 0.21%), Shandong (68,368$\mu g/m^3$, 0.18%), Yunnan (63,530 $\mu g/m^3$, 0.38%), Hebei (60,344 $\mu g/m^3$, 0.20%); in seven provinces, the $PM_{2.5Cement}$ was between 40,000–60,000 $\mu g/m^3$, which can be ordered as follows: Hubei, Shanxi, Liaoning, Fujian, Jilin, Henan, Chongqing. The area with an annual $PM_{2.5Cement}$ between 20,000–40,000 $\mu g/m^3$ covered seven provinces, which can be ordered as follows: Guangxi, Guangdong, Gansu, Jiangxi, Shanxi, Xinjiang, Qinghai. Provinces with an annual $PM_{2.5Cement}$ value between 0–20,000 $\mu g/m^3$ included Inner Mongolia, Guizhou, Ningxia, Heilongjiang. Provinces with the lowest the annual $PM_{2.5Cement}$ value were Beijing, Shanghai, Tianjin, Hainan province, and Tibet Autonomous Region (Figures 1a and 2a).

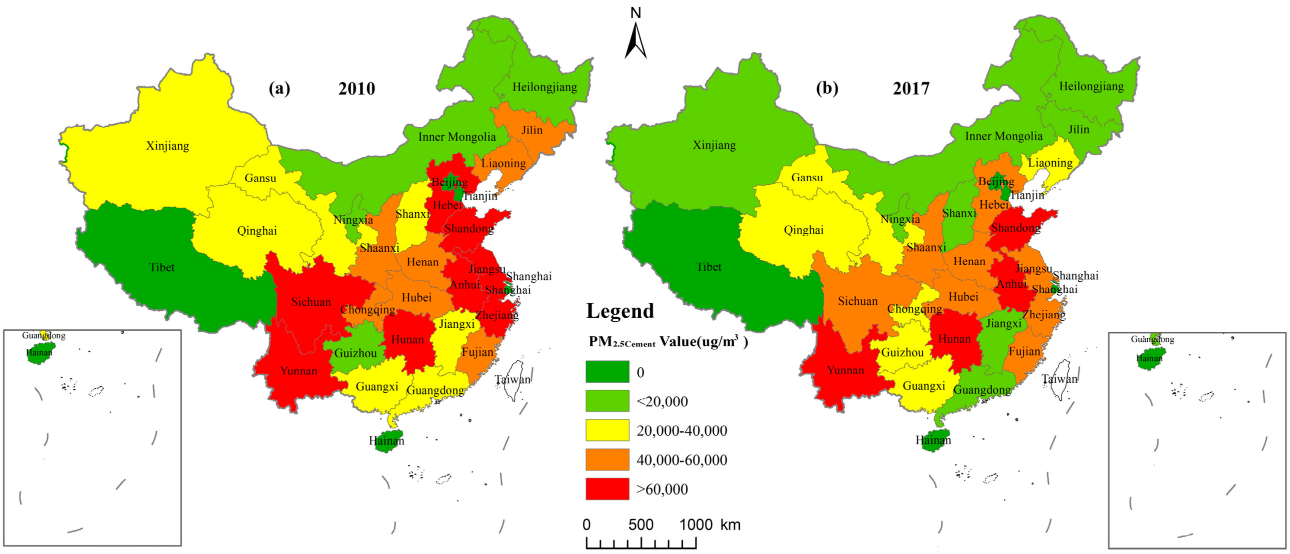

Figure 1. Spatial distribution of the annual $PM_{2.5Cement}$ in 2010 and 2017.

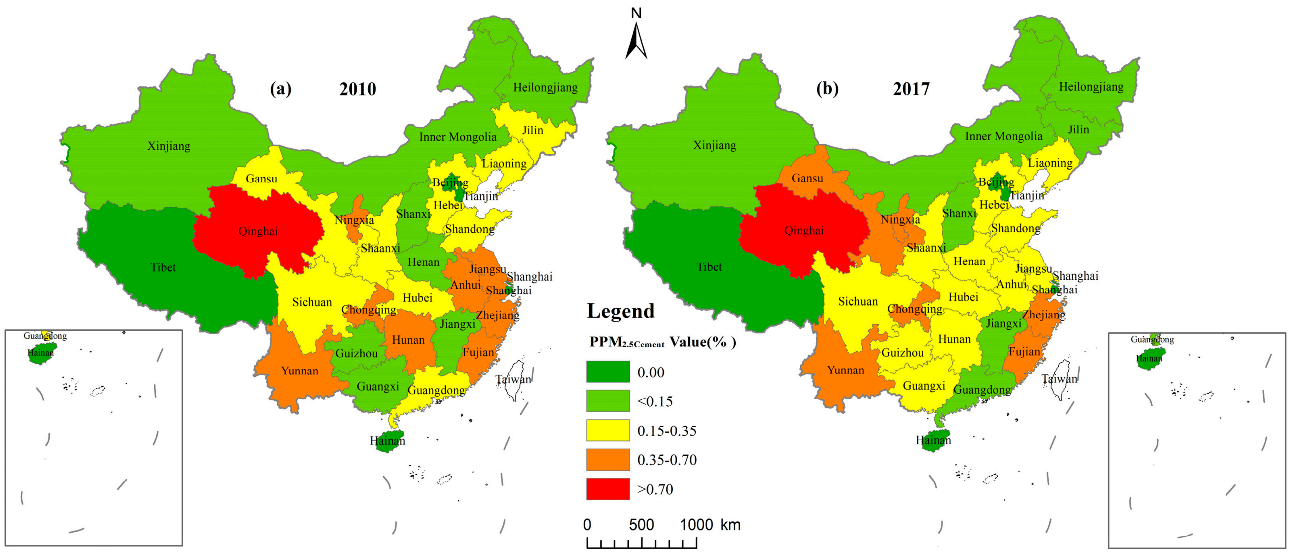

Figure 2. Spatial distribution of the $PPM_{2.5Cement}$ in 2010 and 2017.

The annual $PM_{2.5Cement}$ in 2017 showed a decreasing trend compared with 2010 (Figure 4A). The region with high $PM_{2.5Cement}$ value shifted to the midwest region (Figure 1b), and the high $PPM_{2.5Cement}$ value also migrated to the northwest (Figure 2b). The number of provinces with $PM_{2.5Cement}$ > 60,000 μg/m^3 decreased from seven in 2010 to four in 2017. The four provinces included Hunan (76,120 μg/m^3, 0.28%), Anhui (74,786 μg/m^3, 0.31%), Yunnan (70,200 μg/m^3, 0.55%), and Shandong (62,456 μg/m^3, 0.22%). The $PM_{2.5Cement}$ value in Hunan and Anhui decreased from 125,408 μg/m^3 to 97,686 μg/m^3 from 2010 to 2017 (Figure 4A), and their $PPM_{2.5Cement}$ values decreased by 0.28% and 0.24%, respectively (Figure 4B). However, Shandong and Yunnan provinces showed a slightly decreasing trend, indicating that the cement industry was still a very severe air pollution emission source. For Jiangsu, Zhejiang, Sichuan, and Hebei provinces, the annual $PM_{2.5Cement}$ value dropped to 40,000–60,000 μg/m^3. There were eight provinces in this value range and another four provinces were Hubei, Henan, Shaanxi, and Fujian. Six provinces were in the range between 20,000–40,000 μg/m^3, including Chongqing, Guangxi, Gansu, Liaoning, Guizhou, Qinghai. Eight provinces were in the range of 0–20,000 μg/m^3, including Xinjiang, Ningxia, Guangdong, Shanxi, Jiangxi, Inner Mongolia, Jilin, Heilongjiang. No $PM_{2.5Cement}$ value was provided for Beijing, Shanghai, Tianjin, Hainan province, and Tibet Autonomous Region (Figure 1b).

3.2. Gravity Center Transfer of the Cement Industry

The standard deviation ellipse and gravity center transfer analysis showed that the $PM_{2.5Cement}$ center of gravity shifted 100.8 km from east to west, and the $PPM_{2.5Cement}$ center shifted 120.8 km from southeast to northwest (Figure 3) from 2010 to 2017, which reflected that the cement industry in China migrated to the midwest region from the eastern region during 2010 and 2017. The spatial shift might be related to air quality control and a change in the industrial structure policy in China. The gravity center transfer analysis also illustrates that midwestern people were more exposed to environmental pollution from the cement industry.

Figure 3. The standard deviation ellipse and gravity center migration for $PM_{2.5Cement}$ and $PPM_{2.5Cement}$ during 2010 and 2017.

The $PPM_{2.5Cement}$ was the highest in Qinghai among the region, with a value of 1.22% in 2010 and 1.35% in 2017 (Figure 4B). The $PPM_{2.5Cement}$ in 2017 was slightly higher than that in 2010, but its annual $PM_{2.5Cement}$ value was down from 23,463.5 μg/m^3 in 2010 to 20,115.13 μg/m^3 in 2017 (Figure 4A). Except the no-emission source regions, the lowest annual $PM_{2.5Cement}$ ($PPM_{2.5Cement}$) was found for Heilongjiang in both years; the value was 13,164 μg/m^3 ($PPM_{2.5Cement}$, 0.03%) in 2010 and 7828 μg/m^3 (0.02%) in 2017 (Figure 4). The $PM_{2.5Cement}$ value dropped more than 40% during this period. With China's transformation from extensive to intensive development during 2010–2017 and with it supervised by the stringent pollution control measures since 2013, $PM_{2.5Cement}$ in each province has decreased to some extent, but the magnitude is limited to minimal decreases, except larger decreases in Hunan and Anhui.

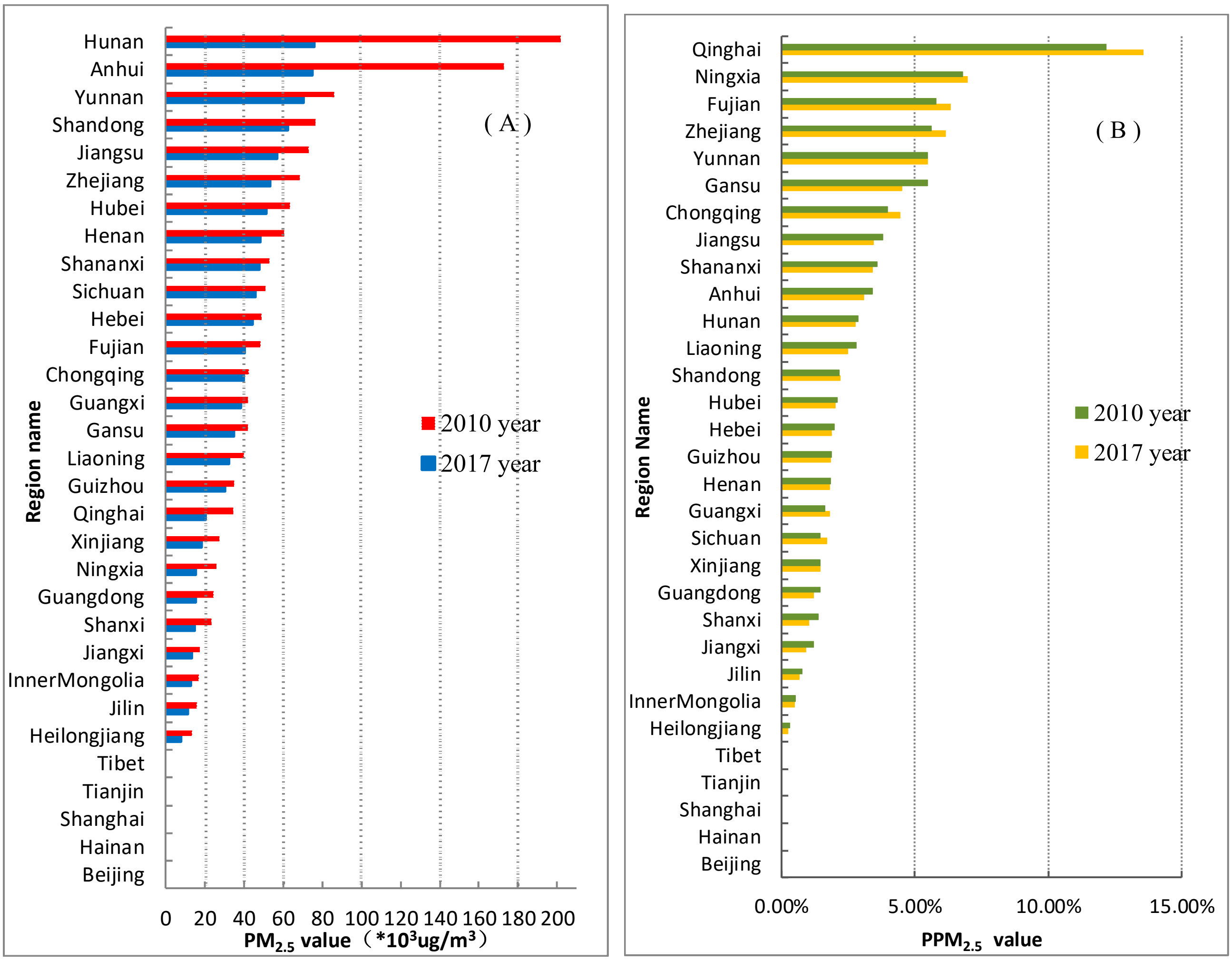

Figure 4. The annual $PM_{2.5Cement}$ value (**A**) and $PPM_{2.5Cement}$ value (**B**) of each province in the study area in 2010 and 2017.

3.3. Geographical Dtection of Driving Factors

3.3.1. Influence of Detection Factor

The explanatory intensity of $PM_{2.5Cement}$ based on factor detection (q value) includes 14 factors. According to the q value classification, the explanatory intensity in 2010 was GDP (0.57) > the proportion of secondary industry (0.47) > the road length (0.42) > the number of labor (0.38) > the industrial smoke (powder) dust emission (0.37) > the sunshine duration (0.36) > the air temperature (0.35) > the number of green patents (−0.34) > the Green patent application (−0.32) > the green area (−0.32) > the rainfall (−0.29) > the science and technology expenditure (−0.27) > the wind speed (−0.19) > the comprehensive utilization rate of general industrial solid waste (−0.11) (Table 1, Figure 5).

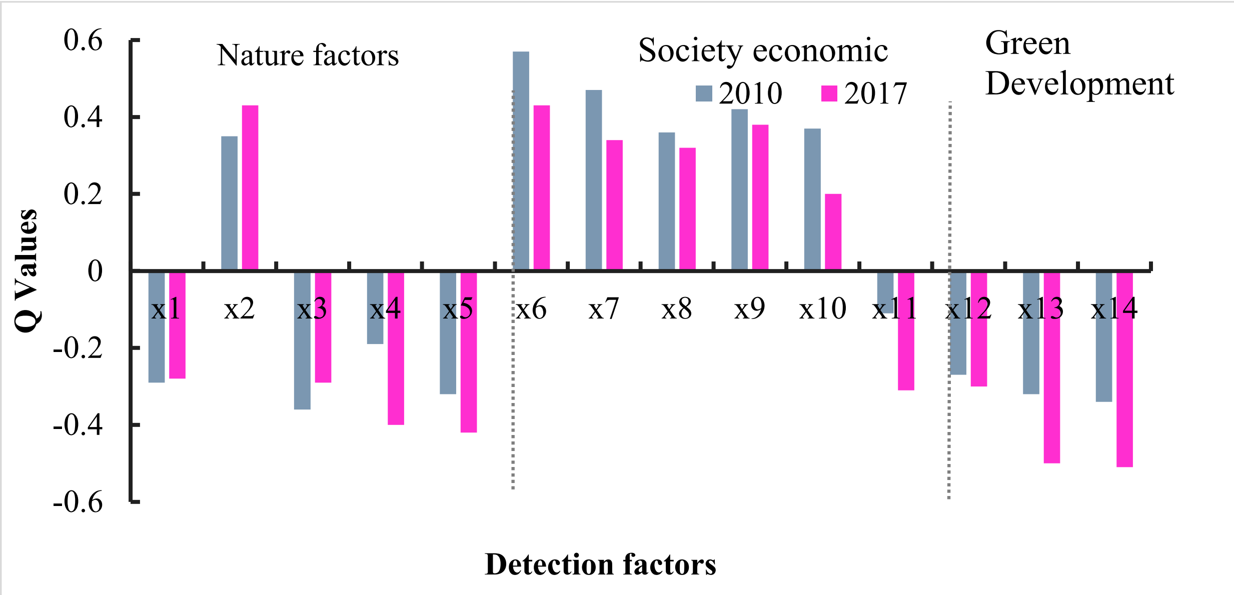

Figure 5. The geographic detector model analysis on the contribution of each single factor to regional $PM_{2.5Cement}$. x1…x14 were the 14 factors for natural, society economical, and green development aspects in Table 1.

In 2017, ranking order on contribution of each factor was the green patent authorization (−0.51) > the green patent application (−0.50) > the GDP (0.43) > the air temperature (0.43) > the green area (−0.42) > the wind speed (−0.40) > the road area at the end of the year (0.38) > the proportion of secondary industry (0.34) > the number of the labor force (0.32) > the comprehensive utilization rate of general industrial solid waste (−0.31) > the science and technology expenditure (−0.30) > the rainfall (−0.28) > the sunshine duration (−0.29) > the industrial smoke (powder) dust emission (0.20) (Table 1). From 2010 to 2017, with the change in China's development mode and the regional government's mounting attention to green technology, the strengthened pollution prevention and control, energy conservation, as well as the emission reduction, the cement industry's emissions of air pollutants have relieved (Figure 5).

I also analyzed factor detection results (q value) for each region and found there existed high variations (Table 3). In 2010, for the eight provinces with $PM_{2.5Cement}$ > 60,000 µg/m^3, the top three factors with the highest explanation were the industrial smoke (powder) dust emission (0.72) > GDP (0.53) > the secondary industry (0.44), and the three factors with the lowest explanation were road length (0.07) < wind speed (0.13) < air temperature < (0.16). In 2017, the three factors with the highest q value were industrial smoke (powder) dust emission (0.59) > road length (0.58) > proportion of secondary industry (0.55), and the three factors with the lowest q value were the sunshine duration (0.05) < rainfall (0.17) < science and technology expenditure (0.21). For the $PM_{2.5Cement}$ between 40,000–60,000 µg/m^3, in 2010, the three factors with the highest q value were GDP (0.82) > road length (0.76) > the green space area (0.74), and the three factors with the lowest q value were the temperature (0.13) < rainfall (0.18) < the sunshine duration (0.28). In 2017, the three factors with the highest q value were GDP (0.70) > the comprehensive utilization rate of general industrial solid waste (0.69) > the number of green patents granted (0.61), and the three factors with the lowest q value were meteorological factors: sunshine duration (0.13) < wind speed (0.17) < rainfall (0.18). For $PM_{2.5Cement}$ < 40,000 µg/m^3, the results showed similar explanatory strength. In 2010, factors with the highest q value were GDP (0.85) > the industrial smoke (powder) dust emission (0.84) > the general industrial solid waste comprehensive utilization rate (0.73), and those with the lowest q value were the sunshine duration (0.01) < the rainfall (0.20) < the number of the green patent application and green patent grant (0.21). In 2017, factors with the largest q value were the road length (0.95), the industrial dust emission (0.95) > GDP (0.89), and the three factors with the least q value were the sunshine duration (0.18) < the air temperature (0.19) < the number of green patents granted (0.26) (Table 3).

Table 3. Differentiation and factor detection from the Geographic detector model. The Effect (+/−) was the promoting or inhibiting factors.

Indicators (I)	Indicators (II)	Factors	Effect	q Value of Factors in Different $PM_{2.5Cenment}$ Value Class <40,000		40,000–60,000		>60,000	
				2010	2017	2010	2017	2010	2017
Natural factors	Annual precipitation	X1	−	0.2	0.31	0.18	0.18	0.31	0.17
	Mean annual temperature	X2	+	0.24	0.19	0.13	0.52	0.16	0.24
	Annual sunshine hours	X3	−	0.01	0.18	0.28	0.13	0.43	0.05
	Wind speed	X4	−	0.51	0.64	0.32	0.17	0.13	0.27
	The green area	X5	−	0.62	0.73	0.74	0.6	0.31	0.46
Social economic factors	Gross regional Product (GDP)	X6	+	0.85	0.89	0.82	0.7	0.53	0.48
	The proportion of secondary industry in GDP	X7	+	0.52	0.65	0.36	0.34	0.44	0.55
	Labor force	X8	+	0.61	0.83	0.68	0.3	0.43	0.51
	The length of the road	X9	+	0.71	0.95	0.76	0.27	0.07	0.58
	Industrial smoke (powder) dust emission	X10	+	0.84	0.95	0.55	0.27	0.72	0.59
	Comprehensive utilization rate of general industrial solid waste	X11	−	0.63	0.41	0.52	0.69	0.36	0.49
Green development factors	Science and technology spending	X12	−	0.61	0.83	0.36	0.39	0.28	0.21
	Green patent grant	X13	−	0.21	0.27	0.48	0.53	0.36	0.39
	Green patent filings	X14	−	0.21	0.26	0.34	0.61	0.33	0.47

3.3.2. Interactive Factors

Based on the geospatial characteristics of each driving factor, I used the interaction detection module to analyze the explanatory intensity of $PM_{2.5Cement}$ by driving factor. The q value increased after including the interaction of any two factors. Specifically for the natural environment factors in 2010, the q value gained the greatest increases (0.48, 0.55, 0.57, 0.49) for the green space area interaction with the other four factors, followed by interactions between wind speed and sunshine duration (0.48), air temperature and sunshine duration (0.48) (Table 4). In 2017, the interaction between wind speed and the other four factors enhanced the explanatory intensity, and the q value increased to 0.59, 0.55, 0.59, 0.72, respectively, followed by interactions of sunshine duration and temperature (Table 4). For the green development factors, the q value strength in 2010 increased after including the interaction between science and technology input, such as the factors of the green patent application volume, and the green patent grant volume were 0.72 and 0.65, respectively (Table 5). In 2017, including the interaction between science and technology input and the other two factors also increased the explanatory strength (Table 5). For socioeconomic factors, including the combined effect of GDP and road length increased the q value to 0.85. Including the proportion of secondary industry and the road length increased the q value to 0.82, and including the labor force and industrial smoke (powder) dust emission increased the q value to 0.76. For other factors, including their interactions, all increased the q value (Table 6).

Table 4. Interaction effects of the natural environmental factors on $PM_{2.5Cement}$. The gray shaded items are the top three values in year. X1. . . 54 are the Natural factors found in Table 1.

Natural Factors	**2010**					**2017**				
	X1					X1				
X1	0.29	X2				0.28	X2			
X2	0.44	0.37	X3			0.43	0.45	X3		
X3	0.46	0.48	0.35	X4		0.57	0.55	0.43	X4	
X4	0.42	0.46	0.48	0.2	X5	0.59	0.55	0.59	0.4	X5
X5	0.48	0.55	0.57	0.49	0.32	0.47	0.51	0.54	0.72	0.42

Table 5. Interaction effects of Green Development factors on $PM_{2.5Cement}$. The gray shaded items are the top three values in the two years. X12–14 are the Green Development factors found in Table 1.

Green Development Factors	**2010**			**2017**		
	X12			X12		
X12	0.27	X13		0.3	X13	
X13	0.72	0.32	X14	0.6	0.5	X14
X14	0.65	0.48	0.34	0.58	0.52	0.51

Table 6. Interaction effects of the Social economic factors on $PM_{2.5Cement}$. The gray shaded items are the top three values in the two years. X6–11 are the Social economic factors found in Table 1.

Social Economic Factors	**2010**						**2017**					
	X6						X6					
X6	0.57	X7					0.44	X7				
X7	0.65	0.47	X8				0.75	0.34	X8			
X8	0.56	0.71	0.36	X9			0.54	0.79	0.33	X9		
X9	0.85	0.82	0.54	0.43	X10		0.59	0.82	0.53	0.38	X10	
X10	0.7	0.66	0.76	0.71	0.37	X11	0.68	0.71	0.73	0.78	0.2	X11
X11	0.59	0.35	0.72	0.6	0.46	0.13	0.65	0.86	0.62	0.73	0.86	0.31

Except in 2017, the interaction between GDP and other factors did not enhance explanatory strength. The highest q value was the interaction between the proportion of the secondary industry and the comprehensive utilization rate of general industrial solid waste (0.86), the comprehensive utilization rate of general industrial solid waste, and industrial smoke (powder) dust emissions (0.86). The second highest was interactions between road length and the proportion of the secondary industry (0.83). Clearly, interactions with other factors also increased the q value (Table 6).

4. Discussion

The rapid development of China's industrial economy has caused serious pollution; the Chinese government has been investing mounting efforts on environmental protection [5,41–43]. In 2013, China reinforced national air quality monitoring [44,45]. The $PM_{2.5}$ values, as an important air quality index, was included in the emissions standards. Although, it is a very complex process to determine the source of $PM_{2.5}$ in the atmosphere [41], attributing its sources and revealing its spatial pattern are vital for implementing prevention and control measures [46]. The cement production, as a basic supporting material in urbanization construction, is also a heavy industry with high energy consumption and high pollution. One needs to weigh its impact on the ecological environment, which is directly related to sustainable development.

Here, I quantified the temporal and spatial patterns of the cement industry and atmospheric $PM_{2.5Cement}$ content in two typical years, 2010 and 2017 (before and after the national

$PM_{2.5}$ control). Overall, the annual $PM_{2.5Cement}$ value decreased 30.31% from 2010 to 2017, as a number of cement-related environmental protections and energy saving policies were introduced since 2013, such as the "Technical Policy of Pollution Control in Cement Industry" by the Ministry of Environmental Protection, which has greatly increased the operation cost of the backward production capacity of the cement industry and has reflected the environmental protection requirements in a market-oriented way that affects the price of production factors of enterprises and "forced" industrial transformation and upgrading, structural adjustment, and optimization of the layout, but the reduction magnitudes vary greatly among each province. Hunan and Anhui provinces have witnessed a significant reduction, with a declining rate of 62.23% and 56.64%, respectively. The decreasing values are in line with other studies [21,47,48], in which the implementation of environmental protection policies by the central government are considered, strict emission reform policy for cement enterprises, closure of small and medium-sized cement enterprises, the transformation and upgrading of large enterprises, which were also the main factors for reducing pollution. The decreasing rate for other provinces appeared small, especially for Shandong, Yunnan, Hubei, Shanxi, Sichuan, and Hebei provinces. The main reason is that these provinces play a key role in China's cement production, and they are obligated to improve energy efficiency and reduce air pollution. In addition, the $PPM_{2.5\mathrm{Cement}}$ also varies greatly among provinces. Qinghai, Ningxia, Fujian, Zhejiang, and Chongqing have seen increasing trends of $PPM_{2.5\mathrm{Cement}}$ from 2010 to 2017. These provinces play a key role in China's cement production and have great potential to improve energy efficiency and reduce air pollution.

The cement industry's gravity center shifted from the east to the midwest (Figure 4), to places such as Hunan, Hubei, Sichuan, Shanxi, Guizhou, Henan, Shandong provinces, and so on. This conclusion was consistent with previous studies [49,50]. These regions are all highly populated. Transitioning to green production of cement may be the most efficient way to balance economic development and human well-being [17,42,51,52].

There are great differences in the socioeconomic development levels and the natural environment in each province. The geographic detector model analysis shows that, for the natural factors, only the contribution of green space area was relatively large in the two study years. For the social economic factors, GDP and the second industry area play an important role, which shows that the regional economy and industry regulate the regional cement industry layout. In addition, industrial smoke dust emissions (powder) were also important explanatory variables. The cement industry is the second greatest industry of heavy pollution industries. The rapid social development in China and the increasing demand for cement have added to the regional tolerance for the cement industry. Interestingly, in 2017, road length boosted regional $PM_{2.5Cement}$, and long-distance transportation increased air pollutants. Meanwhile, the q value increased when an interaction of any two factors was considered based on the geospatial characteristics of each driving factor. The three factors of green development showed a higher contribution value in 2017 than that in 2010. It meant that green development has become the main driving force in reducing air pollution in the cement industry. This change is conducive to the sustainable development of the cement industry in China [17,37,41].

5. Conclusions

I analyzed the contribution of the cement industry to $PM_{2.5}$ in each province in China and examined the gravity center shift and the main driving factors on the annual $PM_{2.5\mathrm{Cement}}$ in each province based on their natural, green development, and socioeconomic environments. I found that the annual $PM_{2.5Cement}$ value of all provinces showed a decreased trend from 2010 to 2017, especially in Hunan and Anhui, but the decreasing was slight in other regions. Even $PPM_{2.5Cement}$ for each region was not significantly decreasing, especially in Qinghai, Ningxia, Fujian, and Zhejiang regions, and some of them even saw a slight increase. It seems that the influence of the cement industry on air quality in these regions was still very severe. The cement industry's center of gravity shifted from the east to the midwest of China, which has a large population exposed to the dangers of air pollution. The driving factors analysis showed that social economic development was the main driving factor for the $PM_{2.5Cement}$ in 2010; the main driving factors in 2017, however, changed to green development, regional independent innovation ability, and traffic conditions, while meteorological environment play a less influential role in the two years. At the same time, the contributions of the cement industry to atmospheric $PM_{2.5}$ varies spatially. The cement production process needs to be further refined to minimize pollution effects.

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References

1. Branquinho, C.; Gaio-Oliveira, G.; Augusto, S.; Pinho, P.; Maguas, C.; Correia, O. Biomonitoring spatial and temporal impact of atmospheric dust from a cement industry. *Environ. Pollut.* **2008**, *151*, 292–299. [CrossRef] [PubMed]
2. Koh, D.H.; Kim, T.W.; Jang, S.; Ryu, H.W. Dust exposure and the risk of cancer in cement industry workers in Korea. *Am. J. Ind. Med.* **2013**, *56*, 276–281. [CrossRef]
3. Lian, L.; Chen, S.; Ma, J.; Li, T.; Yang, Y.; Huang, T.; Wang, Y.; Li, J. Population aging driven slowdown in the reduction of economic cost-Attributed to $PM_{2.5}$ Pollution after 2013 in China. *Environ. Sci. Technol.* **2023**, *57*, 1237–1245.
4. Cao, W.; Wang, X.; Li, J.L.; Yan, M.; Chang, C.H.; Kim, J.; Jiang, J.H.; Liao, Y.P.; Tseng, S.; Kusumoputro, S.; et al. NLRP3 inflammasome activation determines the fibrogenic potential of PM2.5 air pollution particles in the lung. *J. Environ. Sci.* **2022**, *111*, 429–441. [CrossRef] [PubMed]
5. Liang, S.L.; Zhao, X.; Liu, S.H.; Yuan, W.P.; Cheng, X.; Xiao, Z.Q.; Zhang, X.T.; Liu, Q.; Cheng, J.; Tang, H.R.; et al. A long-term Global LAnd Surface Satellite (GLASS) data-set for environmental studies. *Int. J. Digit. Earth* **2013**, *6*, 5–33. [CrossRef]
6. Chen, J.Q.; Zhu, L.; Fan, P.; Tian, L.; Raffaele, L. Do green spaces affect the spatiotemporal changes of $PM_{2.5}$ in Nanjing? *Ecol. Process.* **2016**, *5*, 7. [CrossRef] [PubMed]
7. Qin, Y.; Wagner, F.; Scovronick, N.; Peng, W.; Yang, J.N.; Zhu, T.; Smith, K.R.; Mauzerall, D.L. Air quality, health, and climate implications of China's synthetic natural gas development. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 4887–4892. [CrossRef] [PubMed]
8. Mohammed, M.O.A.; Song, W.W.; Ma, W.L.; Li, W.L.; Li, Y.F.; Khan, A.U.; Ibrahim, M.A.E.M.; Maarouf, O.A.; Ahmed, A.A.; Ambuchi, J.J. Potential Toxicological and Cardiopulmonary Effects of PM2.5 Exposure and Related Mortality: Findings of Recent Studies Published during 2003-2013. *Biomed. Environ. Sci.* **2016**, *29*, 66–79. [CrossRef] [PubMed]
9. Tian, L.; Hou, W.; Chen, J.; Chen, C.; Pan, X. Spatiotemporal Changes in PM2.5 and Their Relationships with Land-Use and People in Hangzhou. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2192. [CrossRef]
10. Rahmani, A.H.; Almatroudi, A.; Babiker, A.Y.; Khan, A.A.; Alsahly, M.A. Effect of exposure to cement dust among the workers: An evaluation of health related complications. *Open Access Maced. J. Med. Sci.* **2018**, *6*, 1159–1162. [CrossRef]
11. Hu, Y.; Zang, Z.; Chen, D.; Ma, X.; Liang, Y.; You, W.; Pan, X.; Wang, L.; Wang, D.; Zhang, Z. Optimization and evaluation of SO2 emissions based on WRF-Chem and 3DVAR Data assimilation. *Remote Sens.* **2022**, *14*, 220. [CrossRef]
12. Chu, M.J.; Wu, S.S.; Wang, W.; Yu, Y.H.; Zhang, M.J.; Sang, L.L.; Tian, T.; Lu, Y.H.; Yuan, W.W.; Huang, Q.Q.; et al. Functional variant of the carboxypeptidase M (CPM) gene may affect silica- related pneumoconiosis susceptibility by its expression: A multistage case-control study. *Occup. Environ. Med.* **2019**, *76*, 169–174. [CrossRef] [PubMed]
13. Mahlet, M.; Alemayehu, H.; Tamrat, S.; Seid, A.M. Emission level of $PM_{2.5}$ and its association with chronic respiratory symptoms among workers in cement industry: A case of mugher cement industry, central ethiopia. *Avicenna J. Environ. Healthc. Eng.* **2018**, *5*, 1–7.
14. Ekinci, E.; Kazancoglu, Y.; Mangla, S.K. Using system dynamics to assess the environmental management of cement industry in streaming data context. *Sci. Total Environ.* **2020**, 715. [CrossRef] [PubMed]
15. Sleight, R.B.; Tiffin, J. Industrial noise and hearing. *J. Appl. Psychol.* **1948**, *32*, 476. [CrossRef]
16. Caravaca, F.; Lozano, Z.; Rodriguez-Caballero, G.; Roldan, A. Spatial Shifts in Soil Microbial Activity and Degradation of Pasture Cover Caused by Prolonged Exposure to Cement Dust. *Land Degrad. Dev.* **2017**, *28*, 1329–1335. [CrossRef]
17. Marques, M.; Neves-Silva, R. Decision support for energy savings and emissions trading in industry. *J. Clean. Prod.* **2015**, *88*, 105–115. [CrossRef]

18. Zhang, C.Y.; Yu, B.Y.; Chen, J.M.; Wei, Y.M. Green transition pathways for cement industry in China. *Resour. Conserv. Recycl.* **2021**, *166*, 105355. [CrossRef]
19. Chopping, M.; North, M.; Chen, J.Q.; Schaaf, C.B.; Blair, J.B.; Martonchik, J.V.; Bull, M.A. Forest Canopy Cover and Height From MISR in Topographically Complex Southwestern US Landscapes Assessed With High Quality Reference Data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2012**, *5*, 44–58. [CrossRef]
20. Mbelambela, E.P.; Eitoku, M.; Muchanga, S.M.J.; Villanueva, A.F.; Hirota, R.; Pulphus, T.Y.; Sokolo, G.J.; Yasumitsu-Lovell, K.; Komori, K.; Suganuma, N. Prevalence of chronic obstructive pulmonary disease (COPD) among Congolese cement workers exposed to cement dust, in Kongo Central Province. *Environ. Sci. Pollut. Res.* **2018**, *25*, 35074–35083. [CrossRef]
21. Li, M.; Zhang, Q.; Kurokawa, J.; Woo, J.H.; He, K.B.; Lu, Z.F.; Ohara, T.; Song, Y.; Streets, D.G.; Carmichael, G.R.; et al. MIX: A mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. *Atmos. Chem. Phys.* **2017**, *17*, 935–963. [CrossRef]
22. Zhang, S.H.; Worrell, E.; Crijns-Graus, W.; Krol, M.; de Bruine, M.; Geng, G.P.; Wagner, F.; Cofala, J. Modeling energy efficiency to improve air quality and health effects of China's cement industry. *Appl. Energy* **2016**, *184*, 574–593. [CrossRef]
23. Xu, J.H.; Fleiter, T.; Fan, Y.; Eichhammer, W. CO2 emissions reduction potential in China's cement industry compared to IEA's Cement Technology Roadmap up to 2050. *Appl. Energy* **2014**, *130*, 592–602. [CrossRef]
24. Lei, Y.; Zhang, Q.A.; Nielsen, C.; He, K.B. An inventory of primary air pollutants and CO2 emissions from cement production in China, 1990-2020. *Atmos. Environ.* **2011**, *45*, 147–154. [CrossRef]
25. Meng, J.; Liu, J.F.; Xu, Y.; Tao, S. Tracing Primary PM2.5 emissions via Chinese supply chains. *Environ. Res. Lett.* **2015**, *10*, 054005. [CrossRef]
26. Li, M.G.; Wang, L.L.; Liu, J.D.; Gao, W.K.; Song, T.; Sun, Y.; Li, L.; Li, X.R.; Wang, Y.H.; Liu, L.L.; et al. Exploring the regional pollution characteristics and meteorological formation mechanism of PM2.5 in North China during 2013-2017. *Environ. Int.* **2020**, *134*, 105283. [CrossRef] [PubMed]
27. Zhang, S.; Xie, Y.; Robet, S.; Yue, H.; Shu, Y. Potentials of energy efficiency improvement and energy–emission–health nexus in Jing-Jin-Ji's cement industry. *J. Clean. Prod.* **2021**, *278*, 123335. [CrossRef]
28. Roth, G.A.; Abate, D.; Abate, K.H.; Abay, S.M.; Abbafati, C.; Abbasi, N.; Abbastabar, H.; Abd-Allah, F.; Abdela, J.; Abdelalim, A. Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: A systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **2018**, *392*, 1736–1788. [CrossRef]
29. Han, F.; Li, J. Spatial Pattern and Spillover of Abatement Effect of Chinese Environmental Protection Tax Law on PM2.5 Pollution. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1440. [CrossRef]
30. Huang, J.; Pan, X.; Guo, X.; Li, G. Health impact of China's Air Pollution Prevention and Control Action Plan: An analysis of national air quality monitoring and mortality data. *Lancet Planet. Health* **2018**, *2*, 313–323. [CrossRef]
31. Liu, T.; Cai, Y.; Feng, B.; Cao, G.; Lin, H.; Xiao, J.; Li, X.; Liu, S.; Pei, L.; Fu, L. Long-term mortality benefits of air quality improvement during the twelfth five-year-plan period in 31 provincial capital cities of China. *Atmos. Environ.* **2018**, *173*, 53–61. [CrossRef]
32. Sun, D.; Fang, J.; Sun, J. Health-related benefits of air quality improvement from coal control in China: Evidence from the Jing-Jin-Ji region. *Resour. Conserv. Recycl.* **2018**, *129*, 416–423. [CrossRef]
33. Li, G.; Fang, C.; Wang, S.; Sun, S. The effect of economic growth, urbanization, and industrialization on fine particulate matter (PM2.5) concentrations in China. *Environ. Sci. Technol.* **2016**, *50*, 11452–11459. [CrossRef] [PubMed]
34. The State Council of China. China's National Action Plan on Air Pollution Control. State Counc China. 2013. Available online: http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm (accessed on 12 March 2021).
35. Wang, Y.H.; Gao, W.K.; Wang, S.; Song, T.; Gong, Z.Y.; Ji, D.S.; Wang, L.L.; Liu, Z.R.; Tang, G.Q.; Huo, Y.F.; et al. Contrasting trends of PM2.5 and surface-ozone concentrations in China from 2013 to 2017. *Natl. Sci. Rev.* **2020**, *7*, 1331–1339. [CrossRef] [PubMed]
36. U.S. EPA. *EPA's Incident Waste Management Planning and Response Tool*; US Environmental Protection Agency: Washington, DC, USA, 2017; *Report Number EPA/600/S-17/184.31*.
37. Zhang, R.; Ma, Y.; Ren, J. Green Development Performance Evaluation Based on Dual Perspectives of Level and Efficiency: A Case Study of the Yangtze River Economic Belt, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9306. [CrossRef]
38. Byun, D.; Schere, K.L. Review of the governing equations, computational algorithms, and other components of the models-3 Community Multiscale Air Quality (CMAQ) modeling system. *Appl. Mech. Rev.* **2006**, *59*, 51–77. [CrossRef]
39. Zheng, G.H.; Jiang, D.F.; Luan, Y.F.; Yao, Y. GIS-based spatial differentiation of ethnic minority villages in Guizhou Province, China. *J. Mt. Sci.* **2022**, *19*, 987–1000. [CrossRef]
40. Wang, J.f.; Xu, C.D. Geodetector: Principle and prospective. *Acta Geogr. Sin.* **2017**, *72*, 116–134.
41. Lu, J.Y.; Cao, X. PM2.5 Pollution in Major Cities in China: Pollution Status, Emission Sources and Control Measures. *Fresenius Environ. Bull.* **2015**, *24*, 1338–1349.
42. Talaei, A.; Pier, D.; Iyer, A.V.; Ahiduzzaman, M.; Kumar, A. Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation options for the cement industry. *Energy* **2019**, *170*, 1051–1066. [CrossRef]
43. Zheng, Y.X.; Xue, T.; Zhang, Q.; Geng, G.N.; Tong, D.; Li, X.; He, K.B. Air quality improvements and health benefits from China's clean air action since 2013. *Environ. Res. Lett.* **2017**, *12*, 114020. [CrossRef]
44. Zhang, Q.; Streets, D.G.; Carmichael, G.R.; He, K.B.; Huo, H.; Kannari, A.; Klimont, Z.; Park, I.S.; Reddy, S.; Fu, J.S.; et al. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos. Chem. Phys.* **2009**, *9*, 5131–5153. [CrossRef]

45. Zheng, B.; Tong, D.; Li, M.; Liu, F.; Hong, C.; Geng, G.; Li, H.; Li, X.; Peng, L.; Qi, J.; et al. Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. *Atmos. Chem. Phys.* **2018**, *18*, 14095–14111. [CrossRef]
46. Zhang, Q.; Zheng, Y.X.; Tong, D.; Shao, M.; Wang, S.X.; Zhang, Y.H.; Xu, X.D.; Wang, J.N.; He, H.; Liu, W.Q.; et al. Drivers of improved PM2.5 air quality in China from 2013 to 2017. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 24463–24469. [CrossRef] [PubMed]
47. Liu, J.; Tong, D.; Zheng, Y.X.; Cheng, J.; Qin, X.Y.; Shi, Q.R.; Yan, L.; Lei, Y.; Zhang, Q. Carbon and air pollutant emissions from China's cement industry 1990-2015: Trends, evolution of technologies, and drivers. *Atmos. Chem. Phys.* **2021**, *21*, 1627–1647. [CrossRef]
48. Liu, Y.S.; Cao, Y.; Hou, J.J.; Zhang, J.T.; Yang, Y.O.; Liu, L.C. Identifying common paths of CO2 and air pollutants emissions in China. *J. Clean. Prod.* **2020**, *256*, 120599. [CrossRef]
49. Tang, Y.; Wang, S.X.; Wu, Q.R.; Liu, K.Y.; Wang, L.; Li, S.; Gao, W.; Zhang, L.; Zheng, H.T.; Li, Z.J.; et al. Recent decrease trend of atmospheric mercury concentrations in East China: The influence of anthropogenic emissions. *Atmos. Chem. Phys.* **2018**, *18*, 8279–8291. [CrossRef]
50. Liu, J.; Mauzerall, D.L.; Chen, Q.; Zhang, Q.; Song, Y.; Peng, W.; Klimont, Z.; Qiu, X.H.; Zhang, S.Q.; Hu, M.; et al. Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 7756–7761. [CrossRef]
51. Zhang, F.F.; Xing, J.; Zhou, Y.; Wang, S.X.; Zhao, B.; Zheng, H.T.; Zhao, X.; Chang, H.Z.; Jang, C.; Zhu, Y.; et al. Estimation of abatement potentials and costs of air pollution emissions in China. *J. Environ. Manag.* **2020**, *260*, 110069. [CrossRef]
52. Gao, T.M.; Shen, L.; Shen, M.; Liu, L.T.; Chen, F.N.; Gao, L. Evolution and projection of CO2 emissions for China's cement industry from 1980 to 2020. *Renew. Sustain. Energy Rev.* **2017**, *74*, 522–537. [CrossRef]