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Investigating the Effects of the Built Environment on $PM_{2.5}$ and PM_{10}: A Case Study of Seoul Metropolitan City, South Korea

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Abstract: Air pollution has a major impact on human health and quality of life; therefore, its determinants should be studied to promote effective management and reduction. Here, we examined the influence of the built environment on air pollution by analyzing the relationship between the built environment and particulate matter (i.e., $PM_{2.5}$ and PM_{10}). Air pollution data collected in Seoul in 2014 were spatially mapped using geographic information system tools, and $PM_{2.5}$ and PM_{10} concentrations were determined in individual neighborhoods using an interpolation method. $PM_{2.5}$ and PM_{10} failed to show spatial autocorrelation; therefore, we analyzed the associations between PM fractions and built environment characteristics using an ordinary least squares regression model. $PM_{2.5}$ and PM_{10} exhibited some differences in spatial distributions, suggesting that the built environment has different effects on these fractions. For instance, high PM_{10} concentrations were associated with neighborhoods with more bus routes, bus stops, and river areas. Meanwhile, both $PM_{2.5}$ and PM_{10} were more likely to be high in areas with more commercial areas and multi-family housing, but low in areas with more main roads, more single-family housing, and high average gross commercial floor area. This study is expected to contribute to establishing policies and strategies to promote sustainability in Seoul, Korea.

Keywords: air pollution; built environment; geographic information system; particulate matter

1. Introduction

Korea, particularly its capital Seoul, has experienced substantial economic growth; however, such development has also had adverse effects on the environment, including a rise in air pollution [1]. Air pollution is recognized as a serious problem in metropolitan cities in Korea and worldwide. According to the World Health Organization (WHO), about 4.2 million people die annually from air pollution-related diseases. Moreover, approximately 91% of the world's population lives in areas with air pollutant levels that exceed the WHO standards [2]. Increased exposure to higher concentrations of air pollutants has a detrimental effect on health and can trigger respiratory, cardiovascular, and lung diseases [3,4]. Therefore, it is necessary to identify the influence of the built environment on air pollution to build safe neighborhoods that are protected from air pollution.

Dust can be classified into total suspended particles and particulate matter (PM) fractions based on particle size, such as PM_{10} (<10 µm in diameter) and $PM_{2.5}$ (<2.5 µm in diameter). Prolonged exposure to high levels of PM may increase the risk of diabetes and respiratory disease [5,6]. Meanwhile, exposure to $PM_{2.5}$ is associated with heart and respiratory diseases [7], and the WHO has designated $PM_{2.5}$ as a Group 1 carcinogen [8].

According to the Organisation for Economic Co-operation and Development (OECD) statistics, the average $PM_{2.5}$ level in Korea was 32 µg/m^3 in 2015, more than three times the WHO standard of

10 $\mu g/m^3$, representing the worst $PM_{2.5}$ level among the OECD countries [9]. Many studies within a wide array of fields, such as public health, environment, urban planning, transportation, and medicine, have investigated both PM_{10} and $PM_{2.5}$ with the aim of investigating air pollution problems [10–13]. However, in Korea, because $PM_{2.5}$ has only been measured and managed since 2013, there is relatively little research on $PM_{2.5}$ compared to PM_{10} [14,15].

From the studies on PM, the association of PM with the built environment is of interest. However, there is controversy regarding the relationship between land use and PM concentrations. For instance, some studies have demonstrated a positive relationship between $PM_{2.5}$ and residential area [11,16,17], while others have found lower PM concentrations in residential areas [18–20]. In particular, Chen et al. [21] and Rivera et al. [22] showed that PM_{10} was high in residential areas and especially high in high-density residential areas. Commercial areas have also been shown to have a positive relationship with PM levels [10,18–20]. For instance, in a study on air pollution around roads, the number of commercial facilities (e.g., restaurants) had a greater influence on $PM_{2.5}$ than the general presence of commercial land use [23]. Meanwhile, most studies have found high PM_{10} and $PM_{2.5}$ concentrations in industrial areas [12,13,16–18,20,21,23–25]. Finally, many studies have found lower PM_{10} and $PM_{2.5}$ levels in green areas [10,19,26,27]. However, McCarty and Kaza [28] found high PM_{10} levels in green areas and Weichenthal et al. [20] showed the same result for $PM_{2.5}$. Other studies have assessed the association of PM with other land use variables (e.g., river area [11,20,23,24] and urbanization area [25]). These findings showed that $PM_{2.5}$ and PM_{10} have a dependency on the typology of measurement site but not the metal content [29]. Built environment attributes related to transportation are also associated with PM concentration. Traffic volume on roads was found to have a significant effect on PM [16,23,27,30]. Regarding vehicle type, truck density and truck route length were found to be positively correlated with $PM_{2.5}$ [20,31,32]. Moreover, Rivera et al. [22] showed that $PM_{2.5}$ was higher in regions with more vehicles and motorcycles. In addition, road type has been found to affect PM. Liu et al. [24] found that $PM_{2.5}$ levels were positively associated with highway intensity in Shanghai, China. Several studies have revealed a positive association between road length and PM [11,12,16,17,21]. In a study of intersections in Toronto, Canada, Weichenthal et al. [10] revealed a positive relationship between intersections and $PM_{2.5}$. By contrast, Hankey and Marshall [16] found a negative correlation between intersections and $PM_{2.5}$ in Minneapolis, USA. In addition, road width [13,18], bus route length [10,16], and the number of bus stops [16] have been examined as determinants of PM.

Development density has also been studied as a determinant of PM [11,13,18,30]. Weichenthal et al. [18] found a positive relationship between average building height and $PM_{2.5}$. Meanwhile, Wolf et al. [11] showed that $PM_{2.5}$ levels were higher in areas with more buildings. In addition, Tang et al. [13] found high PM_{10} levels in areas with high building volumes. Oh and Chung [30] further divided the number of buildings into residential areas, commercial areas, and industrial areas to study the impact of development density on PM_{10} by land type. The number of buildings in residential and commercial areas had positive relationships with PM_{10}; however, the number of buildings in industrial areas had a negative relationship. Meanwhile, Oh and Chung [30] examined the relationship between PM_{10} and gross building floor area of individual residential, commercial, and industrial areas. The gross residential and commercial floor areas were positively associated with PM_{10}, while the gross industrial floor area was negatively associated.

Although many studies have examined the relationship between PM and the built environment, the results show dependency on the spatiotemporal characteristics unique to each study; therefore, continuous research on the relationship between the built environment and PM is needed. Moreover, there is little research on $PM_{2.5}$ specific to Korea. Therefore, we investigated the association between PM and the built environment in neighborhoods in Seoul, Korea. We classified PM into $PM_{2.5}$ and PM_{10} to further investigate the differences in the effects of the built environment (e.g., land use, transportation, housing, and urban development density) on these two fractions of PM. This study will help contribute to the development of eco-friendly environmental policies and interventions to support sustainability in Seoul.

2. Materials and Methods

2.1. Study Area

This study was conducted using air quality monitoring data from Seoul collected in 2014. Seoul is the capital city of the Republic of Korea and is the center of politics, economy, culture, and transportation in Korea. The total area of Seoul is 605.21 km^2. Seoul has a population of about 9.8 million, with 25 autonomous districts and 424 neighborhood-level administrative units. The total area of Seoul comprises 20% residential area, 30% green area, 13% residential and commercial mixed-use area, and 6% commercial and official area.

2.2. Data

2.2.1. Air Pollution

This study used air quality monitoring data from 2014 provided by the Korea Environment Corporation (KECO) [33]. These data included six types of air pollutants measured and collected at 40 monitoring stations, including 25 municipal air monitoring stations located in each of Seoul's autonomous districts and 15 main road air monitoring stations (Figure 1). This study focused on $PM_{2.5}$ and PM_{10} among the six air pollutants to examine the differences in the effects of the built environment on $PM_{2.5}$ and PM_{10}. The 40 air pollution monitoring stations were geocoded and displayed on a geographic information system (GIS) map for considering the spatial attributes of the air pollutants. The concentrations of $PM_{2.5}$ and PM_{10} collected from the 40 monitoring stations were converted into a GIS-compatible database.

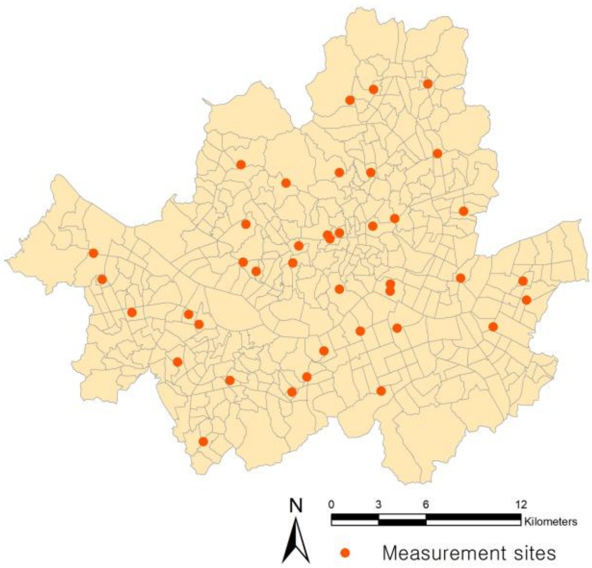

Figure 1. Air monitoring stations in Seoul.

2.2.2. Land Use

Land-use data from 2014 provided by the National Geographic Information Institute (NGII) were used [34]. In Korea, land use in urban areas is classified into four categories: residential, commercial, industrial, and green areas. Data on river areas were obtained from the Seoul Open Data Plaza [35].

2.2.3. Transportation

Transportation-related data were provided from the Korea Transportation Database (KTDB), the road name address guidance system, and the Korea Local Information Research & Development Institute (KLID) [36]. These transportation data were based on GIS maps, and include spatial coordinate information, bus routes, bus stops, subway station, road type, and road length.

2.2.4. Housing Type and Development Density

The characteristics of housing type were obtained from data on building use from the road name address guidance system, as well as the transportation data [36]. These data include the number of ground floors, underground floors, and spatial coordinate information for individual buildings, such as single-family housing, multi-family housing, sports facilities, business facilities, etc. In this study, we extracted housing data related to single-family and multi-family housing to identify the effects of neighborhood development density in residential areas on $PM_{2.5}$ and PM_{10}.

In addition, we examined the differences in the influence of urban development density in residential and commercial areas. Development density was obtained from the National Spatial Data Infrastructure Portal, which provides an OPEN API service [37]. These data include information on the building structure, land area, height, coverage ratio, and building area (e.g., gross floor area and floor area ratio). Using these data, we measured the average of gross floor area in residential and commercial areas by neighborhood.

2.3. Measurement of Variables

2.3.1. Spatial Unit of Analysis

We set the neighborhood-level administrative unit (*dong*, in Korean) as the spatial unit of analysis to identify the characteristics of the built environment related to $PM_{2.5}$ and PM_{10} at the neighborhood level. We analyzed the overall characteristics of air pollution in Seoul by measuring $PM_{2.5}$ and PM_{10} at the neighborhood level, rather than analyzing only the built environment around the 40 air pollution monitoring stations. The accuracy of analyses can be improved by using the smallest unit of administration as a spatial unit. Therefore, we expected our analysis to offer an accurate description of the current status of PM pollution in Seoul to help establish efficient air pollution reduction policies and strategies at the neighborhood level.

2.3.2. Dependent Variables

The $PM_{2.5}$ and PM_{10} concentrations at the neighborhood level were used as the dependent variables. $PM_{2.5}$ and PM_{10} concentrations, which were geocoded and built into the geodatabase, were determined using the inverse distance weighted (IDW) interpolation method for GIS. The size of the raster used in the IDW interpolation method was 25 m $\times$ 25 m, representing the smallest area used in previous studies [38]. Finally, the $PM_{2.5}$ and PM_{10} values from the IDW interpolation method were determined at the neighborhood level through the GIS zonal statistics tool.

Figures 2 and 3 show the processes used to determine the $PM_{2.5}$ and PM_{10} concentrations at the neighborhood level. $PM_{2.5}$ and PM_{10} at the neighborhood level in Seoul were in the range of 21–37 $\mu g/m^3$ and 43–62 $\mu g/m^3$, respectively. In Korea, the air-quality standard for $PM_{2.5}$ is an annual average of 15 $\mu g/m^3$; therefore, the $PM_{2.5}$ concentrations in all neighborhoods in Seoul exceeded the standard, indicative of potentially detrimental atmospheric conditions in Seoul. Meanwhile, the annual air-quality standard of PM_{10} is 50 $\mu g/m^3$; therefore, only some neighborhoods in Seoul had PM_{10} concentrations of concern. Moreover, the GIS maps in Figures 2 and 3 showed markedly different spatial distributions of $PM_{2.5}$ and PM_{10}. This suggests that the neighborhood-level built environment may have had different effects on $PM_{2.5}$ and PM_{10}; therefore, it was necessary to examine the differences between the effects of the built environment on $PM_{2.5}$ and PM_{10}.

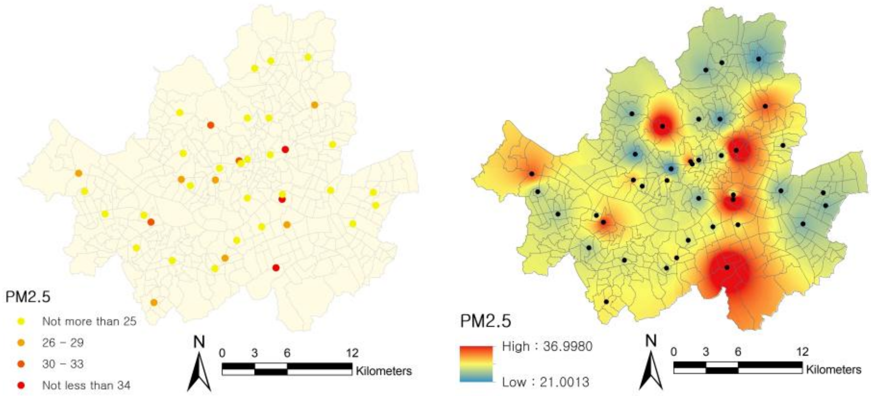

Figure 2. Spatial distribution of particulate matter ($PM_{2.5}$) in Seoul.

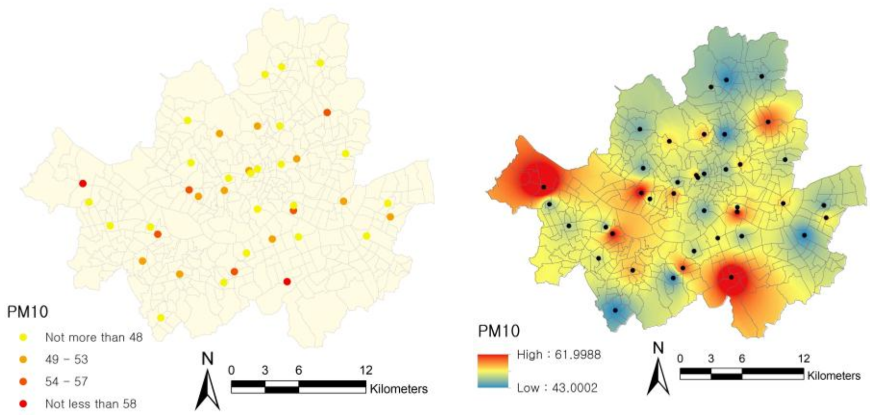

Figure 3. Spatial distribution of PM_{10} in Seoul.

2.3.3. Independent Variables

The independent variables were classified into four categories: land use, transportation, housing, and development density. Regarding the characteristics of land use, the proportions of commercial area, industrial area, green area, and river area were considered as features of the built environment. The land-use mix index, a measure differentiating between single or mixed use in a neighborhood, was also set as a variable where the index value ranged from 0 (single use) to 1 (perfectly mixed use) [39].

For the transportation attributes, the number of bus routes per hectare, number of bus stops per hectare, proportion of neighborhood streets, proportion of main roads, number of intersections per hectare, and presence of subway stations (dummy) were included in the analysis. In relevance to development density, this study considered the difference in residential density according to the type of housing and the distinction between residential density and commercial density. Development density can be represented as the factor for the degree of land use. High development density may significantly increase the consumption of energy and the operations of urban facilities. The number of single-family houses per hectare and the number of multi-family houses per hectare were included in the model to examine the degree of development density by housing type in residential areas. In addition, the average gross floor area of residential areas and the average gross floor area of commercial areas were measured to distinguish the differences in development density between residential and commercial areas. Finally, all variables were reported in terms of density, proportion, and average to minimize analysis errors caused by differences in neighborhood area.

3. Results and Discussion

3.1. Spatial Autocorrelation Analysis

Air pollutants naturally have spatial attributes, given the transport of dust in the atmosphere; therefore, it was necessary to assess the spatial autocorrelation of the PM fractions using Moran's I test. Spatial autocorrelation is defined as a measure of spatial similarity between nearby observations. Spatially, parameters that are nearby have a similar tendency as parameters that are far away. If spatial autocorrelation is found, it should be analyzed using a spatial econometrics model that can control for spatial autocorrelation. If spatial autocorrelation does not appear, it is appropriate to employ the ordinary least squares (OLS) regression model.

Table 1 shows the Moran's I test results for $PM_{2.5}$ and PM_{10} using ArcGIS. $PM_{2.5}$ (Moran's I = −0.22, p = 0.18) and PM_{10} (Moran's I = −0.21, p = 0.22) failed to show spatial autocorrelation, indicating that they were influenced more by the neighborhood-level built environment than by each other. Therefore, this study used the OLS regression model, as described previously [10,24,40].

Table 1. Moran's I test for spatial autocorrelation.

Air Pollutants	Moran's I	*p*-Value
$PM_{2.5}$	−0.224	0.181
PM_{10}	−0.210	0.220

3.2. Descriptive Statistics of Variables

Table 2 shows the descriptive statistics of variables considered in this study. The neighborhood mean of annual average concentrations of $PM_{2.5}$ and PM_{10} were 26 μg/m^3 and 48 μg/m^3, respectively. Among the built environment characteristics, land-use-related attributes (e.g., commercial, industrial, green, and river areas) showed large variations among neighborhoods. The mean land-use mix index was 0.21, indicative of relatively low levels of mixed land use in neighborhoods in Seoul. Regarding the transportation attributes, the average densities of bus routes and bus stops were 0.3 counts/ha and 0.2 counts/ha, respectively, and about 50% of the neighborhoods in Seoul had at least one subway station. Meanwhile, there was an average of 0.21 intersections/ha in the neighborhoods. In terms of roads, 57% were neighborhood streets and 25% were main roads. Residential areas had an average of 8.73 single-family houses/ha and 3.28 multi-family houses/ha. The average gross floor area in residential areas and commercial areas were 4714 m^2 and 2903 m^2, respectively. These results revealed a relatively low degree of urban development in commercial areas compared to residential areas, despite the presence of commercial land use.

Table 2. Descriptive statistics of variables.

Variables		Definition (Measures of Neighborhood)	Unit	Mean	Std. Deviation
Particulate matter	$PM_{2.5}$	Annual average concentration of $PM_{2.5}$	μg/m^3	25.54	1.54
	PM_{10}	Annual average concentration of PM_{10}	μg/m^3	48.44	2.16
Land use	Commercial area	Proportion of commercial area	%	5.25	13.18
	Industrial area	Proportion of industrial area	%	3.70	13.34
	Green area	Proportion of green area	%	19.99	24.82
	Water area	Proportion of water area	%	4.65	10.10
	Mixed use	Land-use mix index	$0 \leq \times \leq 1$	0.21	0.18
Transportation	Bus route	Number of bus routes per hectare	counts/ha	0.30	0.26
	Bus stop	Number of bus stops per hectare	counts/ha	0.23	0.13
	Intersection	Number of intersections per hectare	counts/ha	0.21	0.12
	Neighborhood road	Proportion of neighborhood roads	%	57.21	17.46
	Main road	Proportion of main roads	%	25.11	15.41
	Subway station	Presence of subway station (0 = no presence, 1 = presence)	dummy	0.50	0.50
Housing type	Single-family housing	Number of single-family houses per hectare	counts/ha	8.78	7.60
	Multi-family housing	Number of multi-family houses per hectare	counts/ha	3.28	2.55
Development density	Gross commercial floor area	Average gross floor area of commercial areas	Avg. (m^2)	2903.64	21,370.91
	Gross residential floor area	Average gross floor area of residential areas	Avg. (m^2)	4714.19	54,272.23

3.3. Regression Analysis

Table 3 shows the results of the regression models. The adjusted R^2 values of $PM_{2.5}$ and PM_{10} were 10.7% and 13.1%, respectively, indicating that the PM_{10} model was slightly more explanatory than the $PM_{2.5}$ model. However, the adjusted R^2 values of both models were relatively low so that the models did not seem to explain very much of this variability. This could suggest the limitation of the variables considered in this model that does not effectively take into account the direct pollutant sources of $PM_{2.5}$ and PM_{10}. For more precise and effective pollution management and measurement, it also suggests that it is necessary to build more air monitoring stations in addition to the existing 40 monitoring stations. Overall, the $PM_{2.5}$ and PM_{10} results were similar, although some built environment characteristics had different effects on $PM_{2.5}$ and PM_{10}. This suggests that it may be necessary to consider individual PM fractions to support more efficient targeted air pollution reductions, rather than general, comprehensive air pollution reduction plans.

Among the land-use characteristics, the proportion of commercial area had a significant effect in both the $PM_{2.5}$ and PM_{10} models. However, interestingly, both $PM_{2.5}$ and PM_{10} were likely to be lower in neighborhoods with a greater proportion of commercial area. These results are inconsistent with a previous study [18] but may represent the unique characteristics of land use in Seoul, Korea. In Seoul, even when land use is zoned as commercial land, the actual level of development of commercial land tends to be low. However, when considering urban development density characteristics indicative of the actual degree of development density, the average gross floor area of commercial areas showed a positive correlation with both $PM_{2.5}$ and PM_{10} concentrations. Therefore, it may be necessary to consider inconsistencies between the development status of land use and typical land use [10,30].

Table 3. Results of the regression models.

		$PM_{2.5}$		PM_{10}	
	Variable	**β**	***t*-Value**	**β**	***t*-Value**
	Constant	25.094	28.126***	46.992	38.192 ***
Land use	Commercial area	−0.025	−3.055 ***	−0.033	−2.936 ***
	Industrial area	0.003	0.427	0	−0.027
	Green area	−0.007	−1.212	0.009	1.204
	Water area	0.002	0.264	0.022	1.908 *
	Mixed use	0.206	0.376	0.072	0.095
Transportation	Bus route	−0.128	−0.372	1.249	2.628 ***
	Bus stop	−0.184	−0.277	1.563	1.705 *
	Intersection [a]	0.014	0.104	0.244	1.349
	Neighborhood road	0.007	0.904	0.003	0.315
	Main road	0.025	3.104 ***	0.032	2.890 ***
	Subway station (dummy)	−0.037	−0.238	0.193	0.895
Housing type	Single-family housing [a]	0.18	2.875 ***	0.162	1.876 *
	Multi-family housing [a]	−0.583	−4.793 ***	−0.344	−2.052 **
Development density	Gross commercial floor area [a]	0.089	3.868 ***	0.12	3.769 ***
	Gross residential floor area [a]	−0.052	−0.645	−0.075	−0.674
	F	4.395 ***		5.237 ***	
	R-Square	0.139		0.161	
	Adj. R-Square	0.107		0.131	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, [a], log transformation.

The $PM_{2.5}$ and PM_{10} models failed to show a statistical significance with the industrial area, in contrast to the findings of previous literature [12,13,16–18,20,21,23–25]. This finding may be related to urban policies that led to the reduction in air pollution through factory relocations or changes that were made to factories in existing industrial areas located in the city center, such as by their replacement with eco-friendly commercial complexes and residential complexes. Green areas also failed to yield statistically significant associations with $PM_{2.5}$ or PM_{10} in agreement with literature [26–29]. Interestingly, higher PM_{10} concentrations were associated with neighborhoods with more river areas, although the significance of this relationship was low. This counterintuitive result may be due to the fact that the main traffic corridors within Seoul are located along the north and south banks of the Han River. Finally, the land-use mix index was not significantly associated with $PM_{2.5}$ or PM_{10}.

Of the transportation attributes, the proportion of neighborhood streets was not significantly associated with $PM_{2.5}$ or PM_{10}. However, the proportion of main roads, which tend to have high traffic volumes, showed a strong positive relationship with both $PM_{2.5}$ and PM_{10}, similar to previous studies [12,16,17,21]. The presence of subway stations in a neighborhood, which is considered to reflect the association between PM and subways as a form of public transportation that helps mitigate road traffic, showed no significant association with $PM_{2.5}$ or PM_{10}. Finally, no significant relationship between $PM_{2.5}$ or PM_{10} and the number of intersections was found, which was considered to represent the influence of air pollution due to idling vehicles in the city center. This is in contrast to the positive correlation shown in previous studies [10,16]. Interestingly, bus-related variables showed different results for $PM_{2.5}$ and PM_{10}. The densities of bus routes and bus stations were positively associated with higher levels of PM_{10} but showed no association with $PM_{2.5}$. This is consistent with the literature [10,16] and suggests that pollutants emitted by buses may be associated more with PM_{10} than $PM_{2.5}$. The distinction observed for bus-related factors in $PM_{2.5}$ and PM_{10} could suggest that buses have a larger emission in the coarse fraction (2.5 µm < particles < 10 µm in diameter). This is compatible with a larger contribution of non-exhaust emissions of buses compared to cars [41].

Regarding housing type and urban development density, higher $PM_{2.5}$ and PM_{10} concentrations tended to be associated with neighborhoods with higher average gross commercial floor area, similar to previous research [30]. However, $PM_{2.5}$ or PM_{10} was not associated with the average gross residential floor area, unlike previous studies [16,22] that showed higher $PM_{2.5}$ levels in high-density residential areas. Regardless, the more detailed built environmental characteristics of residential areas showed interesting findings. Contrary to the results of Rivera's study [22], lower $PM_{2.5}$ and PM_{10} levels were associated with neighborhoods with more multi-family houses, whereas both $PM_{2.5}$ and PM_{10} tended to be higher in areas with more single-family houses. This distinction between multi-family and single-family housing may be due to the Korean-specific housing characteristic where community complexes of high-rise multi-family housing, which is a typical type of multi-family housing in Korea, tend to be well-organized and include parks and green areas.

4. Conclusions

Air pollution has a major impact on human health and quality of life, necessitating the identification of the determinants of air pollutants to support air pollution reductions. The purpose of this study was to examine the effects of the built environment on urban air pollution in Seoul, Korea, with a focus on the distinction between the effects on $PM_{2.5}$ and PM_{10} as the most serious atmospheric pollutants in Korea.

The $PM_{2.5}$ and PM_{10} models showed similar associations with many of the investigated neighborhood-level built environment characteristics. For example, $PM_{2.5}$ and PM_{10} tended to be low in neighborhoods with greater proportions of commercial areas and multi-family housing. By contrast, neighborhoods with greater proportions of main roads, single-family housing, and higher average gross residential floor area were associated with higher $PM_{2.5}$ and PM_{10} concentrations. However, clear discrepancies between $PM_{2.5}$ and PM_{10} were also observed. For instance, bus-related features (e.g., bus stops and bus routes) and the proportion of river area were associated only with higher PM_{10} levels.

These findings suggest the need to establish targeted policies and strategies that acknowledge the differences between $PM_{2.5}$ and PM_{10}. In particular, for urban sustainability in Seoul, efficient planning and management of the built environment—such as land use, transportation, housing, and development density considered in this study—is needed beyond the management of direct air pollutant sources. Finally, the results of this study highlight the need for additional research to obtain more detailed data, especially time series data of air pollution and built environments, to inform policy interventions and provide specific policy recommendations.

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