Article

Analysis of the Effects of Floor Area Ratio Change in Urban Street Canyons on Microclimate and Particulate Matter

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Abstract: Air pollution, such as particulate matter (PM), and extreme weather are causing increasingly complex problems and socioeconomic damage in urban environments year-round. This study predicts extreme weather and air pollution changes that occur in urban street canyons as the basic data necessary for research on energy conservation. Changes in PM and microclimate elements based on the change in floor area ratio are analyzed. In addition, the effects of microclimate elements on the distribution of PM factors are examined. Based on the change in floor area ratio, high-concentration PM was negatively correlated with PM$_{2.5}$, PM$_{10}$, NO$_x$, NO$_2$, Ta, T$_{mrt}$, and T$_{surface}$. Extreme heat was observed to be negatively correlated with T$_{mrt}$ and T$_{surface}$, and extreme cold negatively correlated with PM$_{2.5}$, PM$_{10}$, NO$_2$, and NO$_x$. The higher the floor area ratio, the higher the wind speed (WS), indicating a positive correlation between the two factors. Ta, T$_{mrt}$, and T$_{surface}$ were observed to be negatively correlated with PM$_{2.5}$, PM$_{10}$, NO$_2$, and NO$_x$. WS showed negative correlations with PM$_{2.5}$, PM$_{10}$, NO$_2$, and NO$_x$. The results of this study can be used as basic data for the derivation of evaluation indices and to determine prediction and response strategies with respect to a combination of extreme weather and air pollution to ensure a suitable and sustainable quality of life. This study helps predict energy loads according to urban street canyon structures and examines whether trees and green walls are effective in reducing extreme weather and air pollution and saving energy.

Keywords: floor area ratio; extreme weather; Envi-met; particulate matter; urban street canyons; microclimate

1. Introduction

1.1. Background and Significance of Study

Extreme heat and cold, which are long-term effects of climate change, occur frequently. Furthermore, global damage from frequent floods, droughts, and increasingly powerful cyclones is increasing. The occurrence of particulate matter (PM), in addition to heat waves, heavy rains, and droughts, affects people’s health and the economy in all seasons. In particular, increasing populations in cities are worsening climate change phenomena such as air pollution and urban heat islands. Given the current trend of population growth and urbanization, urban areas are expected to triple in size from approximately 40,000 km$^2$ in 2010 to approximately 1.2 million km$^2$ by 2030, and approximately 90% of the world population (approximately 8 billion people) will live in cities by 2025. As a result of this urban growth, the area of artificial covers in urbanized areas will increase [1]. In South Korea, the acceleration of urbanization during the 1980s led to an increase in the urbanized areas: approximately 95% from 2133 km$^2$ (2.1% of national land) to 4154 km$^2$ (4.1% of national land) in the 2000s [2]. Accelerated urbanization, extreme weather, and air pollution have adverse effects on people’s health [1]. Owing to health concerns such as thermal and respiratory diseases and allergies, an increasing number of people are becoming vulnerable to climate change and socioeconomic damage [3]. Due to their population concentration,
high-density cities continuously increase impermeable areas, green areas, and artificial heat. Furthermore, PM accounts for a significant amount of automotive emissions [4]. To create a suitable atmospheric environment and microclimate, a climate measurement and forecast system must be built at the height within which humans operate. Because various weather factors caused by climate change have complex effects on the urban environment, an integrated review and urban planning management considering the complexity of climate change effects are required.

1.2. Previous Studies

Major studies related to the review of the effects of climate elements due to climate change on the urban environment and humans and the creation of a suitable urban environment are introduced below.

Among the studies on the close correlations between environmental problems and urban climate, the correlations between urban climate and suspended PM were investigated in Dar es Salaam, Tanzania, and a positive correlation was observed between the urban heat island at night and the PM level [5]. To claim the need to consider the connection between urban heat and air pollution in air quality management strategy, empirical evidence linking urban heat to the increased ozone level in large cities in the US has been presented [6]. A study on the aerosol pollution load in Beijing reported that the polluted area in Beijing is the center of the Beijing heat island and suggested a correlation between the heat island effect and the existence of polluted areas [7]. Another study examined the correlations among the urban heat island, aerosol, cloud ratio, and land parameters in Shanghai [8]. In India, the relationships between the formation of urban heat islands and PM concentrations were analyzed [9].

The effects of land cover on the weather and spatial distribution of air pollutants in Paris have been analyzed. The urban heat islands yielded higher values during the night compared to the day, and the urban effects during the night and day had significant effects on the primary and secondary pollutants [10]. The correlation between urban heat islands and air quality was examined using urban weather data obtained from cities in Taiwan [11]. In Dar es Salaam, Tanzania, patterns and differences during the wet and dry seasons as well as during the day and night in a coastal city were studied by examining the correlations between air pollutants and weather parameters (intensity of urban heat island, wind speed, temperature, and relative humidity). Urban heat island and wind parameters were found to be correlated with air pollutants [5].

Extreme weather and PM occur continuously in all seasons, thus aggravating socioeconomic damage. To address this phenomenon, complex perspectives on the change of air pollutants and extreme weather-related elements should be examined.

This study conducted a quantitative analysis considering a combination of extreme weather and PM.

1.3. Objective and Method of Study

The structure of a city, such as its size, population, building density, surface permeability, artificial heat, and land use have direct effects on the urban microclimate and atmospheric environment. Artificial coverage and density in particular are strongly correlated with the change in urban microclimate and atmospheric environment [2]. To ensure a suitable urban space, a strategy for the integrated management of urban heat islands, air pollution, and extreme weather is required. This study aims to quantify the effects of various urban elements on the urban environment.

A case study on urban street canyons wherein buildings are concentrated along roads in central commercial areas with high population density, artificial coverage, and artificial heat was conducted. To examine the effects of floor area ratio in urban street canyons on air pollutants and microclimate, 3D microclimate modeling was performed using the Envi-met V4.5 program. The dates during which extreme heat and cold and air pollutant values were high were selected as the analysis periods.
Results were deduced after extreme temperature conditions (intense heat and cold) and periods of high concentration of fine dust with high air pollution level were selected as the analysis periods. Changes in fine dust factors (PM2.5 and PM10) and microclimate factors (Ta and Tmrt) with respect to the changes in floor space index were investigated. SPSS V18 statistical analysis program was used to identify the correlation between the floor space index and microclimate factors (Ta, Tmrt, Tsurface, and WS) and fine dust factors (PM2.5, PM10, O3, NO2, and NOx).

2. Materials and Methods

2.1. 3D Microclimate Model

Envi-met is a simulation program used to determine the climate of urban areas in typical grid shapes of 0.5–10.0 m in 10 s intervals. Envi-met can output various meteorological parameters such as air temperature, relative humidity, and wind speed as well as thermal comfort indices such as mean radiant temperature (MRT) and predicted mean vote (PMV). Studies that have applied Envi-met simulation can be classified into two categories. One investigated the effects of urban design on the outdoor microclimate, that is, the thermal environment [12–15] and air quality [16–21]. The other evaluated the performance of Envi-met by comparing the simulation results with the field experiment data. These studies demonstrated that the Envi-met model can simulate spatial and temporal temperatures and wind speed to a permissible accuracy for the evaluation of microclimate in both simple and complex urban areas [15,17,20–26].

2.2. Simulation Conditions

The simulation execution conditions are listed in Table 1. The simulation periods include extreme heat, extreme cold, and high-concentration PM, which belong to the range of extreme environments. The date during which the temperature was highest (1 August 2018) was selected as extreme heat period, that during which the temperature was lowest (24 January 2016) was selected as the extreme cold period, and that during which the PM value was highest (6 April 2018) was selected as the high-concentration PM period. The Automated Surface Observing System (ASOS) was used to obtain meteorological data.

| Variable                                | Extreme Heat | Extreme Cold |
|-----------------------------------------|--------------|--------------|
| Start simulation at day (DD.MM.YYYY)    | 06.04.2018   | 24.01.2016   |
| Start simulation at time (HH:MM:SS)     | 01.08.2018   |              |
| Total simulation time (h)               |              | 24           |
| Wind speed measured in 10 m height (m/s)| 3.0          | 1.7          |
| Wind direction (deg)                    | 255.4        | 321.3        |
| (0 = from North . . . 180 = from South) | 214.0        |              |
| Roughness length at measurement site    | 0.1          |              |
| Initial temperature of atmosphere (°C)  | 7.2          | 30.5         |
| Relative humidity in 2 m (%)            | 74.0         | 55.8         |

Table 2 shows the distribution of traffic flow for setting the traffic-related data in the city in this study. The daily traffic values were set based on the Seoul Traffic Survey Report, and the number of lanes was set to 4, as four-lane roads account for 25% of paved roads in cities and provinces. The contributions of the vehicle category to the overall traffic were set using the vehicle registration data for Seoul by vehicle type and size and the Seoul Open
Data Plaza. These data are used to calculate emissions by vehicle type and hour, which are then applied to the simulation.

Table 2. Distribution of traffic flow.

| Variable                                           | Type of Street Segment | Inner-Urban Road |
|----------------------------------------------------|------------------------|-------------------|
| Daily traffic value (Veh/24 h)                     |                        | 48,884            |
| Number of lanes in this street segment              |                        | 4                 |
| Contribution of vehicle category to overall traffic in percent (%) |                        |                   |
| Light duty vehicles                                 |                        | 59.0              |
| Heavy duty vehicles                                 |                        | 24.5              |
| Motorcycles                                         |                        | 12.2              |
| Public transport                                    |                        | 0.2               |
| Coaches                                            |                        | 0.1               |
| Passenger cars                                      |                        | 3.1               |

In this study, the ambient temperature ($T_a$), MRT ($T_{mrt}$), surface temperature ($T_{surface}$), and wind speed (WS) were used as microclimate elements and PM2.5, PM10, O3, NO2, and NOx as PM elements. For $T_{mrt}$, the temperature was determined at a height of 1.4 m within the measurement area.

2.3. Case Study

2.3.1. Conditions for Case Study

Figure 1 shows an outline of the case study for the analysis of the effects of change in floor area ratio on the microclimate and PM. The extreme environment caused by climate change has long-term effects on urban life. This study selected the periods of extreme heat and extreme cold, which are extreme weather conditions, and high-concentration PM for analysis. The analysis hours were 10:00, 12:00, 14:00, 16:00, and 18:00.

Figure 1. Outline of the case study.

We selected a central commercial area with busy traffic and a concentration of artificial covers and artificial heat, and urban street canyons that could potentially influence the pollutant diffusion of the city were modeled [27,28]. The building coverage ratio and floor area ratio were set within ranges that satisfied the criteria for the central commercial area. Based on the urban planning ordinance of Seoul (building coverage ratio: 60% or lower, floor area ratio: 1000% or lower), the building coverage ratio was assumed to be 30% or lower, and the floor area ratios were 200%, 500%, and 700%, respectively (Figure 2). Microclimate elements categorized under human urban activities, and PM elements with long-term effects on health were derived.
We selected a central commercial area with busy traffic and a concentration of artificial covers and artificial heat, and urban street canyons that could potentially influence microclimate elements with long-term effects on health were derived.

2.3.2. Case Model Overview

An area in Seoul was selected for this case study because Seoul has the highest population density in South Korea and being an economic hub (latitude: 37°33’41”, longitude: 126°58’41”) reports high emissions of air pollutants. Figures 3 and 4 show an outline of the simulation case model and simulation measurement ranges, respectively. The study area of the case study measured 172.0 × 88.0 m², and the building was set in a straight-line layout along the road. The building size was modeled as 20.0 × 20.0 m². The road was set as the scope of the simulation measurement owing to the large amount of dust caused by vehicle traffic and the resulting PM (172.0 × 12.0 m²). Vehicle traffic and the traffic data on urban locations in Seoul were reflected via a four-lane road. The simulation space was 86.0 × 44.0 × 120.0 m³, and the grid size was 2.0 m. The materials of the study area were set as asphalt for the surface and concrete for the building. For the evaluation indices, the microclimate and PM elements were calculated at a height of 1.4 m from the ground, which is the height at which humans breathe.

Figure 2. Case study floor area ratio setting.

Figure 3. Simulation case model overview.
3. Results and Discussion

Figure 5 show the graph of the changes in PM elements (PM$_{2.5}$, PM$_{10}$) and microclimate elements ($T_a$, $T_{mrt}$) according to the floor area ratio. The measurement times were averaged (10:00, 12:00, 14:00, 16:00, and 18:00), and high-concentration PM and extreme weather (extreme heat and extremely cold days) were selected as the measurement periods. Figure 6 is the resulting image of PM$_{2.5}$, $T_a$, and WS according to the floor area ratio.

![Figure 4. Simulation measurement range.](image)

![Figure 5. Correlations between floor area ratio and PM (PM$_{2.5}$, PM$_{10}$) and microclimate ($T_a$, $T_{mrt}$) elements: (a) $T_a$ within the measurement range based on the change in floor area ratio; (b) $T_{mrt}$ within the measurement range based on the change in floor area ratio; (c) PM$_{2.5}$ within the measurement range based on the change in floor area ratio; (d) PM$_{10}$ within the measurement range based on the change in floor area ratio.](images)
density, the lower the floor area ratio, the higher the air temperature and urban heat island phenomenon. This is consistent with the results obtained by existing studies [29,30]. A slight difference in $T_a$ in the measurement range was observed according to the change in the floor area ratio. The lower the floor area ratio was, the higher the air temperature was. Furthermore, $T_mrt$ was also relatively higher when the floor area ratio is relatively lower (28.91 °C during the high-concentration PM period, 19.49 °C during the extreme heat period, and 5.93 °C during the extreme cold period).

(a) Figure 6. Cont.
Figure 6. Cont.
Figure 6. (a) Analysis result of high concentration PM according to floor area ratio (PM2.5, WS, Ta). (b) Analysis result of extreme cold according to floor area ratio (PM2.5, WS, Ta). (c) Analysis result of extreme heat according to floor area ratio (PM2.5, WS, Ta).

PM$_{2.5}$ and PM$_{10}$ were observed to increase when the floor area ratio was lower during periods of high-concentration PM and extreme cold (the difference in PM$_{2.5}$ is approximately 0.91 μg/m$^3$ and that in PM$_{10}$ is approximately 1.90 μg/m$^3$). In particular, during extreme cold, the change in PM$_{2.5}$ and PM$_{10}$ values according to the change in the floor area ratio was large (difference in PM$_{2.5}$ is approximately 2.23 μg/m$^3$ and that in PM$_{10}$ is approximately 4.52 μg/m$^3$). During extreme heat, a slight difference in PM concentration was observed.
Ta results for the measurement range according to the change in floor area ratio show that the Ta is higher in the measurement range at the floor area ratio of 200% compared to 700% (the difference between the floor area ratio of 200% and 700% is ~1.81 °C during the high-concentration PM period, 0.80 °C during the extreme heat period, and 0.93 °C during the extreme cold period). This suggests that in an urban area with high density, the lower the floor area ratio, the higher the temperature and urban heat island phenomenon. This is consistent with the results obtained by existing studies [29,30]. A slight difference in Ta in the measurement range was observed according to the change in the floor area ratio. The lower the floor area ratio was, the higher the temperature was. Furthermore, T_{mrt} was also relatively higher when the floor area ratio is relatively lower (28.91 °C during the high-concentration PM period, 19.49 °C during the extreme heat period, and 5.93 °C during the extreme cold period).

PM$_{2.5}$ and PM$_{10}$ were observed to increase when the floor area ratio was lower during periods of high-concentration PM and extreme cold (the difference in PM$_{2.5}$ is approximately 0.91 µg/m$^3$ and that in PM$_{10}$ is approximately 1.90 µg/m$^3$). In particular, during extreme cold, the change in PM$_{2.5}$ and PM$_{10}$ values according to the change in the floor area ratio was large (difference in PM$_{2.5}$ is approximately 2.23 µg/m$^3$ and that in PM$_{10}$ is approximately 4.52 µg/m$^3$). During extreme heat, a slight difference in PM concentrations according to the change in the floor area ratio was observed (difference in PM$_{2.5}$ was approximately 0.31 µg/m$^3$ and that in PM$_{10}$ was approximately 0.61 µg/m$^3$).

When the floor area ratio was higher, the surface temperature is believed to have decreased due to the shade, whereas relatively more solar radiant heat was absorbed and the heat circulation and wind speed were inhibited when the floor area ratio was lower, thus increasing the Ta, T$_{mrt}$ and PM$_{10}$, PM$_{2.5}$ values.

Table 3 shows the results of the correlation analysis using the SPSS V18 statistical analysis program to examine the effects of the change in floor area ratio on the microclimate and PMs.

**Table 3. Effects of floor area ratio on microclimate and air quality.**

| Factors | Result | Particulate Matter (PM) Factors | Microclimate Factors |
|---------|--------|--------------------------------|---------------------|
| Floor area ratio | PM$_{2.5}$ | PM$_{10}$ | O$_3$ | NO$_2$ | NO$_x$ | T$_a$ | T$_{mrt}$ | T$_{surface}$ | WS |
| High-concentration PM | -0.971 ** | -0.973 ** | -0.932 ** | -0.949 ** | -0.968 ** | -0.680 ** | -0.801 ** | -0.782 ** | 0.980 ** |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.005 | 0.000 | 0.001 | 0.000 |
| Extreme heat | -0.418 | -0.417 | -0.390 | -0.331 | -0.399 | -0.164 | -0.685 ** | -0.682 ** | 0.924 ** |
| 0.121 | 0.122 | 0.860 | 0.228 | 0.140 | 0.560 | 0.036 | 0.005 | 0.000 |
| Extreme cold | -0.923 ** | -0.922 ** | 0.008 | -0.924 ** | -0.924 ** | -0.237 | -0.245 | -0.394 | 0.711 ** |
| 0.000 | 0.000 | 0.978 | 0.000 | 0.000 | 0.395 | 0.378 | 0.146 | 0.003 |

Correlation coefficient; **Significance probability; $p^* < 0.05$, $p^{**} < 0.01$; $p$: Significance level.

The correlation between PM and microclimate elements depending on the change in the floor area ratio was analyzed during the high-concentration PM period. PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$, and NO$_x$ were observed to be strongly negatively correlated with the floor area ratio.

For PM$_{2.5}$, $r = -0.971$ and $p < 0.000$, for PM$_{10}$, $r = -0.973$ and $p < 0.000$, for ozone, $r = -0.932$ and $p < 0.000$, for NO$_2$, $r = -0.949$ and $p < 0.000$, and for NO$_x$, $r = -0.968$ and $p < 0.000$. These results show that the lower the floor area ratio, the higher the PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$, and NO$_x$ values.

In addition, strong negative correlations were observed between microclimate elements T$_a$, T$_{mrt}$, and T$_{surface}$ and the floor area ratio. WS exhibited a strong positive correlation with floor area ratio (for T$_a$, $r = -0.680$ and $p < 0.005$, for T$_{mrt}$ $r = -0.801$ and $p < 0.000$, for T$_{surface}$ $r = -0.782$ and $p < 0.001$, and for WS, $r = 0.980$ and $p < 0.000$). Clearly, the lower the floor area ratio, the higher the T$_a$, T$_{mrt}$, and T$_{surface}$ values, and the lower the floor area ratio, the lower the WS.
The correlations between the floor area ratio and PM and microclimate elements during the period of extreme heat were examined. The floor area ratio exhibited weak correlations with PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$, and NO$_x$. In addition, regarding the correlations between floor area ratio and microclimate elements, T$_{mrt}$ and T$_{surface}$ were found to be strongly negatively correlated with the floor area ratio (for T$_{mrt}$, r = −0.655 and p < 0.008, and for T$_{surface}$, r = −0.682 and p < 0.005), and WS exhibited a strong positive correlation (r = 0.924, p < 0.000) with the floor area ratio. It was clear that the lower the floor area ratio, the higher the T$_{mrt}$ and T$_{surface}$ values, but the lower the WS.

The correlations between the floor area ratio and the PM and microclimate elements during the period of extreme cold were examined. The floor area ratio exhibited strong correlations with microclimate elements (for PM$_{2.5}$, r = −0.923 and p < 0.000; for PM$_{10}$, r = −0.927 and p < 0.000; for NO$_2$, r = −0.924 and p < 0.000; and for NO$_x$, r = −0.924 and p < 0.000) and a weak correlation with O$_3$. Furthermore, T$_a$, T$_{mrt}$, and T$_{surface}$ exhibited strong correlations with the floor area ratio, but WS exhibited a strong correlation with the floor area ratio (r = 0.711, p < 0.003).

The floor area ratio commonly exhibited a positive correlation with WS during all periods. This suggests that the higher the floor area ratio, the higher the wind speed. High-rise buildings cause changes in the wind environment around buildings, and a building wind phenomenon occurs wherein the wind speed rises in the external space of the building, that is, in the pedestrian space.

Table 4 outlines the results of the correlation analysis examining the effects of microclimate elements on the PM elements using data obtained during the high-concentration PM period.

| Microclimate factors | Particulate Matter (PM) Factors |
|----------------------|-------------------------------|
|                      | PM$_{2.5}$ | PM$_{10}$ | O$_3$ | NO$_2$ | NO$_x$ |
| T$_a$                | 0.646 **  | 0.649 ** | 0.789 ** | 0.591 * | 0.638 * |
|                      | 0.009     | 0.009    | 0.000   | 0.020  | 0.010   |
| T$_{mrt}$            | 0.765 **  | 0.762 ** | 0.925 ** | 0.700 ** | 0.755 ** |
|                      | 0.001     | 0.001    | 0.000   | 0.004  | 0.001   |
| T$_{surface}$        | 0.730 **  | 0.732 ** | 0.902 ** | 0.665 ** | 0.721 ** |
|                      | 0.002     | 0.002    | 0.000   | 0.007  | 0.002   |
| WS                   | −0.960 ** | −0.964 ** | −0.916 ** | −0.940 ** | −0.957 ** |
|                      | 0.000     | 0.000    | 0.000   | 0.000  | 0.000   |

Correlation coefficient; ** Significance probability: p < 0.05; * Significance probability: p < 0.01; p: Significance level.

T$_a$ exhibited strong positive correlations with PM$_{2.5}$, PM$_{10}$, and O$_3$. Thus, the higher the air temperature, the higher the PM$_{2.5}$, PM$_{10}$, and O$_3$ values (for PM$_{2.5}$, r = 0.646 and p < 0.009, for PM$_{10}$, r = 0.649 and p < 0.009, and for O$_3$, r = 0.789 and p < 0.000). T$_{mrt}$ exhibited strong positive correlations with PM elements (PM$_{2.5}$, PM$_{10}$, NO$_2$, and NO$_x$) (for PM$_{2.5}$, r = 0.765 and p < 0.001, for PM$_{10}$, r = 0.762 and p < 0.001, for NO$_2$, r = 0.700 and p < 0.004, and for NO$_x$, r = 0.700 and p < 0.004). In particular, T$_{mrt}$ exhibited a very strong positive correlation with O$_3$ (r = 0.925, p < 0.000). When the MRT increased, the O$_3$ value was observed to also increase. T$_{surface}$ exhibited strong positive correlations with PM elements (PM$_{2.5}$, PM$_{10}$, NO$_2$, and NO$_x$) (for PM$_{2.5}$, r = 0.730 and p < 0.002, for PM$_{10}$, r = 0.732 and p < 0.002, for NO$_2$, r = 0.665 and p < 0.007, and for NO$_x$, r = 0.721 and p < 0.002). In particular, T$_{surface}$ exhibited a very strong positive correlation with O$_3$ (r = 0.902, p < 0.000). When the surface temperature increased, the O$_3$ value was observed to increase as well. WS exhibited very strong positive correlations with PM elements (PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$, and NO$_x$). As the wind speed increased, the PM elements decreased.

4. Conclusions

Due to accelerated urbanization and extreme weather events driven by climate change, the urban environment causes long-term effects on daily life through complicated mecha-
nisms. This causes various health concerns such as thermal and respiratory diseases and allergies, thereby increasing socioeconomic losses.

To create a pleasant urban environment, it needs to be set at a level that humans can tolerate. An integrated review of the meteorological factors caused by extreme weather events is also required.

In this study, an analysis of central commercial areas in a city with high traffic, population density, artificial coverage, and artificial heat was conducted based on the change in the floor area ratio (200%, 500%, and 700%). Urban street canyons among other urban areas were targeted for the case study. The periods of extreme heat, extreme cold, and high-concentration PM, which affect the urban environment, were selected as the analysis periods.

First, the effects of the change in floor area ratio on the PM and microclimate elements were analyzed. The results showed that the lower the floor area ratio, the higher the \( T_a \), \( T_{mrt} \), \( PM_{2.5} \), and \( PM_{10} \) values. (In the floor area ratio from 200% to 700%, the difference in \( T_a \) was \( \sim 1.81 \) °C during the high-concentration PM period, 0.80 °C during the extreme heat period, and 0.93 °C during the extreme cold period. The difference in \( T_{mrt} \) is \( \sim 28.91 \) °C during the high-concentration PM period, 19.49 °C during the extreme heat period, and 5.93 °C during the extreme cold period. The difference in \( PM_{2.5} \) is 0.91 µg/m\(^3\) during the high-concentration PM period, 0.31 µg/m\(^3\) during the extreme heat period, and 2.23 µg/m\(^3\) during the extreme cold period. The difference in \( PM_{10} \) is 1.90 µg/m\(^3\) during the high-concentration PM period, 0.61 µg/m\(^3\) during the extreme heat period, and 4.52 µg/m\(^3\) during the extreme cold period.) The higher the floor area ratio, the higher the wind speed and building shade affecting the \( T_a \), \( T_{mrt} \), \( PM_{2.5} \), and \( PM_{10} \) in urban areas with high population densities.

The correlation between the PM elements and microclimate elements according to the change in the floor area ratio was examined. During the period of high-concentration PM, the floor area ratio exhibited negative correlations with \( PM_{2.5} \), \( PM_{10} \), \( O_3 \), \( NO_2 \), \( NO_x \), \( T_a \), \( T_{mrt} \), and \( T_{surface} \). During the period of extreme heat, the floor area ratio exhibited negative correlations with \( T_{mrt} \) and \( T_{surface} \). During the period of extreme cold, the floor area ratio exhibited negative correlations with \( PM_{2.5} \), \( PM_{10} \), \( O_3 \), \( NO_2 \), and \( NO_x \). In addition, the higher the floor area ratio, the higher the WS, indicating a positive correlation.

The correlation between the PM elements and microclimate elements was analyzed during the high-concentration PM period. \( T_a \), \( T_{mrt} \), and \( T_{surface} \) were positively correlated with \( PM_{2.5} \), \( PM_{10} \), \( O_3 \), \( NO_2 \), and \( NO_x \). WS showed negative correlations with \( PM_{2.5} \), \( PM_{10} \), \( O_3 \), \( NO_2 \), and \( NO_x \). This indicates that PM can be reduced by improving the microclimate and also by implementing various ways to increase WS.

Quantitative evaluation of the effect of building energy load is required considering the ventilation method setting according to the particulate matter concentration and microclimate change; this will be conducted in the follow-up research.

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

| Symbol | Description                      |
|--------|----------------------------------|
| T_a    | atmospheric temperature [°C]     |
| T_mrt  | mean radiant temperature [°C]    |
| T_surface | surface temperature [°C]   |
| WS     | wind speed [m/s]                 |
| PM     | particulate matter [µg/m³]       |

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