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Spatial-Temporal Characteristics and Influencing Factors of Particulate Matter: Geodetector Approach

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Abstract: In 2019, South Korea's Framework Act on The Management of Disasters and Safety was revised to include respirable particulate matter as a social disaster. Urban air pollution, especially particulate matter pollution, has been a serious threat to socioeconomic development and public health. In order to address this problem, strong climate crisis response strategies and policies to improve urban air quality are necessary. Therefore, it is of great importance to assess the frequency of urban air pollution occurrence and its influencing factors. The objective of this study is to develop consistent methodologies for the construction of an index system and for assessing the influencing factors of urban particulate matter pollution based on population, social welfare, land use, environmental, transportation, and economic governance considerations. We applied the local indicators of spatial association and geographical detector methods, and 35 influencing factors were selected to assess their influence on urban air pollution occurrence in 229 cities and counties in South Korea. The results indicated the spatial pattern of the particulate matter concentration in these locations showed strong spatial correlation, and it was confirmed that there was a difference in distribution according to the season. As a result of the analysis of influencing factors, it was found that environment and land use characteristics were the main influencing factors for PM_{10} and $PM_{2.5}$. The explanatory power between the two influencing factors of particulate matter was greater than that of a single influencing factor. In addition, most influencing factors resulted in both positive and negative effects on urban fine particulate matter pollution. The interaction relationship of all factors showed a strong action effect in the case of both PM_{10} and $PM_{2.5}$, so it was confirmed that all influencing factors were interdependent. In particular, the findings proved that combining the two factors would have a more pronounced effect on particulate matter than when they were independent. We confirmed the significant results for the factors affecting particulate matter. This study offers suggestions on reducing urban air pollution occurrence that can be used to provide a basis and reference for the government to form policies on urban air pollution control in cities and counties.

Keywords: coarse particulate matter (PM_{10}); fine particulate matter ($PM_{2.5}$); spatial analysis; geographical detector; climate change; urban planning

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1. Introduction

Particulate matter is an air pollutant that is very harmful to humans and has been designated as a class 1 carcinogen by the International Institute for Cancer Research under the World Health Organization (WHO). The problem of inhalable particulate matter has increased sharply over the last decade; it has become an issue for all seasons and is no longer purely a simple environmental issue but also a policy matter that should be resolved by governments.

The South Korean government revised the Basic Act on Disaster and Safety Management in March 2019 and began to define particulate matter as a social problem. Since February 2019, emergency reduction measures to deal with high concentrations of particulate matter have been officially implemented under the Special Act on Particulate matter

Reduction and Management [1], while the Comprehensive Countermeasures for Particulate matter Management are currently being developed and promoted. From a macro perspective, this policy response aims to reduce the annual average concentration of particulate matter based on a nationwide target. Since it has been suggested that a limitation of this relatively uniform policy is that it is unable to take into account regional characteristics, it can be said that spatial characteristics should be discussed.

In addition, the focus is on managing emission sources through the regulation of automobile exhaust gases and the Indoor Air Quality Control Act. However, the concentration of particulate matter in the atmosphere is affected by a number of characteristics, such as weather, land use, and topography, in addition to pollutant [2–4], and its distribution depends on several other factors. Since it is difficult to achieve the particulate matter concentration target only by reducing emissions within the scope of existing policies, the legislation suggests that factors such as land use, urban environment, and human activities should be considered [5]. In addition, it is not always possible to conclude that all influencing factors act independently, but they are inevitably interdependent; therefore, it is necessary to consider the effects that they can cause when they interact.

This study analyzes the spatial and temporal distribution characteristics of particulate matter in Korea and captures them by region and season. Secondly, the factors influencing the dust are derived, the interactions between the factors are considered, and the differences in the degree of influence are compared and analyzed. Finally, the results of the study are synthesized and policy implications for dust reduction are proposed.

2. Literature Review

2.1. Main Causes of Respirable Particulate Matter

Air pollution and climate change are already critical environmental issues worldwide. The WHO has used satellite and atmospheric transport models to observe atmospheric conditions in more than 100 countries and more than 3000 urban and rural areas around the world [6]. It has been estimated that the number of deaths due to air pollution has reached 4.2 million per year, based on 2016 data, and among the air pollutants, particulate matter has been reported to have a significant effect on the human body [7]. Particulate matter consists of solid and liquid particles suspended in the atmosphere and is mainly classified by particle size. It is divided into coarse particles of 2.5 μm or more generated by mechanical processes on the surface of the earth (PM_{10}) and fine particles of 2.5 μm or less generated by physical and chemical processes such as condensation or agglomeration ($PM_{2.5}$) [8]. There, it has been judged necessary to look at the two pollutants (PM_{10} and $PM_{2.5}$) separately because their physical properties and chemical composition differ depending on their origin.

Some studies have mentioned particulate matter generated in cities, and research has pointed out that weather and topographical conditions and emission sources are the main causes of it [2–4,9]. The interesting points are also meaningfully related to natural factors such as topography and meteorological conditions, which can have a large impact on the process of diffusion and removal of atmospheric pollutants, and thus may be related to the causes of differences in the distribution of particulate matter in different seasons or regions [10,11]. Due to southeastern winds and high rainfall in August in South Korea, atmospheric pollutants are washed away, and their concentration is lower than in winter, but in winter the northwesterly winds blow from China and Russia due to the influence of high pressure over Siberia. Thus, based on this meteorological characteristic, it is possible to speculate on the reasons for the differences in temporal and spatial distribution depending on the wind direction [12].

Although the causes of particulate matter have been debated, there is still no clear consensus on the urban characteristics or distribution dispersion pathways [13]. If the problem of particulate matter can be resolved by one-sided emission sources alone, it should not be difficult to find a corresponding solution. It cannot be concluded that particulate matter is influenced only by directly occurring sources. Therefore, it is necessary to consider the factors that may influence particulate matter from the perspective of urban planning. For example, while it may be influenced by overall factors that come into focus at the national level, it may also be influenced not only by a variety of factors related to by regional characteristics but also by indirect policy decisions and socioeconomic factors that may become relevant to the distribution of particulate matter.

2.2. Influencing Factors of Particulate Matter Distribution

To analyze the factors influencing the distribution of particulate matter, it is essential to review the previous studies on the subject. It has been shown that it is necessary to look at the urban planning perspective, so this study considers factors related to (1) demographic characteristics, (2) human social activity, (3) economic governance, (4) land use, (5) the environment, and (6) transportation.

In attempts to illustrate demographic characteristics, methods such as evaluation of city size or population structure have mainly been used. With demographic changes, human activities such as increased energy consumption and the rising number of private cars are necessary stages that lead to the deterioration of air quality in the short term [14–16]. Thus, there is continuing discussion about urbanization, industrialization, and high population density being the main causes of deteriorating air quality [17–19]. It is necessary to analyze the significance of demographic structure on social issues, mainly by studying population numbers and dependency payments, and to confirm that these indicators also have an impact on environmental issues [20].

In discussing the relationship between urban characteristics and micro-dust, most studies observing social welfare characteristics have aimed to measure the welfare of humans within cities. Regarding social welfare characteristics, variables such as number of hospital beds, number of doctors, and ratio of health and social welfare enterprises have been utilized [21]. This is related to the adaptive capacity of cities. Previous studies have discussed the relationship between adaptive capacity and the reduction of dust in a way that implies that the degree of adaptive capacity affects the distribution of dust. For the same reason, a study of economic governance–related considerations consisting of factors that can account for the adaptive capacity of the economy and the size of the city economy was conducted. For this, the rate of change of GDP (Gross Domestic Product), GDP per capita, industrial structure, and business structure were considered [22,23].

To examine air pollution's relationship with land use, many studies have analyzed the effects of urban landscape structure and urban morphology on air pollution, confirming the existence of meaningful relationships [24–26]. At the microscopic level, the most representative factors are the type and intensity of land use, which directly affect the emission of air pollutants. At the macroscopic level, the most representative factor is the urban spatial structure, which also affects the spatial distribution and occurrence of pollutants. [25]. As variables to analyze the effect of land use on particulate matter, the most representative ones are the ratio of green space and commercial, industrial, residential, and river areas. Using variables that can account for the degree of mixing and diversity level of land use, the compact spatial structure of population growth rate compared with the rate of increase of municipalized area has been calculated as a variable [27–29].

Compared with other influencing factors, environment characteristics can be more intuitively appreciated and therefore considered as variables that directly affect the occurrence of particulate matter. It has been reported that industrial emissions from human activities and dust from construction have already had a direct impact on air quality [30]. The analysis of air pollutant emissions from urban activities and production activities from point, surface, and mobile sources can be done visually, such as from industrial activities and waste emissions. In South Korea, quantitative emissions statistics from various sectors are currently provided by the Atmospheric Policy Support System (CAPSS) of the Ministry of Environment. Furthermore, as studies proposing the problem of micro-dust generation due to incineration are gradually being discussed, open burning performed in agricultural activities or the incineration ratio among domestic waste disposal methods, for example, can be used as variables [31].

Analyzing the relationship between particulate matter and automobile traffic, which is often named as a source of pollution in existing studies, is an essential process. The number of vehicle registrations, road area ratio, and total annual vehicle distance traveled are generally considered [32–35]. The study by Song and Nam (2009) concluded that the higher the proximity ratio between workplace and residence, calculated in terms of internal traffic volume compared with total traffic volume, the lower the traffic energy consumption; therefore, the direct residence proximity fee was used as a variable of the relevant factor [27].

From previous studies, it is possible to understand that particulate matter is influenced by a variety of factors in cities. Most of the research has discussed the degree of influence when capturing the relationship between dust and the influencing factors so that not only positive or negative influence but the strength of the influence can be identified. The factors identified from prior research are not independent effects, but rather the characteristics of a city that cannot but coexist. This implies that when the factors are combined, they have other influences on micro-dust. Therefore, it is necessary to analyze what kind of positive and negative effects occur when factors interact with each other, rather than consider independent effects.

2.3. Summary

This study seeks to identify if there are differences in the spatial and temporal distribution patterns of particulate matter and outline the factors that affect the particulate matter concentration and the interactions between them. The previous study confirmed the existence of spatial and temporal distribution differences due to various factors. The meteorological characteristics of Korea imply that there are differences in concentrations between seasons, and it is assumed that the areas with high concentrations are located in the capital region due to a combination of influencing factors. In addition, to identify specific factors influencing the distribution of particulate matter, this study focuses on the characteristics of population, social welfare, land use, environment, transportation, and economic governance based on the basic correlations proposed by many studies. In addition, a hypothesis is proposed that the relationships are different when they are independent and when they interact with each other. In this study, the following research questions and hypotheses have formulated based on previous studies and theoretical investigations:

Q1. *Is there a difference in the temporal and spatial distribution pattern of particulate matter?*

H1. *There will be spatial differences between seasons and regions.*

Q2. *What specific factors affect the distribution of particulate matter, and is there an interaction relationship between the factors?*

H2-1. *Specific factors affecting the distribution of particulate matter are related to characteristics of population, social welfare, land use, environment, transportation, and economic governance.*

H2-2. *Because the factors have an interdependent relationship, the effect will be greater when they interact than when they are independent.*

In this study, the influencing factors of particulate matter have been considered based on six characteristics—demographics, social welfare, land use, the environment, transportation, and economic management—using the Geodetector analysis method. The importance of each influencing factor on dust has been calculated, and the degree of influence observed, to confirm whether the relevant factors are positive or negative for particulate matter. Finally, the differences in the degree of influence on dust when the influencing factors are independent and when they interact with each other have been compared and analyzed, and policy implications have been drawn as the final goal of this study.

3. Materials and Methods

3.1. Research Implementation Process

In this study, the temporal and spatial distribution characteristics of particulate matter and the influencing factors were analyzed in cities, counties, and districts across South Korea. The research flowchart of this study is shown in Figure 1. First, the indicators required for the analysis were selected, and the spatial clustering pattern of dust distribution by season was captured by using the Local Indicators of Spatial Association (LISA) analysis of the GeoDa program. Finally, the q statistics were calculated by implementing the Geodetector analysis. This is used to derive the factors influencing the dust and to grasp the interactions between the factors.

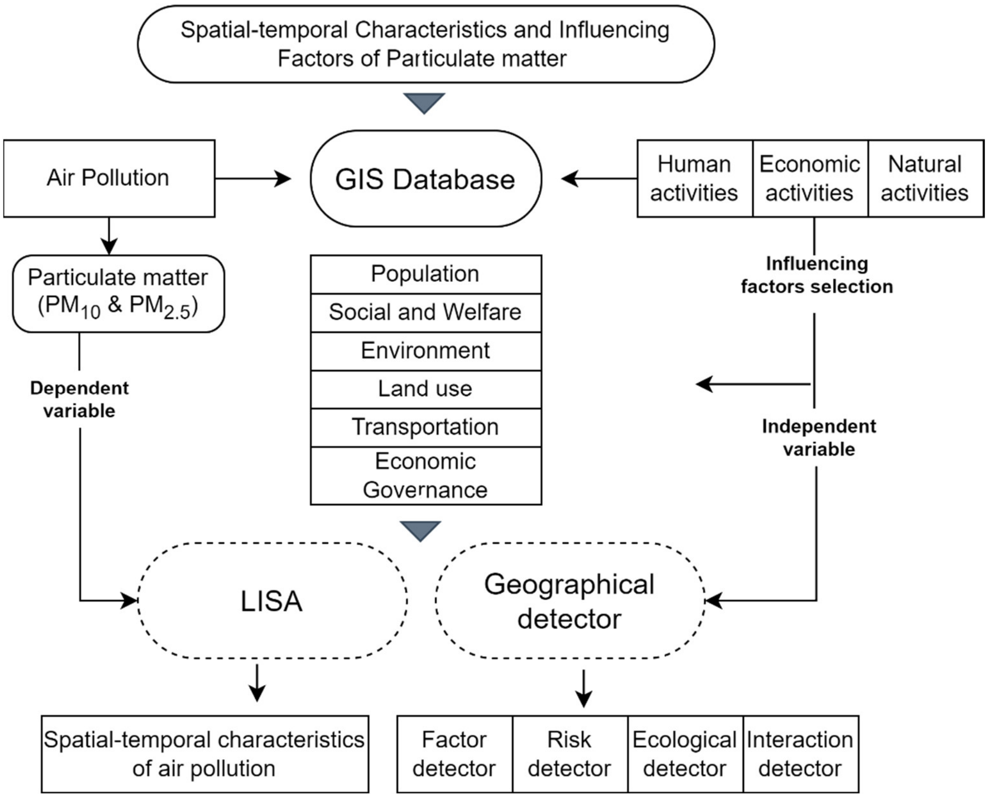


Figure 1. Study flowchart.

3.2. Study Area and Materials

The units of analysis for this study were set as administrative area cities, counties, and districts, and a total of 229 cities, counties, and districts, including 226 basic self-governing bodies, Sejong Special Self-Governing City, and Jeju City and Seogwipo City in Jeju Special Self-Governing Province, were used with the base year set at 2019. This study mainly used the 2019 data, but the Job-housing balance ratio and GRDP data of 2019 were not updated and difficult to obtain, so the data of Job-housing balance ratio and GRDP (Gross Regional Domestic Product) was used for 2016 and 2017, respectively.

According to the purpose of this study, the dependent variables used for the annual average and seasonal average concentrations of $PM_{2.5}$ and PM_{10} for 2019 were taken by the Ministry of Environment and AirKorea. The information collected for this period was site-specific concentration information based on points, so it was difficult to appreciate the current status of unmeasured areas. In addition, since the location and number of measurement stations were not categorized by area, it was difficult to select specific concentration information that would be representative of a local self-governing group. Therefore, the information collected was spatial data centered on having location information, and therefore a spatial interpolation method of ArcGIS was used to supplement the concentration values with a spatial resolution of 1 km × 1 km [36,37].

Based on the research hypotheses, the factors influencing the dependent variables were selected based on prior studies and constituted the indicators for analysis. In general, the analysis was divided into six sectors, namely demographic, social welfare, land use, environmental, transportation, and economic governance characteristics, and detailed indicators were selected (Table 1). For the environmental budget indicators in the economic governance characteristic, only the information on the atmosphere, environmental protection, and nature budget, which are considered to be related to dust, were extracted and used.

Table 1. Variables.

Large Category	Detail Variable	Reference
Dependent Variable	PM_{10} seasonal, annual average concentration	Air Korea
	$PM_{2.5}$ seasonal, annual average concentration	Air Korea
Population (6)	Population density	Statistics Korea
	Dependency ratio	Statistics Korea
	Medical expenses for patients with malignant neoplasms of the bronchi and lung	Statistics Korea
	Primary industry worker ratio	Statistics Korea
	Secondary industry worker ratio	Statistics Korea
	Tertiary industry worker ratio	Statistics Korea
Social and Welfare (4)	Percentage of health and social service businesses	Statistics Korea
	Number of hospital beds per thousand population	Statistics Korea
	Number of hospital doctors per thousand population	Statistics Korea
	Percentage of the population within the living area park area	National Geographic Information Institute
Land Use (8)	Land use compression	National Geographic Information Institute
	Land use complexity	National Geographic Information Institute
	Compact space structure *	Statistics Korea
	Green ratio	Ministry of Environment
	River ratio	National Geographic Information Institute
	Commercial area ratio	Statistics Korea
	Industrial area ratio	Statistics Korea
	Residential area ratio	Statistics Korea
Environment (7)	Incineration rate of domestic waste treatment methods	Ministry of Environment
	Number of workplaces that emit air pollutants *	Ministry of the Interior and Safety
	Emissions from agricultural activities	CAPSS
	Emissions from industrial activities	CAPSS
	Emissions from waste	CAPSS
	Emissions from vehicles	CAPSS
	NDVI (Normalized Difference Vegetation Index)	Landsat8
Transportation (5)	Number of vehicle registrations	Statistics Korea
	Road ratio	Statistics Korea

	Job-housing balance ratio *	Korea Transport Database
	Pedestrian road ratio	Statistics Korea
	Total vehicle mileage per year	Statistics Korea
Economic Governance (5)	Environmental budget per capita *	Ministry of the Interior and Safety
	Ratio of social welfare budget in general account	Statistics Korea
	GRDP	Statistics Korea
	Financial independence of local government	Statistics Korea
	Number of businesses	Statistics Korea

Note: * Author's edit.

3.3. Methods

3.3.1. LISA Analysis

Particulate matter is a substance in the air and cannot exist in complete isolation; therefore, it can only have the characteristic of interdependence. The closer the distance, the higher the correlation. This is called spatial autocorrelation, and it can be analyzed from both global and local perspectives.

Global spatial autocorrelation refers to the presence of a specific pattern between a variable and a location, or the presence of a high value for a particular variable at that location, while the surrounding values also show high values. It refers to the similarity between these locations and variables. Moran's I coefficient, which usually confirms this, has a positive spatial autocorrelation range of +1 and a negative spatial autocorrelation of −1. It has been seen to show a positive spatial autocorrelation with similar values [21]. It is closer to −1 because the adjacent regions are different, and it appears closer to 0 because autocorrelation is not present.

However, because Moran's I index displays relationships across study sites as a single value, it cannot explain the local structure of spatial relationships for each target area analyzed when the target area is large [37]. Local spatial autocorrelation can be confirmed by LISA analysis, a technique used to explore spatial clustering patterns based on the numerical similarity of attributed values between adjacent regions [38]. Four clusters have been derived. High–High (HH) and Low–Low (LL) indicate correlation between adjacent regions, while Low–High (LH) and High–Low (HL) indicate dissimilarity between adjacent regions. HH clusters are those where the corresponding region has high values and the surrounding region shows a tendency to be high; LL clusters are those where the surrounding region has low values and the corresponding region has low values. LH clusters are those where the corresponding region has low values and the surrounding area shows a high trend. At this point, it can be confirmed that HH and LL clusters each have positive spatial correlation and LH and HL clusters each have negative correlation, so they can be seen as spatially isolated regions [39].

Therefore, this approach is a suitable tool for identifying specific regions of location-based data and analyzing spatial distribution patterns. In this study, to analyze the spatial magnetic correlation of the dust distribution, LISA analysis was performed using GeoDa spatial analysis software 1.20.

3.3.2. Geodetector

Particulate matter is a spatially distributed pollutant, so for the study of its spatial and temporal distribution characteristics and influencing factors, econometric and spatial econometric models are mainly used. Spatial autocorrelation has been mentioned previously, and the models reflecting this situation include the spatial lag model (SLM), spatial error model (SEM), and general spatial autocorrelation model (GSAM), which are all spatial analysis methods. However, in order to use spatial data, both spatial magnetic correlation and spatial stratified heterogeneity should be considered [40]. Spatial heteroskedasticity is a characteristic of spatial data and can be explained by the uneven distribution of relationships between characteristics, events, and regions [41,42]. The q statistic of the

Geodetector model, which reflects this situation, has been used in many recent studies. In addition, the existing traditional methods have some shortcomings in terms of quantifying the interaction of influencing factors. The interaction of two factors can actually be combined in many forms, but in traditional regression methods, it is generally expressed as the product of two factors, although this does not have sufficient ability to account for spatially stratified heterogeneity [43]. Therefore, unlike prior studies that have used multiple linear methods, this study has concluded that the Geodetector model, which reflects the characteristics of spatial data, would be more appropriate, along with the nonlinear model.

The Geodetector method has several advantages compared with other models. First, it can consider the space [40]. Second, the relationship between the dependent and independent variables analyzed using the Geodetector method has the advantage of being more reliable than classical regression models [44]. Third, the problem of multicollinearity is excluded because no linearity assumption is made on the factors [45]. Fourth, the priority order of the influencing factors can be derived, and the change of the degree of influence over time can be analyzed [46]. With these advantages, the Geodetector method has been applied to many fields, including natural sciences and social sciences, and can be fully applied to the environmental field.

The Geodetector method is a statistical method that conducts analyses based on the hypothesis of similarity in the spatial distribution of dependent and independent variables when the independent variable has a significant influence on the dependent variable. In other words, if a particulate matter's high concentration based on a certain characteristic is induced in a city, this concentration will show spatial distribution similar to that characteristic, which can indicate the existence of a causal factor. In addition, if the present model is used, the concept of spatial dispersion can be used to observe the interactions between independent variables. In the former case, after analyzing the influence of emission factors of various industries on urban $PM_{2.5}$ pollution concentrations, buildings and traffic were identified as the main influencing factors [47]. In addition, the results of a latter study, which used this model to analyze the influencing factors of lead (Pb) in particulate matter in residential areas, showed that automobile exhaust, human daily life activities, and industrial emissions interacted to produce the effects [48].

The main framework of the Geodetector model is to first divide the study site into the dependent variable Y-strata (Y layer) and the influencing factor (independent variable) X-strata (Figure 2) [44].

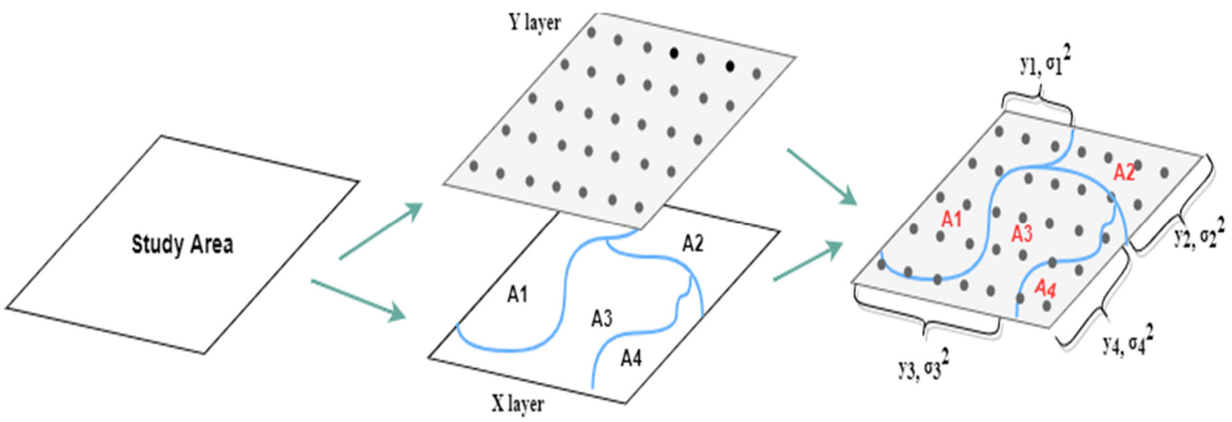


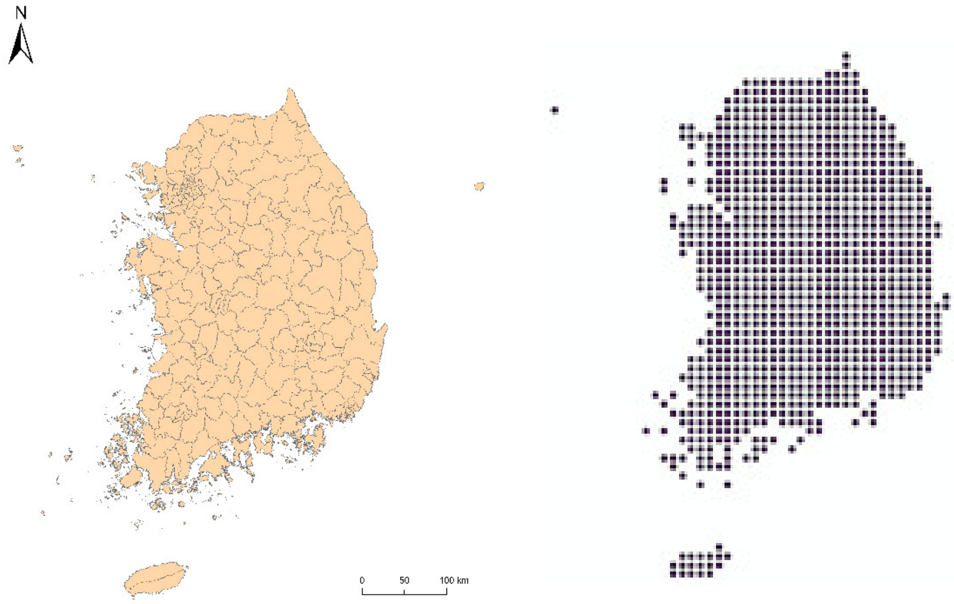
Figure 2. The principle of the geographical detector (Source:[44] Wang & Xu, 2017).

Next, the *q* statistic is used to explain the degree of influence of the influencing factor X on the dependent variable Y. The *q* statistic takes values in the range (0,1), which can be interpreted in such a way that the higher the *q* statistic, the greater the influence of the influencing factor X on the dependent variable Y. The formula for calculating the *q*-statistic is as follows:

$$q = 1 - \frac{\sum_{i-1}^{A} N_i \sigma_i^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \quad (1)$$

$$SSW = \sum_{i-1}^{A} N_i \sigma_i^2, SST = N\sigma^2. \quad (2)$$

Using the ArcGIS program, the study area was transformed into a grid of 10 km × 10 km (Figure 3). Since the independent variable used in this model is a type variable, it should be graded [40,44]. Therefore, for data pre-processing, all data were divided into 5 classes using ArcGIS's Natural Breaks classification method and applied to the grid (Appendix A).



(**a**) Study area (**b**) Sampling point

Figure 3. Grid transformation method; (**a**) study area, (**b**) sampling point.

The analysis results of the Geodetector method are divided into factor detector, risk detector and interaction detector, and the principles and concepts are the same as those in Table 2 [40,44]. First, factor detector is used to verify the spatial dispersion of each influencing factor, and the main factors are selected by prioritizing them according to the *q* statistic. Risk detector analyzes the direction of influence of each factor on the dust and indicates whether it is positive or negative. Interaction detector evaluates whether the combination of two influencing factors diminishes or intensifies the influence on the dependent variable (Y), and whether the influence is independent.

Table 2. Conceptual framework of the geographical detector method.

Detector	Illustration
Factor Detector	Uses the *q* value to assess the impact of demographic, socioeconomic, environmental, and land use factors on the spatial pattern of particulate matter ($PM_{10}/PM_{2.5}$) emissions. High q value means the influencing factor has a stronger contribution to the occurrence of particulate matter emissions.
Risk Detector	Compares the differences in average particulate matter ($PM_{10}/PM_{2.5}$) emission rates between subregions generated by demographic, socioeconomic, environmental, and land use factors. It uses T-test to identify whether the average $PM_{10}/PM_{2.5}$ emission rates among different subregions are significantly different. Greater differences mean greater impact to particulate matter ($PM_{10}/PM_{2.5}$) emissions within the subregion.
Interaction Detector	Uses the *q* value to compare the combined contribution of individual influencing factors to particulate matter ($PM_{10}/PM_{2.5}$) emissions. It assesses whether the two influencing factors weaken or enhance each another, or whether they independently influence the development of the particulate matter ($PM_{10}/PM_{2.5}$).

Source: [40,44] Wang et al., 2016; Wang & Xu, 2017.

4. Results

4.1. LISA Results

Exploratory spatial analysis was performed to understand the spatial association pattern of particulate matter. Prior to the analysis, the spatial autocorrelation of the index was confirmed through Moran's I test, and then LISA analysis was performed to confirm the spatial clustering pattern of the temporal and spatial distribution of particulate matter at the local level.

According to a previous study confirming spatial autocorrelation, it was judged that there was spatial autocorrelation when Moran's I coefficient was 0.267 [49]. Choi et al. (2018) judged that a coefficient value of 0.2857 showed a significant level of positive spatial autocorrelation [21]. Yeom et al. (2020) confirmed exponential values of 0.398, 0.607, and 0.483 for the three indicators and found that they appeared to have high spatial autocorrelation [38].

Figure 4 shows the results of the analysis of global spatial autocorrelation by annual mean concentration and season in this study. The average annual mean was 0.37 for both $PM_{2.5}$ and PM_{10}, showing a significant level of positive spatial autocorrelation. In spring and winter, it was confirmed that both materials had a high spatial correlation by checking an index value of 0.4 or higher. In the case of autumn, a positive spatial autocorrelation of 0.27 was also confirmed. However, in the case of summer, the index values of $PM_{2.5}$ and PM_{10} were 0.080 and 0.044, respectively, and the spatial autocorrelation was found to be rather weak. Through this, the spatial distribution of PM_{10} and $PM_{2.5}$ across Korea was positive and confirmed to have spatial autocorrelation.

Through the global spatial autocorrelation analysis, the correlation in the distribution of particulate matter throughout Korea was confirmed. Furthermore, using the local Moran's I and LISA analysis, local correlation was identified, as shown in Figure 5. As a result of the analysis, it was confirmed that this correlation had interdependent characteristics and influence with neighboring regions. In addition, it was found that the distribution of $PM_{2.5}$ and PM_{10} was spatially different according to the season. It was confirmed that HH-type hot spot clusters appeared in the metropolitan area. Therefore, the hypothesis of question 1 of this study was satisfied.

In all seasons, except summer, and average annual results, a cluster type with a generally similar shape was found between $PM_{2.5}$ and PM_{10}. HH type (hotspot cluster) was found in some areas of Chungcheongnam-do and North Korea centering on the metropolitan area. The LL type (cold spot cluster) was identified in the southern and eastern regions of the Korean Peninsula. In the former case, it was because the road transportation infrastructure is relatively well developed around Seoul. It is considered to be an area with high development density due to high population density and land use compression. In addition, South Korea has the characteristic of land development in that urbanization centered on the metropolitan area has been actively carried out. This is believed to be due to the relatively insufficient green area. In the latter case, there is a region in the southeast that has achieved economic growth mainly in secondary industries. Compared with the metropolitan area, the population density and land use compression are relatively low, so the development density is low. In addition, there are many cities centered on primary industries, and these are judged to have excellent environment characteristics.

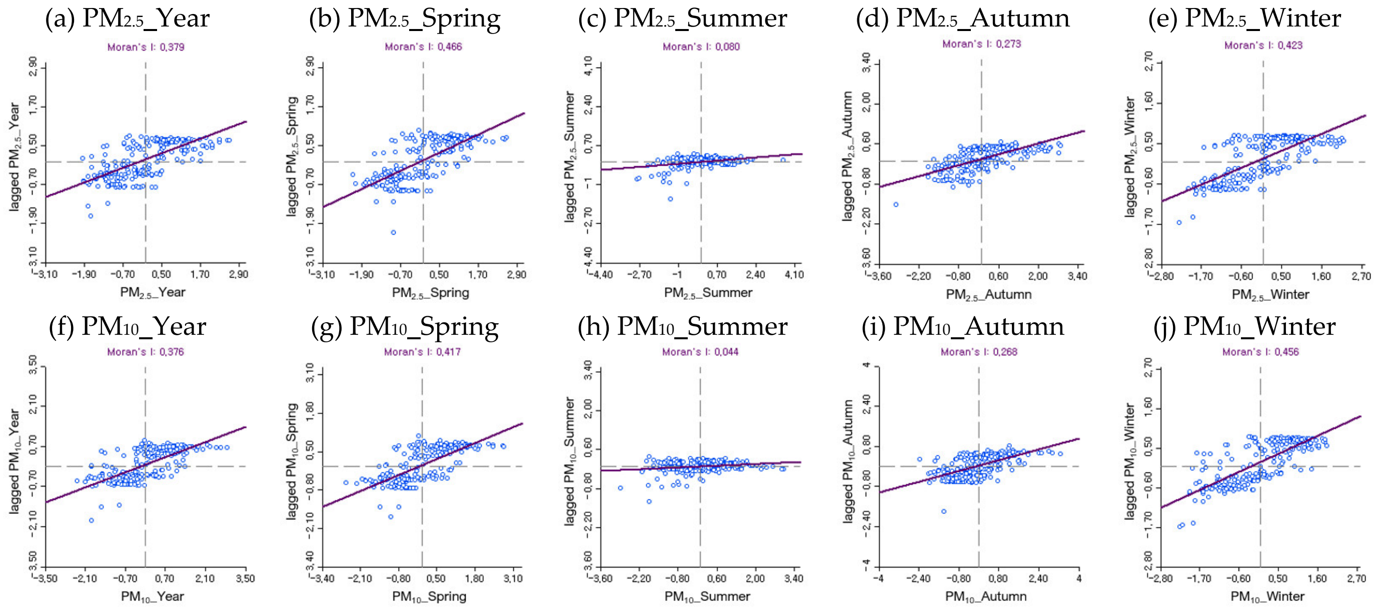


Figure 4. Moran's I analysis results.

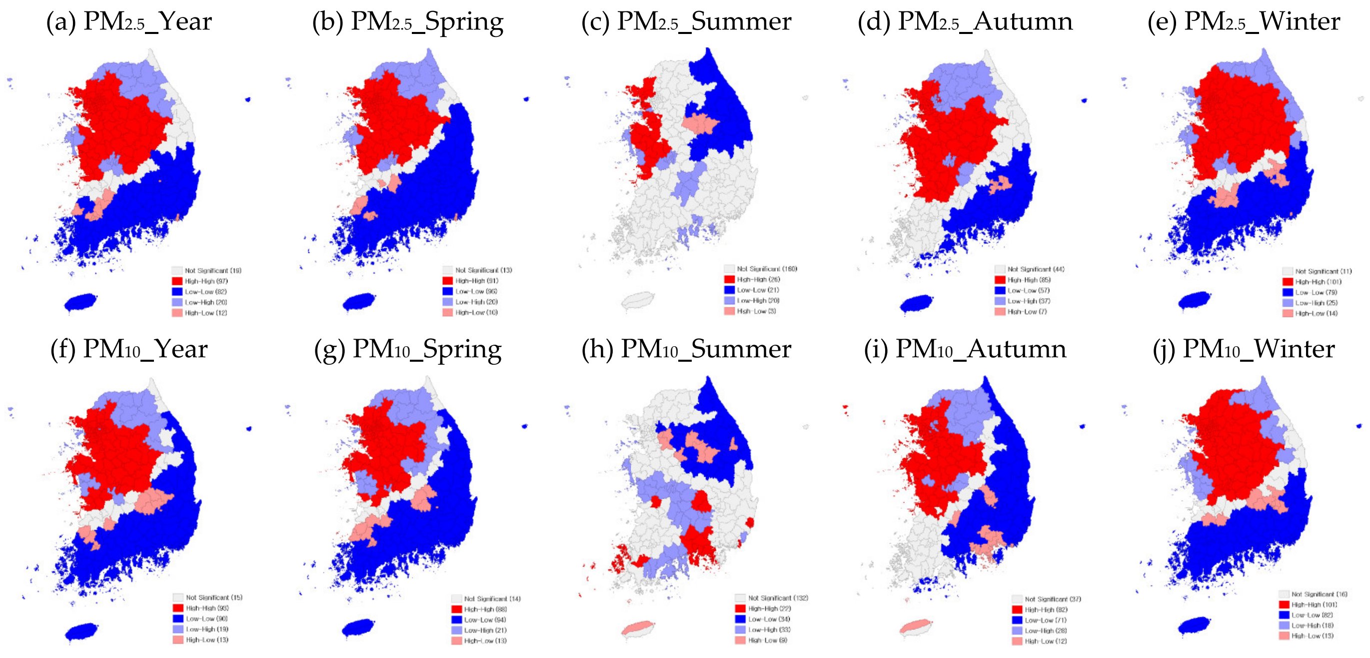


Figure 5. LISA analysis results.

4.2. Geodetector Results

4.2.1. Factor Detector

Factor detector can measure not only the spatial heteroskedasticity of the dependent variable Y but also the degree of influence of the influencing factor X on the dependent variable Y through the *q* statistic. Factor detector results for the average annual concentrations of PM_{10} and $PM_{2.5}$ are presented in Table 3, and only factors within the significance level of 0.1 have been extracted and are shown in Figure 6. In order to better compare the degree of influence of the influencing factors on PM_{10} and $PM_{2.5}$, the priorities of the influencing factors were sorted according to the value of the *q* statistic. The range of the *q* statistic for each factor was 0.038 to 0.208 for $PM_{2.5}$ and 0.077 to 0.376 for PM_{10}. Overall, the degree of influence on PM_{10} was confirmed to be greater than that of $PM_{2.5}$. In addition, the number of workplaces emitting air pollutants (XE2) and waste emission (XE5) and green area (XL4) were found to have the greatest impact for both pollutants. The emission source that contributed the most to the concentration of particulate matter was workplace emission facilities, which is consistent with previous research, namely that it amounts to about 38% [50]. The effect of green spaces on the reduction of particulate matter was judged to be clear, as has been revealed in several studies [51–53]. From the results of this study, we can conclude the degree of influence of the function of green areas to be very large.

Agricultural activity emission (XE3) and incineration rate among domestic waste treatment methods (XE1) ranked next in $PM_{2.5}$. Biological combustion such as incineration can be interpreted to be the cause of high local concentration of $PM_{2.5}$. This is considered consistent with the results of previous studies that have reported it to be one of the factors influencing the occurrence of $PM_{2.5}$ and shown a rather low ranking for PM_{10} [31]. On the other hand, in PM_{10}, total mileage per year (XT5) ranked second, but this factor ranked slightly lower in $PM_{2.5}$. These results suggest that there is a difference in the factors affecting PM_{10} and $PM_{2.5}$. Combining the analysis results, it was confirmed that the environmental (XE), land use (XL), and transportation (XT) characteristics were large through the priority results of factors affecting the distribution of particulate matter.

Table 3. The results of factor detection for the influencing factors of urban PM_{10} and $PM_{2.5}$ in 2019.

Large Category		**Factor**	**PM_{10}**		**$PM_{2.5}$**	
			q	**Rank**	***q***	**Rank**
Population	XP1	Population density	0.2183 ***	9	0.0950 **	12
	XP2	Dependency ratio	0.1695 ***	15	0.0724	19
	XP3	Medical expenses for patients with malignant neoplasms of the bronchi and lung	0.1031 ***	26	0.0402	30
	XP4	Primary industry worker ratio	0.0835 ***	29	0.0379 ***	31
	XP5	Secondary industry worker ratio	0.0772 ***	30	0.0280	33
	XP6	Tertiary industry worker ratio	0.1728 ***	14	0.0917 ***	13
Social and Welfare	XS1	Percentage of health and social service businesses	0.1100 ***	24	0.0569 ***	27
	XS2	Number of hospital beds per thousand population	0.1094 ***	25	0.1026 ***	10
	XS3	Number of hospital doctors per thousand population	0.0119	35	0.0063	35
	XS4	Percentage of the population within the living area park area	0.1265 ***	22	0.0592 ***	25
Land Use	XL1	Land use compression	0.1416	19	0.0525	28

	XL2	Land use complexity	0.2242 ***	7	0.1082 *	8
	XL3	Compact space structure*	0.0680	32	0.0832	18
	XL4	Green ratio	0.2905 ***	3	0.1710 ***	4
	XL5	River ratio	0.0383	33	0.0106	34
	XL6	Commercial area ratio	0.0253	34	0.0322	32
	XL7	Industrial area ratio	0.1150	23	0.0866 *	14
	XL8	Residential area ratio	0.0682	31	0.0603 **	24
Environment	XE1	Incineration rate of domestic waste treatment methods	0.1436 ***	18	0.1082 ***	7
	XE2	Number of workplaces that emit air pollutants*	0.3759 ***	1	0.2076 ***	2
	XE3	Emissions from agricultural activities	0.1317 ***	20	0.1612 ***	5
	XE4	Emissions from industrial activities	0.2355	4	0.1727	3
	XE5	Emissions from waste	0.3428 ***	2	0.2083 ***	1
	XE6	Emissions from vehicles	0.1993	11	0.1237	6
	XE7	NDVI	0.0856	28	0.0686	21
Transportation	XT1	Number of vehicle registrations	0.2199 ***	8	0.0854 **	16
	XT2	Road ratio	0.1920	12	0.0721	20
	XT3	Job-housing balance ratio *	0.1269	21	0.0493	29
	XT4	Pedestrian road ratio	0.1517 ***	17	0.0683 ***	22
	XT5	Total vehicle mileage per year	0.2314***	5	0.0863 **	15
Economic Governance	XG 1	Environmental budget per capita*	0.0917 ***	27	0.0591 ***	26
	XG 2	Ratio of social welfare budget in general account	0.1829 ***	13	0.0980 ***	11
	XG 3	GRDP	0.2181 ***	10	0.0844	17
	XG 4	Financial independence of local government	0.1627 ***	16	0.0680	23
	XG 5	Number of businesses	0.2250 ***	6	0.1029 **	9

Note: Significance levels: *~$p < 0.1$, **~$p < 0.05$, ***~$p < 0.01$.

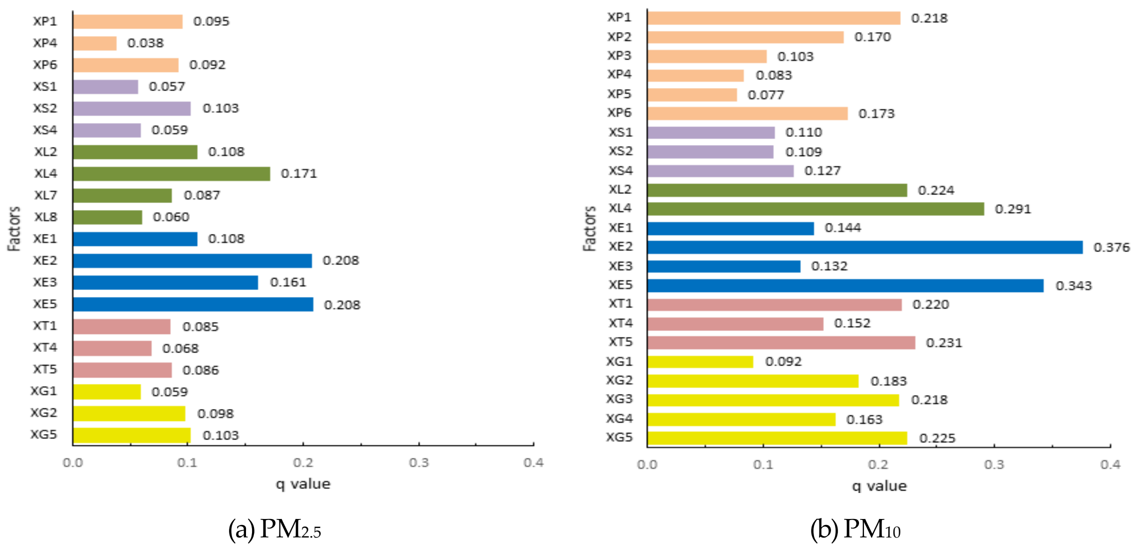


Figure 6. *q* statistics for factor detector**.**

4.2.2. Risk Detector

Risk detector can use the T statistic to determine the direction of the influencing factor. The relationship between particulate matter and influencing factors is shown in five linear and non-linear relationships (Table 4). Positive (+) and negative (−) mean that the higher the natural break grade of the influencing factors, the linear relationship increases and decreases, respectively. (±) indicates a non-linear relationship. Negative/positive (−/+) means changing from decreasing to increasing, and positive/negative (+/−) means an increasing and decreasing relationship.

Looking at the results of the analysis, the effects of environmental factors on particulate matter are more complex than those of population, land u se, transportation, and economic governance characteristics (Table 4, Appendix B). First, environmental characteristics such as agricultural activity (XE3), industrial activity (XE4), waste (XE5), and automobile (XE6) emissions show a distinct non-linear effect on particulate matter. The effect of the number of workplaces emitting air pollutants (XE2) on particulate matter tends to increase according to grade (Appendix B). In this case, the closer to 1st grade, the smaller the number of workplaces. Second, the relationship between particulate matter and the number of influencing factors of population, land use, transportation, and economic governance characteristics shows a gradually decreasing or increasing trend.

Table 4. The results of risk detection for the influencing factors of urban PM_{10} and $PM_{2.5}$ in 2019**.**

Large Category	Factor		Relation
Population	XP1	Population density	+
	XP2	Dependency ratio	+
	XP3	Medical expenses for patients with malignant neoplasms of the bronchi and lung	−
	XP4	Primary industry worker ratio	+
	XP5	Secondary industry worker ratio	−
	XP6	Tertiary industry worker ratio	−/+
Social and Welfare	XS1	Percentage of health and social service businesses	+/−
	XS2	Number of hospital beds per thousand population	+/−
	XS3	Number of hospital doctors per thousand population	+/−

	XS4	Percentage of the population within the living area park area	+
Land Use	XL1	Land use compression	+
	XL2	Land use complexity	+
	XL3	Compact space structure*	−/+
	XL4	Green ratio	−
	XL5	River ratio	±
	XL6	Commercial area ratio	−/+
	XL7	Industrial area ratio	+
	XL8	Residential area ratio	±
Environment	XE1	Incineration rate of domestic waste treatment methods	±
	XE2	Number of workplaces that emit air pollutants*	+
	XE3	Emissions from agricultural activities	±
	XE4	Emissions from industrial activities	±
	XE5	Emissions from waste	+
	XE6	Emissions from vehicles	±
	XE7	NDVI	−
Transportation	XT1	Number of vehicle registrations	±
	XT2	Road ratio	+/−
	XT3	Job–housing balance ratio*	+
	XT4	Pedestrian road ratio	−
	XT5	Total vehicle mileage per year	±
Economic Governance	XG1	Environmental budget per capita*	−
	XG2	Ratio of social welfare budget in general account	+/−
	XG3	GRDP	+
	XG4	Financial independence of local government	+
	XG5	Number of businesses	+

Note: "+" positive effector; "−" negative effector; "±" the relationship between PM_{10} & $PM_{2.5}$ and its influencing factors is complex; "−/+" the influencing factor on PM_{10} & $PM_{2.5}$ changes from negative to positive; "+/−" the influencing factor on PM_{10} & $PM_{2.5}$ changes from positive to negative. Source: [54] Zhou et al., 2021.

4.2.3. Interaction Detector

Interaction detector can verify the interaction between factors. In other words, it analyzes whether the influence on the dependent variable Y increases or decreases when the two influencing factors act in combination. The evaluation method is as follows. The q statistic of each influencing factor is calculated, then the q statistic is calculated when the two influencing factors are combined, and the two results are compared and analyzed. The interaction relationship between the two factors is shown in Table 5, and the analysis results are shown in Appendixes C and D. All interaction relationships of the two factors showed a strong agonistic effect (enhance, bivariate and enhance, nonlinear) on both PM_{10} and $PM_{2.5}$. No weak action relationship was observed for any of the factors.

Table 5. Interaction relationships between two factors**.**

Interaction	Description
Enhance	if $q (X_1 \cap X_2) > q (X_1)$ *or* $q (X_2)$
Enhance, bivariate	if $q (X_1 \cap X_2) > q (X_1)$ *and* $q (X_2)$
Enhance, nonlinear	if $q (X_1 \cap X_2) > q (X_1) + q (X_2)$
Weaken	if $q (X_1 \cap X_2) < q (X_1) + q (X_2)$
Weaken, univariate	if $q (X_1 \cap X_2) < q (X_1)$ *or* $q (X_2)$
Weaken, nonlinear	if $q (X_1 \cap X_2) < q (X_1)$ *and* $q (X_2)$
Independent	if $q (X_1 \cap X_2) = q (X_1) + q (X_2)$

Note: "∩" denotes the intersection between X_1 and X_2. Source: [40,44] Wang et al., 2016; Wang et al., 2017.

The following looks at the interaction relationship analyzed for each characteristic:

In terms of population characteristics (XP), when independent, the population density (XP1) was found to be 0.2183 and 0.0950 for PM_{10} and $PM_{2.5}$, respectively, and the most influential factor among the characteristics. In the case of interaction, the strongest effect relationship (enhance, nonlinear) appeared with the ratio of workers in the secondary industry (XP5), with 0.4060 and 0.2910, respectively, in the same characteristic. In relation to other characteristics, when interacting with the number of workplaces emitting air pollutants (XE2), a stronger effect relationship (enhance, bivariate) was shown, with 0.5419 and 0.4417, respectively.

For the social and welfare characteristics (XS), 0.1265 of the population ratio (XS4) in the living area park area was the largest *q* value for PM_{10}. $PM_{2.5}$ had the largest *q* value, as the number of beds per 1000 population (XS2) was 0.1026. As a result of the interaction analysis, the ratio of health and social welfare organizations (XS1) was found for both PM_{10} and $PM_{2.5}$ with the same characteristics. In other characteristics, the number of workplaces emitting air pollutants (XE2) was found to have the strongest effect (enhance, nonlinear).

In terms of land use characteristics (XL), it was confirmed that the green area ratios (XL4) of PM_{10} and $PM_{2.5}$ were 0.3759 and 0.1710, respectively, which were the largest *q* values. In the case of interaction, for the same characteristic, the residential area ratios (XL8) were 0.4272 and 0.3121, respectively, indicating the strongest effect (enhance, nonlinear). In other characteristics, the number of workplaces emitting air pollutants (XE2) was found to have the strongest effect (enhance, bivariate).

For the environmental characteristics (XE), the number of workplaces emitting air pollutants (XE2) was found to be the most influential factor, with 0.3759 for PM_{10} and 0.2076 for $PM_{2.5}$. In the case of interaction, agricultural activity emissions (XE3) were 0.7550 and 0.2076, respectively, for the same characteristic, indicating the strongest interaction (enhance, nonlinear). In terms of the other characteristics, in the case of PM_{10}, the ratio of health and social welfare organizations (XS1) was found to have the strongest effect (enhance, nonlinear). In the case of $PM_{2.5}$, it was found that the number of doctors in medical institutions per 1000 population (XS3) had the strongest effect (enhance, nonlinear).

In terms of the transportation characteristics (XT), PM_{10} and $PM_{2.5}$ showed 0.2314 and 0.8627 values, respectively, of annual vehicle total mileage (XT5) when independent, and it was found to be the most influential factor. In the case of interaction, it was found that the direct pole proximity ratio (XT3) had the strongest action relationship (enhance, bivariate) in the same characteristic. In the other characteristics, in the case of PM_{10}, the number of workplaces emitting air pollutants (XE2) was 0.5243, indicating that this had the strongest effect (enhance, nonlinear). And in the case of $PM_{2.5}$, agricultural activity emission (XE3) was 0.4414, which showed the strongest effect relationship (enhance, bivariate).

In the economic governance characteristics (XG), the total number of businesses (XG5) was analyzed to be the most influential factor, with 0.2250 for PM_{10} and 0.1023 for $PM_{2.5}$. In the same characteristic, the per capita environmental budget (XG1) was 0.3889 and 0.2884, respectively, indicating the strongest effect relationship (enhance, nonlinear). In the other characteristics, PM_{10} showed the strongest effect (enhance, bivariate) with the number of workplaces emitting air pollutants (XE2), with 0.5352. On the other hand, in the case of $PM_{2.5}$, the agricultural activity emission (XE3) was 0.5352, confirming that it had the strongest effect (enhance, bivariate).

It was confirmed that the factors affecting particulate matter had a greater effect when they interacted than when they were independent. Through this, it was confirmed that all influencing factors were interdependent, and this conclusion proved that Hypothesis 2 of Question 2 of this study was satisfied.

5. Conclusions

This study used the concentration data of PM_{10} and $PM_{2.5}$ in 2019 and classified them into six categories: characteristics of population, social welfare, land use, the environment, transportation, and economic governance. Detailed indicators that can be explained were selected.

Looking at the spatial distribution of particulate matter, it was confirmed that both pollutants have a spatial correlation with the distribution of particulate matter throughout Korea. In particular, each has interdependent characteristics with neighboring regions. In particular, HH-type hotspot clusters were identified centered on the metropolitan area, proving Question 1 and Hypothesis 1. As a result of seasonal analysis, it was found to be high in spring, autumn, and winter and low in summer.

The influencing factors of this study were confirmed to have a greater degree of influence on PM_{10} than on $PM_{2.5}$ as a whole. The number of workplaces emitting air pollutants (XE2) and waste (XE5) and amount of green area (XL4) were found to have the greatest impact on both pollutants, suggesting that they are the major influencing factors. However, by confirming that there is a difference between the two pollutants in the ranking that appears next to the relevant factors, it is possible to show that the factors to be considered for each substance are somewhat different. In addition, the interaction relationship of all factors showed a strong action effect on both pollutants, so it was confirmed that all influencing factors are interdependent. In particular, it was proven that the combinations of population and land use characteristics, population and environmental characteristics, social welfare and environment characteristics, and land use and environment characteristics have a more pronounced effect on particulate matter than when independent.

We would like to suggest some policy proposals to improve air pollution, as follows. First, through the results of the LISA analysis, it was confirmed that air pollution in one area is related not only to the influence within the area but also to the air quality of the surrounding area. Since it has been shown that there is a spatial diffusion effect on particulate matter pollution, it is necessary to strengthen cooperation between neighboring local governments. For example, the findings suggest that the standards for energy conservation and environmental protection among regions should be identical, and that cooperation and enforcement systems for sharing air quality information between regions and responding to emergencies are necessary.

Today, cities are expanding rapidly and continuously, and the reality is that nonurban areas are relatively underdeveloped. Therefore, it is necessary to limit the indiscriminate increase of the population accompanying urban expansion. In addition, it is necessary to establish a land use development plan that considers the balance of economy, social welfare, and resources in consideration of local environment and resource sustainability. Measures prepared by the government are also important in the existing fragmentary management and reduction of emission sources. However, in the future, the influence of urban characteristics, which has a high correlation with the qualitative level of the urban environment, must be considered.

Through this study, we have confirmed significant results for the factors affecting particulate matter. However, it is necessary to discuss the topographical factors that form the basis for land use planning. In addition, an in-depth study on the relationship with the wind direction should be added as the basis for the hypothesis setting. In addition, if time series analysis of more than 10 years is carried out to solve the limitation of the temporal range, it is expected that more effective and specific measures can be proposed.

Author Contributions: Conceptualization, H.M. and M.L.; methodology, H.M. and M.L.; software, M.L.; validation, formal analysis, H.M.; investigation, H.M. and M.L.; resources, H.M. and M.L.; data curation, H.M. and M.L.; writing—original draft preparation, H.M.; writing—review and editing, H.M.; visualization, M.L.; supervision, J.J.; project administration, J.J.; funding acquisition, J.J. All authors have read and agreed to the published version of the manuscript.

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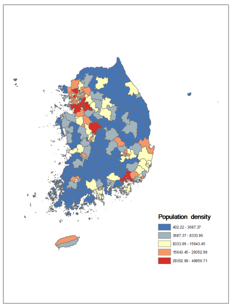
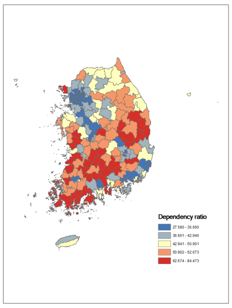
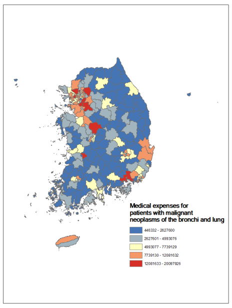
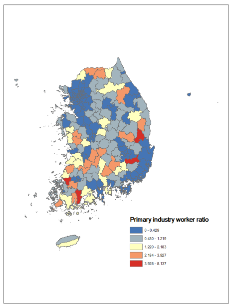
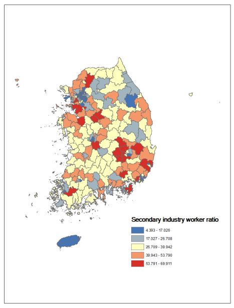
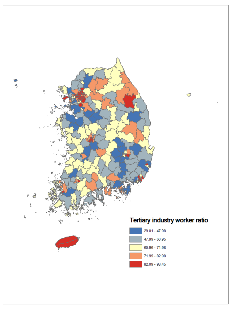
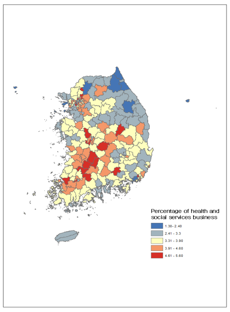
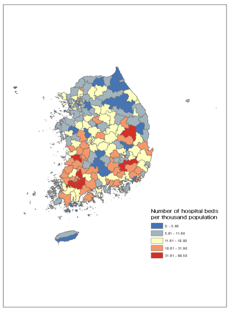
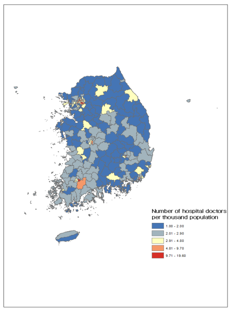
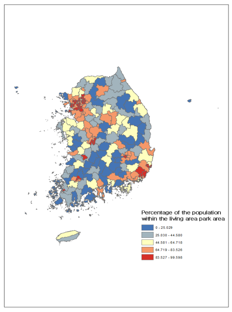
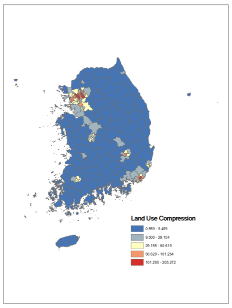
Data Availability Statement: All data are public data that have already been published online, and the source of each data is presented in detail in Figure 1 of this paper. Therefore, the data presented in this study are not separately disclosed.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Natural Break Classify

XP1	XP2	XP3	XP4	XP15
				
XP6	**XS1**	**XS2**	**XS3**	**XS4**
				
XL1	**XL2**	**XL3**	**XL4**	**XL5**



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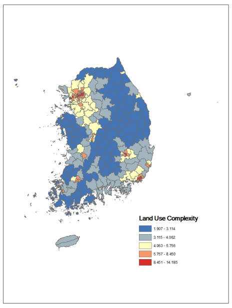

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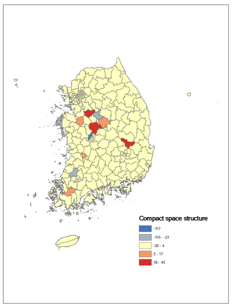

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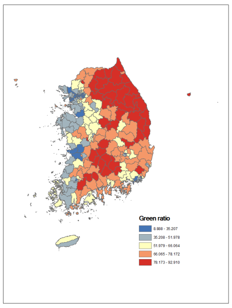
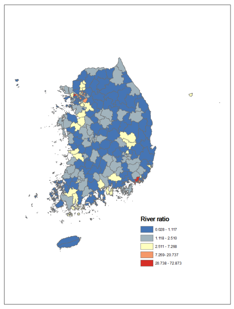


XE1



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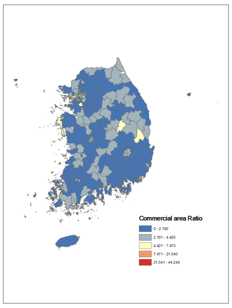

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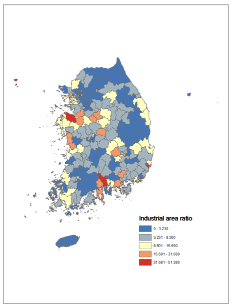

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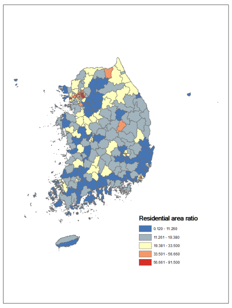
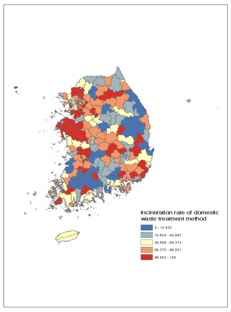
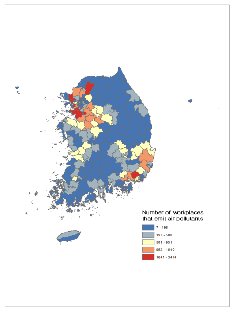


XE5



XE6



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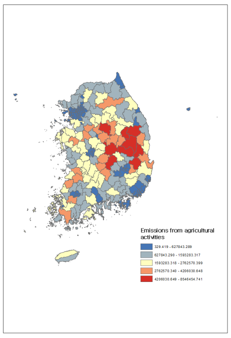

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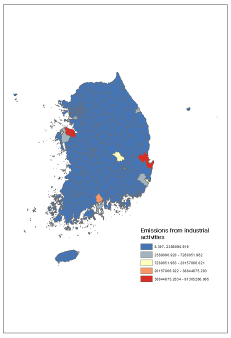

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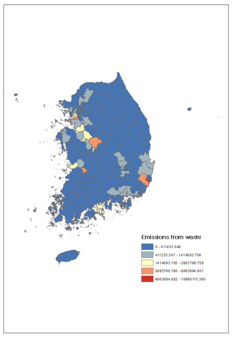

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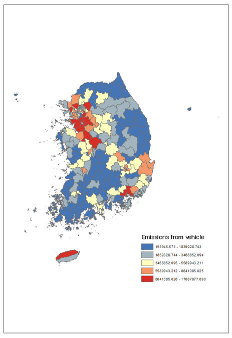

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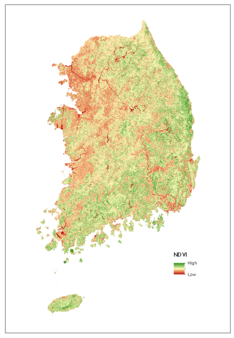
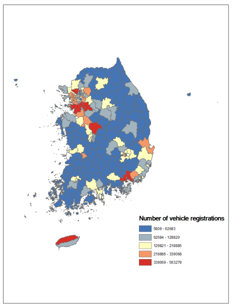
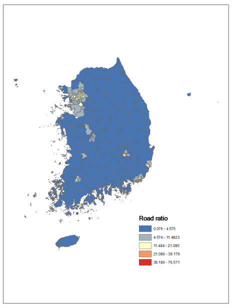


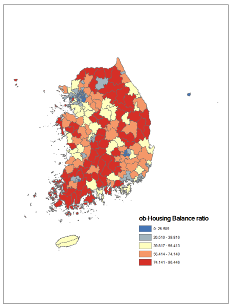
XT5



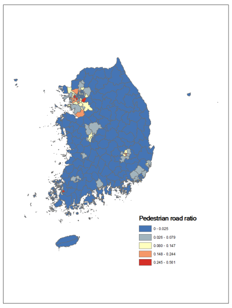
XG1



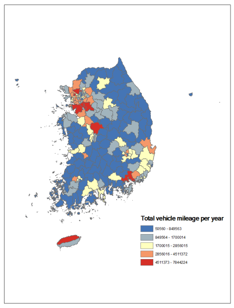
XG2



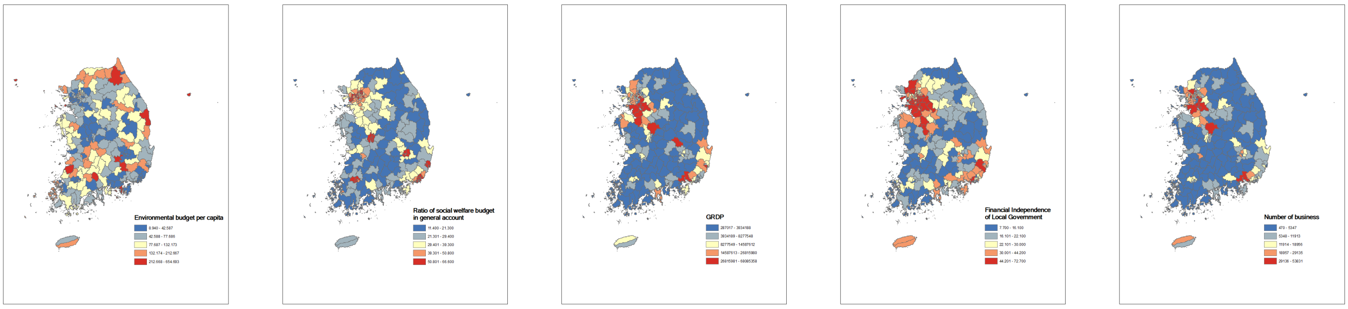
XG3



XG4

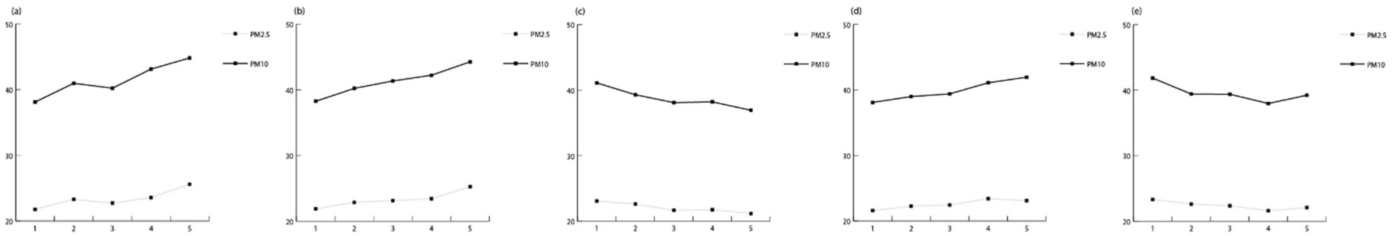


XG5

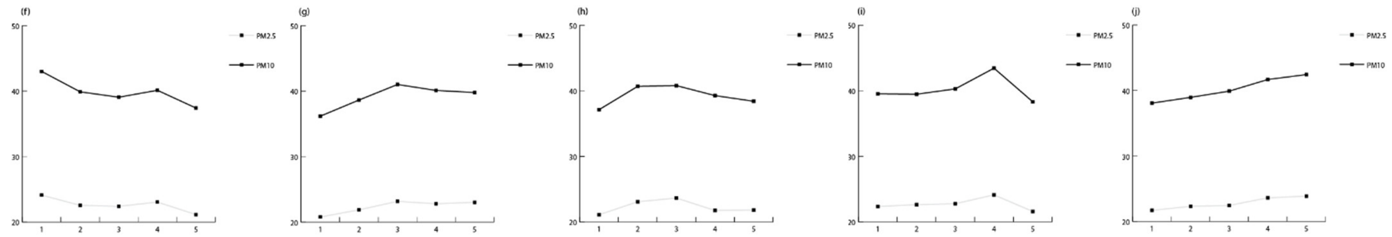


Appendix B. The Risk Detection of the Influencing Factors to PM10 & PM2.5

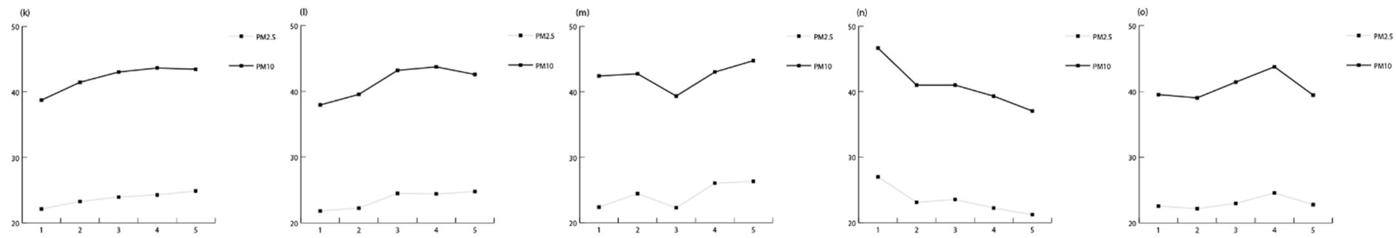
XP1	XP2	XP3	XP4	XP15



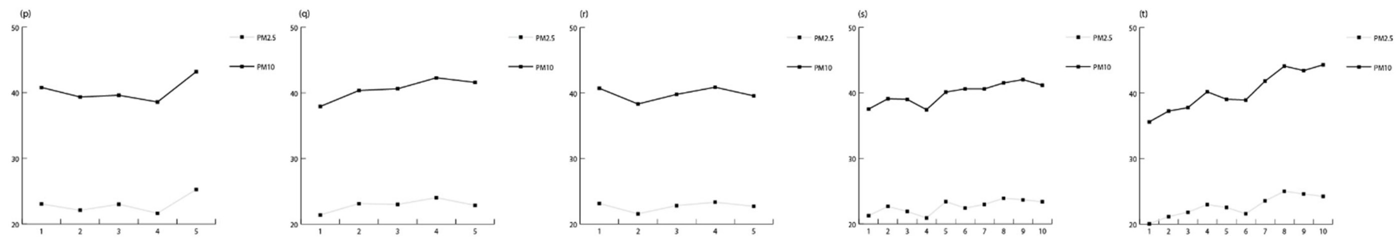
XP6	XS1	XS2	XS3	XS4



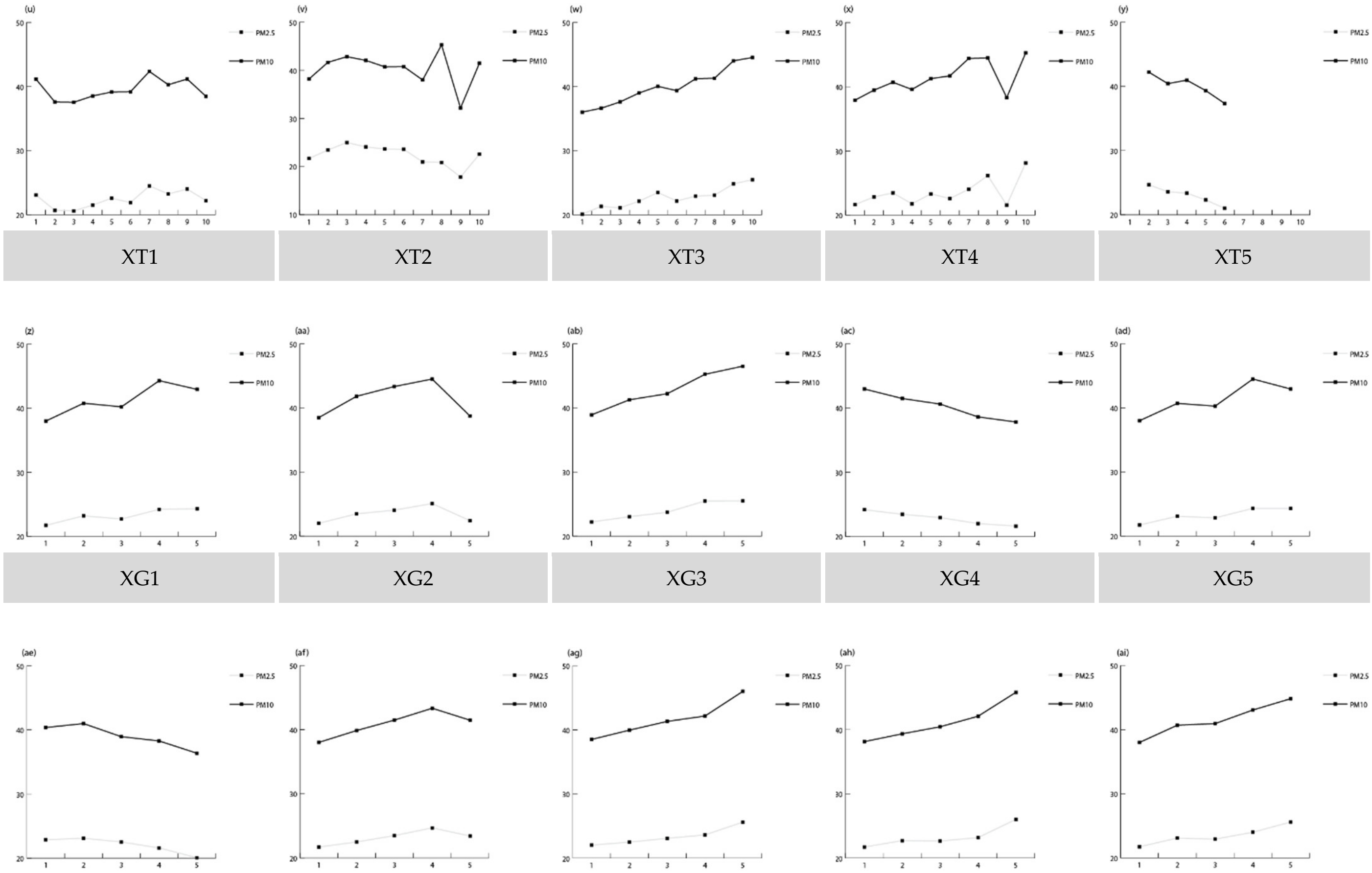
XL1	XL2	XL3	XL4	XL5



XL6	XL7	XL8	XE1	XE2



XE3	XE4	XE5	XE6	XE7


PM2.5
PM10
XT1
XT2
XT3
XT4
XT5
XG1
XG2
XG3
XG4
XG5

Appendix C. The Results of the Interaction Detection for the Influencing Factors of Urban PM_{10} in 2019

	XP1	XP2	XP3	XP4	XP5	XP6	XS1	XS2	XS3	XS4	XL1	XL2	XL3	XL4	XL5	XL6	XL7	XL8
XP1	0.2183																	
XP2	0.2553	0.1695																
XP3	0.2917	0.2611	0.1031															
XP4	0.3540	0.3552	0.2169	0.0835														
XP5	0.4059	0.3794	0.2162	0.1115	0.0772													
XP6	0.3069	0.3393	0.2441	0.3214	0.3556	0.1728												
XS1	0.3643	0.3083	0.3264	0.2964	0.2648	0.3330	0.1100											
XS2	0.3424	0.3117	0.2527	0.2972	0.2502	0.3175	0.2868	0.1094										
XS3	0.2789	0.3070	0.1310	0.1836	0.1619	0.2258	0.1791	0.1499	0.0119									
XS4	0.2586	0.2139	0.1959	0.2648	0.2608	0.2039	0.2783	0.2759	0.1668	0.1265								
XL1	0.2867	0.2468	0.1630	0.2878	0.2540	0.1944	0.2480	0.2760	0.1884	0.2172	0.1416							
XL2	0.3025	0.3059	0.2453	0.3069	0.3144	0.2701	0.3385	0.3134	0.2899	0.2418	0.2293	0.2242						
XL3	0.3011	0.2526	0.1907	0.1347	0.1239	0.2650	0.1747	0.1777	0.0788	0.2162	0.2219	0.2845	0.0680					
XL4	0.4696	0.3903	0.4395	0.4055	0.3732	0.4571	0.3675	0.4025	0.3561	0.4754	0.3961	0.3975	0.3375	0.2905				
XL5	0.2962	0.2384	0.1431	0.1964	0.1713	0.2191	0.1695	0.2113	0.0681	0.2201	0.1908	0.2866	0.1146	0.3646	0.0383			
XL6	0.3326	0.2793	0.1788	0.2401	0.1512	0.2749	0.1886	0.1637	0.0686	0.2865	0.2667	0.3219	0.1267	0.3967	0.1276	0.0253		
XL7	0.3785	0.3692	0.2860	0.2217	0.1993	0.3930	0.2966	0.2603	0.1730	0.3087	0.2956	0.4012	0.2001	0.4148	0.2081	0.3331	0.1150	
XL8	0.3885	0.3409	0.3009	0.2919	0.2577	0.3055	0.2485	0.2581	0.1555	0.3160	0.3064	0.3243	0.1704	0.4272	0.1792	0.1516	0.3200	0.0682
XE1	0.4809	0.5172	0.3713	0.4106	0.3999	0.4555	0.3699	0.3952	0.2947	0.4822	0.3847	0.4559	0.2173	0.5075	0.2831	0.2850	0.4063	0.3567
XE2	0.5419	0.5011	0.4649	0.4905	0.5022	0.4949	0.5968	0.5566	0.5576	0.5070	0.5173	0.5309	0.4215	0.5870	0.5106	0.4862	0.5292	0.5421
XE3	0.4896	0.4654	0.3629	0.4806	0.4950	0.4540	0.3487	0.3908	0.2184	0.4292	0.3758	0.5031	0.2031	0.4577	0.2497	0.2743	0.4162	0.3290
XE4	0.5225	0.5183	0.4100	0.4419	0.3532	0.4935	0.4296	0.4469	0.3486	0.4968	0.4791	0.4987	0.3037	0.5668	0.4181	0.4387	0.4246	0.4192
XE5	0.3997	0.4545	0.4797	0.5421	0.5128	0.4602	0.5775	0.5226	0.4721	0.4883	0.4600	0.4481	0.3849	0.5436	0.4334	0.4688	0.5180	0.5625
XE6	0.4280	0.3897	0.2633	0.4143	0.3768	0.3346	0.4189	0.3818	0.3369	0.3526	0.3000	0.4313	0.2848	0.4910	0.2780	0.4120	0.4319	0.4565
XE7	0.2702	0.2315	0.1742	0.1748	0.1635	0.2482	0.2008	0.2019	0.1022	0.1988	0.2110	0.2725	0.1539	0.3426	0.1245	0.1184	0.2214	0.1514
XT1	0.2556	0.2486	0.3114	0.3401	0.3662	0.3386	0.3593	0.3319	0.2793	0.2880	0.2769	0.3198	0.3203	0.4009	0.2788	0.3327	0.3508	0.3722
XT2	0.2900	0.3018	0.2421	0.2985	0.2966	0.2554	0.3212	0.3140	0.2266	0.2333	0.2114	0.2757	0.2552	0.3750	0.2396	0.3169	0.3338	0.3087
XT3	0.3306	0.2889	0.1789	0.2673	0.2606	0.2211	0.2161	0.3330	0.1861	0.1851	0.1806	0.2744	0.1896	0.3491	0.1489	0.2059	0.3017	0.2618
XT4	0.2776	0.2539	0.2012	0.3318	0.3373	0.2836	0.3407	0.3342	0.2118	0.2160	0.1989	0.2521	0.2479	0.3983	0.2106	0.2178	0.3727	0.2443

XT5	0.3064	0.2974	0.3243	0.3366	0.3610	0.3456	0.3615	0.3743	0.3214	0.3048	0.2735	0.3330	0.3311	0.4525	0.2947	0.3134	0.3730	0.3816
XG1	0.3470	0.3312	0.3113	0.2697	0.2351	0.3825	0.2420	0.2731	0.1256	0.2444	0.2161	0.2868	0.1695	0.3760	0.1489	0.2235	0.2894	0.2764
XG2	0.2897	0.2709	0.2479	0.3842	0.3802	0.2393	0.2845	0.3434	0.2989	0.2306	0.2165	0.2600	0.2651	0.4586	0.2816	0.2828	0.3799	0.3277
XG3	0.3195	0.3519	0.2737	0.3821	0.3821	0.3062	0.3691	0.3574	0.3522	0.2558	0.2584	0.3574	0.2693	0.4828	0.2492	0.3470	0.4155	0.4043
XG4	0.3146	0.2782	0.2707	0.3129	0.2989	0.2949	0.3149	0.2921	0.1880	0.2873	0.2290	0.2823	0.2467	0.4572	0.1977	0.3276	0.3243	0.4047
XG5	0.2610	0.2568	0.3033	0.3490	0.3931	0.3246	0.3749	0.3419	0.3185	0.2655	0.3047	0.3055	0.3061	0.4736	0.2792	0.3321	0.3693	0.3918

	XE1	XE2	XE3	XE4	XE5	XE6	XE7	XT1	XT2	XT3	XT4	XT5	XG1	XG2	XG3	XG4	XG5
XE1	0.1436																
XE2	0.6857	0.3759															
XE3	0.5667	0.7550	0.1317														
XE4	0.5821	0.5618	0.6428	0.2355													
XE5	0.7535	0.5499	0.6714	0.5527	0.3428												
XE6	0.5239	0.5567	0.5451	0.5200	0.5934	0.1993											
XE7	0.2266	0.4238	0.2203	0.3288	0.3962	0.2566	0.0856										
XT1	0.5078	0.5188	0.5280	0.5004	0.4287	0.3804	0.2675	0.2199									
XT2	0.3849	0.5239	0.3924	0.4593	0.4471	0.3209	0.2503	0.2909	0.1920								
XT3	0.3517	0.4961	0.3551	0.4597	0.4704	0.3141	0.1928	0.3299	0.2724	0.1269							
XT4	0.4524	0.5336	0.4109	0.4013	0.4499	0.3242	0.2144	0.2557	0.2515	0.2627	0.1517						
XT5	0.5164	0.5243	0.5242	0.5180	0.4103	0.4170	0.2802	0.2602	0.3216	0.3422	0.2802	0.2314					
XG1	0.3813	0.4967	0.4637	0.3708	0.5254	0.3717	0.1718	0.3733	0.2702	0.2149	0.2496	0.3463	0.0917				
XG2	0.4739	0.5002	0.4499	0.5008	0.4612	0.4016	0.2407	0.2811	0.2934	0.2693	0.2683	0.2971	0.2760	0.1829			
XG3	0.5235	0.4759	0.5156	0.4998	0.4870	0.3984	0.2827	0.3184	0.2636	0.2862	0.3269	0.3422	0.3906	0.3372	0.2181		
XG4	0.4401	0.4858	0.4677	0.4920	0.4027	0.3389	0.2345	0.3267	0.2439	0.2621	0.2516	0.3458	0.2673	0.2871	0.2662	0.1627	
XG5	0.4883	0.5352	0.4851	0.5317	0.3827	0.4351	0.2779	0.2879	0.3215	0.3248	0.2547	0.2890	0.3889	0.2867	0.3157	0.2840	0.2250

Appendix D. The Results of the Interaction Detection for the Influencing Factors of Urban $PM_{2.5}$ in 2019

	XP1	XP2	XP3	XP4	XP5	XP6	XS1	XS2	XS3	XS4	XL1	XL2	XL3	XL4	XL5	XL6	XL7	XL8
XP1	0.0950																	
XP2	0.1232	0.0724																
XP3	0.1836	0.1825	0.0402															
XP4	0.2222	0.2396	0.1493	0.0379														
XP5	0.2910	0.2525	0.1345	0.0450	0.0280													
XP6	0.1617	0.2154	0.1590	0.2368	0.2842	0.0917												
XS1	0.2171	0.1971	0.2363	0.2307	0.1773	0.2078	0.0569											
XS2	0.2484	0.2047	0.1885	0.2598	0.2358	0.2195	0.2336	0.1026										
XS3	0.2119	0.2222	0.0790	0.1429	0.1247	0.1887	0.1151	0.1546	0.0063									
XS4	0.1223	0.1060	0.1360	0.1860	0.1921	0.1125	0.2012	0.2208	0.0993	0.0592								
XL1	0.2122	0.1685	0.0681	0.1419	0.1237	0.0986	0.1532	0.1936	0.1414	0.1584	0.0525							
XL2	0.1610	0.1754	0.1342	0.1745	0.1689	0.1737	0.2011	0.2234	0.2029	0.1368	0.1264	0.1082						
XL3	0.1997	0.1729	0.1679	0.1317	0.1139	0.2115	0.1570	0.2045	0.1013	0.2062	0.1690	0.2182	0.0832					
XL4	0.3122	0.2667	0.2752	0.2762	0.2464	0.3077	0.2430	0.2957	0.2627	0.3399	0.2336	0.2512	0.2770	0.1710				
XL5	0.1525	0.1449	0.0577	0.1438	0.0964	0.1304	0.1160	0.1862	0.0452	0.1291	0.1029	0.1601	0.1307	0.2534	0.0106			
XL6	0.2552	0.1953	0.1365	0.1842	0.1197	0.2164	0.1428	0.1927	0.0750	0.2455	0.2017	0.2328	0.1690	0.2990	0.1047	0.0322		
XL7	0.2607	0.2382	0.2109	0.1803	0.1406	0.3285	0.2102	0.2205	0.1463	0.2874	0.2018	0.2697	0.1976	0.2852	0.1619	0.2954	0.0866	
XL8	0.2760	0.2469	0.2137	0.2414	0.1946	0.2679	0.1759	0.2332	0.1612	0.2509	0.2419	0.2183	0.1898	0.3121	0.1320	0.1202	0.2751	0.0603
XE1	0.3693	0.4244	0.2705	0.3673	0.3680	0.3291	0.2708	0.3895	0.2513	0.4092	0.2861	0.3153	0.2228	0.4122	0.2174	0.3231	0.3834	0.3202
XE2	0.4417	0.3545	0.3110	0.3463	0.3419	0.3725	0.4435	0.4184	0.4621	0.3714	0.3226	0.3016	0.2984	0.4430	0.4272	0.3660	0.4325	0.4121
XE3	0.4360	0.4328	0.3556	0.4429	0.4317	0.4542	0.3066	0.4343	0.2511	0.3889	0.3376	0.4614	0.2643	0.4100	0.2791	0.2866	0.3999	0.3382
XE4	0.4257	0.4379	0.3224	0.3618	0.2759	0.4338	0.3462	0.3798	0.3028	0.4096	0.3926	0.3840	0.2779	0.4454	0.3425	0.3562	0.3239	0.3569
XE5	0.2856	0.3094	0.3732	0.4292	0.3425	0.3565	0.4104	0.4051	0.3392	0.3626	0.3463	0.3183	0.2953	0.4112	0.3287	0.3674	0.3929	0.4498
XE6	0.3480	0.3010	0.1770	0.3334	0.2636	0.2553	0.3722	0.3239	0.3030	0.2530	0.2014	0.3277	0.2131	0.4042	0.2130	0.3229	0.3583	0.3918
XE7	0.1528	0.1331	0.1064	0.1153	0.1037	0.1642	0.1319	0.1692	0.0840	0.1244	0.1179	0.1572	0.1587	0.2189	0.0852	0.1103	0.1789	0.1305
XT1	0.1199	0.1150	0.2065	0.1970	0.2477	0.1826	0.2184	0.2223	0.1915	0.1671	0.1643	0.1829	0.2343	0.2215	0.1236	0.2444	0.2473	0.2470
XT2	0.1556	0.1708	0.1068	0.1666	0.1465	0.1522	0.1765	0.2329	0.1266	0.1122	0.0924	0.1460	0.1759	0.2259	0.1139	0.2405	0.1999	0.2271
XT3	0.1785	0.1785	0.0741	0.1304	0.1326	0.1243	0.1104	0.2400	0.1215	0.1160	0.0757	0.1568	0.1462	0.2031	0.0733	0.1344	0.1984	0.1812
XT4	0.1548	0.1433	0.1142	0.2358	0.2159	0.1926	0.2504	0.2511	0.1214	0.1335	0.1027	0.1300	0.1912	0.2125	0.1113	0.1781	0.2875	0.1676
XT5	0.1416	0.1403	0.1926	0.2067	0.2358	0.1808	0.2061	0.2485	0.2310	0.1556	0.1548	0.1746	0.2329	0.2693	0.1252	0.2182	0.2626	0.2391

XG1	0.2816	0.2239	0.2182	0.2667	0.1470	0.3009	0.2279	0.2239	0.0800	0.2176	0.1264	0.1755	0.1602	0.2599	0.1129	0.1740	0.2520	0.2341
XG2	0.1717	0.1595	0.1803	0.2347	0.2263	0.1450	0.1783	0.2222	0.2412	0.1347	0.1328	0.1339	0.2298	0.2845	0.1927	0.2298	0.2705	0.2502
XG3	0.1786	0.2059	0.1626	0.2018	0.2428	0.1759	0.2128	0.2553	0.2810	0.1239	0.1238	0.1919	0.1764	0.3088	0.1578	0.2226	0.3001	0.2510
XG4	0.1775	0.1744	0.1753	0.2446	0.1879	0.2050	0.2072	0.2260	0.1355	0.1882	0.1303	0.2077	0.2072	0.3044	0.0883	0.2677	0.2457	0.2985
XG5	0.1364	0.1344	0.2042	0.2140	0.2605	0.1907	0.2270	0.2475	0.2391	0.1413	0.1977	0.1763	0.2113	0.3105	0.1506	0.2520	0.2369	0.2631
	XE1	XE2	XE3	XE4	XE5	XE6	XE7	XT1	XT2	XT3	XT4	XT5	XG1	XG2	XG3	XG4		XG5
XE1	0.1082																	
XE2	0.6685	0.2076																
XE3	0.6613	0.6968	0.1612															
XE4	0.5092	0.4490	0.6105	0.1727														
XE5	0.6753	0.4798	0.5879	0.4645	0.2083													
XE6	0.4726	0.4793	0.4928	0.4486	0.4983	0.1237												
XE7	0.1833	0.2711	0.2283	0.2773	0.2720	0.1789	0.0686											
XT1	0.4262	0.4114	0.4461	0.4132	0.3039	0.2959	0.1408	0.0854										
XT2	0.2490	0.3594	0.3361	0.3716	0.3046	0.2115	0.1368	0.1308	0.0721									
XT3	0.2499	0.2839	0.3178	0.3588	0.3303	0.2399	0.1071	0.1781	0.1217	0.0493								
XT4	0.3273	0.3705	0.3716	0.3874	0.3090	0.2509	0.1271	0.1110	0.1162	0.1507	0.0683							
XT5	0.4013	0.4025	0.4414	0.4102	0.2807	0.3318	0.1404	0.1192	0.1603	0.1838	0.1166	0.0863						
XG1	0.3229	0.3283	0.4113	0.3190	0.4217	0.2966	0.1253	0.2981	0.1678	0.1156	0.1850	0.2702	0.0591					
XG2	0.3748	0.3559	0.4751	0.4040	0.3475	0.2921	0.1498	0.1588	0.1753	0.1659	0.1788	0.1651	0.2104	0.0980				
XG3	0.4062	0.3056	0.4466	0.4202	0.3314	0.3107	0.1497	0.1588	0.1164	0.1577	0.2025	0.1694	0.2624	0.1815	0.0844			
XG4	0.3508	0.3102	0.3874	0.4143	0.3163	0.2823	0.1375	0.1668	0.1237	0.1463	0.1385	0.1740	0.1829	0.2001	0.1619	0.0680		
XG5	0.3972	0.3884	0.4335	0.4241	0.2556	0.3525	0.1592	0.1596	0.1754	0.2073	0.1353	0.1373	0.2884	0.1654	0.1451	0.1709		0.1029

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