

Article

Importance of Urban Green at Reduction of Particulate Matters in Sihwa Industrial Complex, Korea

Sin-Yee Yoo , Taehee Kim , Suhan Ham, Sumin Choi and Chan-Ryul Park * 

Urban Forests Research Center, National Institute of Forest Science, 57, Hoegiro, Dongdaemun-gu, Seoul 02455, Korea; dbt1sd194@korea.kr (S.-Y.Y.); kth9064@korea.kr (T.K.); hamsu2498@si.re.kr (S.H.); ciromi@korea.kr (S.C.)

* Correspondence: maeulsoop@korea.kr; Tel.: +82-2-961-2612

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Abstract: The utilization of urban green areas has increased, but it is unclear whether urban green areas can decrease the concentration of particulate matter at an industrial complex city in Korea. We measured the extent of particulate matter (PM) reduction at a buffer green area in the Sihwa Industrial Complex. PM was measured at the industrial complex, the urban green area, and a nearby residential area from April to October 2019. PM reduction rates were highest at the urban green area in August and October, which is related to increased atmospheric mixing height and the active west wind blowing from the industrial complex to the residential area. Reduction rates of PM₁₀ and PM_{2.5} at the urban green area showed the lowest values, namely 14.4% and 25.3%, respectively. The air temperature, wind speed, and humidity could affect the PM reduction rate by influencing the movement and dispersion of PM at the micro-spatiotemporal scale. These results indicated that PM concentration could be reduced by the structural change of a forest layer at a micro scale in urban green areas.

Keywords: urban green area; Sihwa Industrial Complex; air pollutants; PM reduction; atmospheric mixing height; wind speed

1. Introduction

High domestic PM concentration is known to lead to increased human activity at urban green areas in industrial complex cities. The PM concentration in Korea is usually expressed as the same concentration according to the area where the national atmospheric monitoring station is installed. However, the actual PM values vary, and they change in accordance with the existence of the urban green areas [1,2]. Thus, citizens want to know information about the PM concentration under the forest canopy at hiking time. Urban green area is currently regarded as an important PM reduction measure that is highly accessible to citizens, and it also performs the role of atmospheric purification [3–5]. As a result, urban green area is widely used to manage the urban atmosphere [6,7].

Urban green area can reduce PM by absorption, blocking, and deposition. In the process of photosynthesis, the trees in the green area can absorb gaseous air pollutants such as carbon dioxide (CO₂), nitrogen dioxide (NO₂), and sulfur dioxide (SO₂) through the stomata of the leaves [8]. The tree canopy can also reduce the speed and movement of PM, resulting in PM being blocked and then falling to the surface of the ground [9,10]. Areas with large forest cover ratios were found to have lower PM concentrations than highly urbanized areas [2,7]. However, some studies have reported that the effects of urban green area on the urban atmosphere appear to be limited. The presence of roadside green area interferes with the airflow, causing roadside PM to stagnate and resulting in a higher

PM concentration at the roadside green area than at other areas on the roadside [11,12]. The status of PM adsorbed on the leaves could reach the saturation point and block the stoma during the dry winter season [13]. The deposition rate is also sensitive to weather conditions [3,14]. Leaf PM deposition velocity was found to increase with increasing wind speed [15,16], and PM removal rates from the leaf surface were found to be correlated with high rainfall intensity and duration [17]. Therefore, urban green areas have different effects of PM reduction that depend on their structure and the meteorological factors that affect PM movement. It is important to identify the characteristics of PM reduction in urban green areas according to environmental conditions and meteorological factors.

Most studies have focused on identifying the reduction of PM concentration with equations and chamber-based experiments [15–17], so the effects of reducing air pollutants through urban green space need to be verified in the field.

To identify the characteristics of PM reduction in urban green areas, we conducted a study in the buffer green area of the Sihwa Industrial Complex. The research objectives were to determine the effect of urban green area in reducing PM; analyze the relationship between PM, the meteorological factors, and air pollutants; and identify the seasonal patterns of PM reduction by urban green areas.

2. Materials and Methods

2.1. Study Site

The study site, Sihwa (37°22'N, 126°46'E), is a national industrial complex adjacent to the west coast of Korea and consists of steel-, chemical-, and machinery-oriented industries. The main air pollutants of the Sihwa Industrial Complex are NO₂ and SO₂ emissions, which are caused by the operation of vehicles and ships as well as the combustion involved in manufacturing activities during the production process [18]. The Sihwa Industrial Complex has the characteristic of wind blowing in the northwest direction, from the coast to the land. Thus, the buffer green area was established in the 2000s to prevent the spread of air pollutants and odor from the industrial complex to the residential area. The buffer green area is an urban green area located in the center of Sihwa Industrial Complex and New City. The dimensions of this site are 3.46 km (L), 0.18 to 0.25 km (W), and 10 m (H), and it consists of a Japanese black pine (*Pinus thunbergii*) and Japanese red pine (*Pinus densiflora*) community [19]. The densities of the Japanese black pine (*Pinus thunbergii*) and Japanese red pine (*Pinus densiflora*) are 24.5 trees/100 m² and 0.75 trees/100 m², respectively. To analyze the PM reduction effect of the urban green area, we selected three PM monitoring points: Somang park in the industrial complex (IC; 37°20' N, 126°43' E), the urban green area (UG; 37°20' N, 126°43' E), and Jungang park in the residential area (RA; 37°20' N, 126°44' E) (Figure 1). The distance between IC and UG is 1 km, and the distance between RA and UG is 0.76 km. As IC is surrounded by various industries and RA is a nearby apartment complex, we considered that these measuring points could reflect the characteristics of PM in each area. IC is dominated by *Pinus strobus* (4.5 trees/100 m²) and *Pseudotsuga sinensis* (0.5 trees/100 m²). RA is made up of *Pinus rigida* (8.75 trees/100 m²) and *Pinus densiflora* (0.5 trees/100 m²).

2.2. Measurement Method

The PM₁₀ and PM_{2.5} concentrations were measured by a mobile PM measuring device, Dustmate (Turnkey, UK, ±5% accuracy), which was installed 1.5 m above the ground. The use of Dustmate for analyzing PM concentrations proved to be successful in studies [20,21]. Dustmate is a real-time PM mass concentration meter that uses the light scattering method. The Sihwa Industrial Complex is a coastal area and is highly influenced by onshore winds. Thus, Dustmate is suitable for checking varied PM concentrations in real time and can measure at high concentrations. However, in the case of the light scattering method, the concentration can be overestimated because the material can cause interference in light transmission, which could be highly influenced by humidity [22]. We excluded the PM concentration data with humidity values over 80% to avoid overestimation of PM concentrations

due to binding effects of vapor particles and particulate matter. PM monitoring was conducted from April to October 2019; citizens in Korea usually visit urban green areas and enjoy the outdoors during this season. We measured the PM concentration in the morning rush hour (7–9 h), around noontime (11–13 h), and during evening rush hour (16–18 h), considering the peak hours with a large transient population. We measured data at intervals of 1 s and used these data as averages of 5 min. Based on these PM concentration data, we calculated the time mean, monthly average, and reduction rates of PM as follows:

$$\text{PM reduction rate (\%)} = 100 \times \frac{C_{IC} - C_{RA}}{C_{IC}} \quad (1)$$

where C_{IC} is PM concentration in IC and C_{RA} is PM concentration in RA.



Figure 1. The location of measuring points and national atmospheric environmental research station in Siheung City, Gyeonggi-do, Republic of Korea (modified from map.kakao.com). IC: industrial complex; UG: urban green area; RA: residential area; Airkorea-IC: national atmospheric environmental research station located near IC; Airkorea-RA: national atmospheric environmental research station located near RA.

In order to identify the seasonal patterns of PM reduction by UG, the relationship between PM, meteorological factors, and air pollutants was analyzed. We used a portable weather meter to measure temperature, wind direction, wind speed, and humidity at each point for 24 h. Since the Dustmate equipment could not measure the concentrations of air pollutants (ozone (O_3), NO_2 , SO_2 , carbon monoxide (CO)), these concentrations were measured by the national atmospheric environmental research stations located nearby in IC (Airkorea-IC; $37^{\circ}20'N$, $126^{\circ}43'E$) and RA (Airkorea-RA; $37^{\circ}20'N$, $126^{\circ}44'E$) (Figure 1). We hypothesized that the values from those stations could represent the air pollutant concentrations for the measuring points.

2.3. Analysis Method

We grouped the PM concentrations, meteorological factors, and air pollutants measured by season, i.e., spring (April and May), summer (June and August), and fall (September and October). To analyze the seasonal characteristics of PM reduction in UG, we performed the Pearson correlation analysis among these grouped data by using R v.3.0.2 (R Core Development Team 2019). Statistical analysis using the Tukey HSD procedure of R v.3.0.2 was also conducted on PM concentration and PM reduction rate. The least squares mean was used to test significant differences among measuring points and over month and hour at the 5% probability level.

3. Results

3.1. Monthly PM Concentration and PM Reduction Rate

We analyzed the monthly PM concentration, excluding PM data in July when the humidity exceeded 80%. Regardless of PM measuring points, the highest PM₁₀ and PM_{2.5} concentrations were observed in May, with values of 99.7 $\mu\text{g}/\text{m}^3$ and 75.9 $\mu\text{g}/\text{m}^3$, respectively (Figure 2a). During the measuring period, the average PM₁₀ and PM_{2.5} concentrations were shown to be at bad levels (daily mean PM₁₀, 80–150 $\mu\text{g}/\text{m}^3$; daily mean PM_{2.5}, 35–75 $\mu\text{g}/\text{m}^3$) in May, while they were observed to be at normal levels (daily mean PM₁₀, 30–80 $\mu\text{g}/\text{m}^3$; daily mean PM_{2.5}, 15–35 $\mu\text{g}/\text{m}^3$) in April. Thus, the difference between April and May values was high, even though these measurements were collected in the same season. After May, PM levels gradually decreased, with the lowest concentration being observed in August. In September, PM levels began to increase again. Large deviations of PM₁₀ and PM_{2.5} concentrations were observed in the spring, meaning that high PM concentration occurred frequently during that time. On the other hand, summer and fall showed a low deviation of PM concentration, indicating that PM levels were maintained relatively constant compared to spring. Furthermore, no significant differences in PM concentration levels were shown in April, May, and June between the measuring points (Figure 2a). Except for these months, high PM levels were shown, following the order of IC, UG, and RA. In August, monthly PM₁₀ and PM_{2.5} reduction rates were high, with values of 44.3% and 56.4%, respectively. The monthly PM₁₀ and PM_{2.5} reduction rates in October were high as well, reaching 43.5% and 54.2%, respectively. The lowest PM reduction rates were observed in June (Figure 2b).

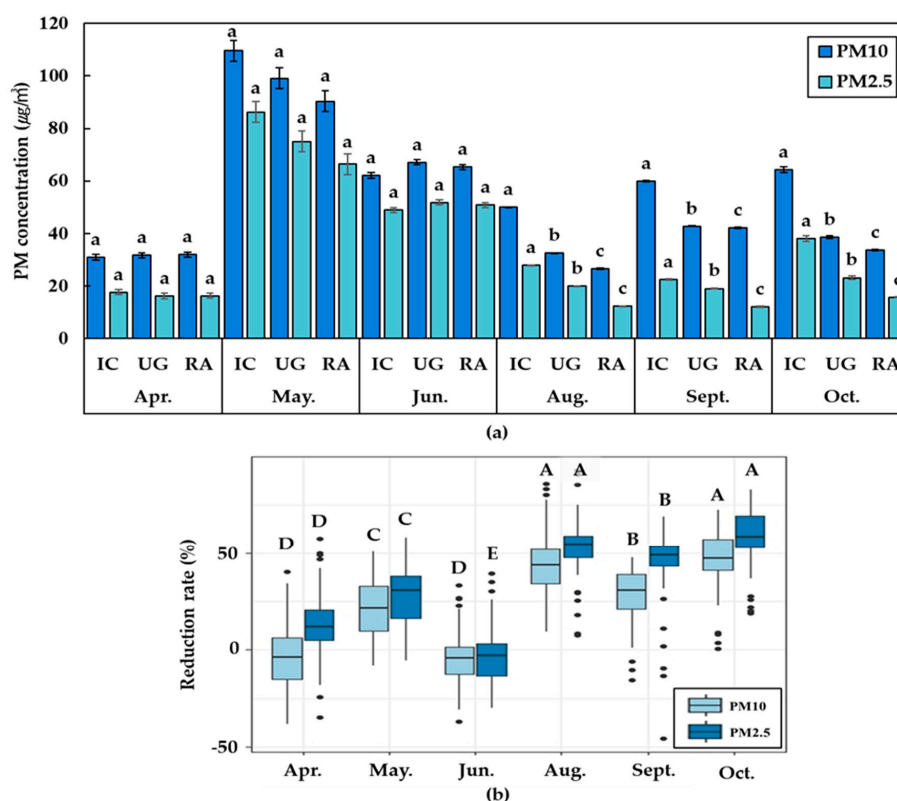


Figure 2. (a) Monthly PM concentration ($\mu\text{g}/\text{m}^3$) at measuring points. (b) Monthly PM reduction rate (%). Different lowercase letters indicate significant difference between measuring points at a 5% level. Different uppercase letters indicate significant difference between months at a 5% level. IC: industrial complex; UG: urban green area; RA: residential area.

3.2. Hourly PM Concentration and PM Reduction Rate

In the case of hourly PM concentration, the PM₁₀ and PM_{2.5} concentrations were the highest during the morning rush hour, reaching 77.9 and 51.4 $\mu\text{g}/\text{m}^3$, respectively (Figure 3a,b). The high PM concentration in the morning rush hour gradually decreased after noon, and the value in the evening rush hour was 30% lower than that in the morning rush hour. PM₁₀ and PM_{2.5} reduction rates were the highest (31.4% and 40.3%, respectively) during the evening rush hour, while those of the morning rush hour were the lowest (15.0% and 26.0%, respectively) (Figure 3c).

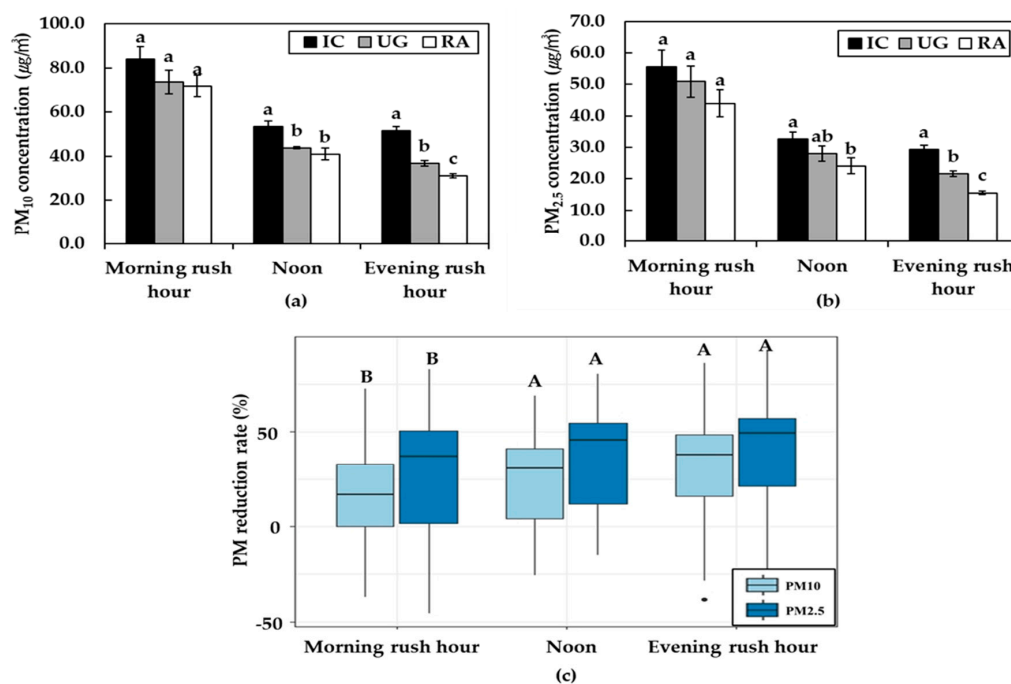


Figure 3. (a) Hourly PM₁₀ concentration ($\mu\text{g}/\text{m}^3$) at measuring points. (b) Hourly PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) at measuring points. (c) Hourly PM reduction rate (%). Different lowercase letters indicate significant difference between measuring points at a 5% level. Different uppercase letters indicate significant difference between hours at a 5% level. IC: industrial complex; UG: urban green area; RA: residential area.

3.3. Relation between PM Concentration, Meteorological Factors, and Air Pollutants by Season

The PM concentration levels are affected by meteorological factors and the amount of emitted air pollutants. In this study, we considered the meteorological factors and air pollutants as factors affecting the PM concentration. Table 1 shows the correlation coefficients between the PM, meteorological factors, and air pollutants. In spring, PM levels shows positive correlation with humidity, NO₂, and CO, while negative correlation was shown with wind speed and O₃. In summer, PM levels were positively correlated with the amount of SO₂ and negatively correlated with the temperature. In the case of fall, correlation between the PM and meteorological factors was the same as in spring, and PM was positively correlated with NO₂, CO, and SO₂.

Table 1. Seasonal correlation coefficients between PM concentration, meteorological factors, and other air pollutants.

Correlation Coefficient	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}
	Spring (April, May)		Summer (June, July)		Fall (September, October)	
Temperature	−0.62	−0.60	−0.86 **	−0.89 **	−0.58	−0.40
Wind speed	−0.95 ***	−0.94 ***	0.54	0.58	−0.82 **	−0.69 *
Humidity	0.96 ***	0.96 ***	0.57	0.57	0.67 *	0.51
O ₃	−0.93 ***	−0.91 ***	−0.48	−0.48	−0.80 **	−0.66
NO ₂	0.90 **	0.88 **	0.50	0.49	0.96 ***	0.88 **
CO	0.86 **	0.84 **	0.67	0.68 *	0.93 ***	0.87 **
SO ₂	0.40	0.36	0.91 ***	0.93 ***	0.38	0.50

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4. Discussion

4.1. Factors Affecting the Monthly PM Reduction in Urban Green Areas

Overall, the PM values were higher at IC than at UG and RA. This result could be attributed to the PM reduction effects of UG. As PM generated from IC passed through UG, trees could absorb PM via leaf stomata [8,23] and remove PM by deposition onto the leaves and branches [24,25]. However, we also considered the spatial distance effect on PM reduction according to the distance from pollutant emission areas. PM₁₀ and PM_{2.5}, which have a long atmospheric lifetime [26], decreased, so we can speculate that the influence of UG on PM reduction was greater than that of distance.

The difference between the PM reduction rates of IC and RA was especially high in August and October. The high PM reduction rate in August seemed to be related not only to PM reduction mechanism of UG but also to an increase of atmospheric mixing height during the summer [27–29]. The dispersion of PM occurred rapidly due to active mixing by air turbulence in the summer [28], leading to a minimum PM concentration. Therefore, it is likely that PM could quickly spread due to the effects of intensive air mixing and prevailing western wind systems, resulting in increasing PM reduction through UG. High PM reduction rates in October were also related to the active atmospheric dispersion affecting the PM reduction, similar to the results observed in August. Moreover, the cleaning effect due to high precipitation in August during the monsoon rainy season should be considered. However, we excluded the effect of PM reduction caused by precipitation because we sampled PM in the dry period, not on rainy days. June, the sharing the summer season with August, had the lowest PM reduction rate. This phenomenon appears to be related to high humidity (remaining in the range of 60% to 70%) in June, whereas other months had lower humidity. The increase of humidity in the atmosphere could reduce solar radiation reaching the earth surface, resulting in adjusting the atmospheric temperature to be similar to that of the earth. As the atmosphere nearer to the surface becomes colder than the upper layers, the air currents seem to decrease and air pollutants become stagnant [30,31]. Therefore, the high humidity interferes with upward-moving air currents, leading to the increase of air pollutant concentrations.

4.2. Factors Affecting the Hourly PM Reduction in Urban Green Areas

High PM levels during the morning rush hour seemed to be related to increased traffic loads. Thus, this result is likely because of the effects of PM generated by vehicles and atmospheric congestion during the early morning. We observed that the PM concentrations in the morning rush hour slightly decreased after noon. This was related to active atmospheric dispersion, as temperature and wind speed slowly increased and humidity decreased after noon. A similar pattern was reported in a metropolitan city in Korea, where high PM concentration and size distribution of PM were affected by

increased traffic volumes during the morning rush hour (6–9 h) and then decreased when the wind speed increased [22].

A great reduction in PM concentration during the evening rush hour was related to the strong west wind blowing from IC to RA. It is likely that the PM-reducing effect of UG is greatly increased when PM in IC passes through the UG due to the strong west wind and active atmospheric diffusion after noon. On the other hand, a low PM reduction rate was shown in the morning rush hour in study areas, which was related to the high PM concentration at RA. In the case of RA, with an increase in traffic during the morning rush hour, PM congestion was caused by the east wind blowing and the residential area being surrounded by high apartments [22,32,33]. PM concentration in RA was more affected by high traffic volume and PM congestion than PM from IC during the morning rush hour. The atmospheric diffusion models indicated that air pollutants would not spread actively in the residential area due to the west wind from the coast and the east wind from land coexisting in the study area [34].

4.3. Factors Affecting the PM Concentration by Season

This study showed a high concentration of PM in May. Recently simulated PM concentrations showed a strong negative correlation with regional wind speed, implying that reduced regional ventilation is likely associated with more stagnant conditions that cause severe pollutant episodes in South Korea [35]. Furthermore, temperature and wind speed had a negative correlation with PM, which is related to active atmospheric diffusion with increasing temperature and wind speed [36], and the high temperature influences convective air currents, resulting in rapid dispersion of PM in the atmosphere [29]. It is known that humidity contributes to the increase in PM concentration by acting as the condensation nucleus of air pollutants [37].

PM concentration was positively correlated with NO₂, CO, and SO₂. This is related to the PM formation, as air pollutants are precursors of PM [38,39]. PM concentration in summer had especially high correlation with SO₂, while NO₂ and CO were highly correlated with PM concentration in spring and fall. In summer, as the atmospheric diffusion becomes more active, the SO₂ diffusion produced by the operation of the industrial complex could affect the overall PM concentrations at the measuring points [3,40]. In spring and fall, as NO₂ and CO produced from the vehicles spread in all directions around the roadside, they could have a greater impact on PM concentration when compared to SO₂ from the industrial complex [3,34]. Thus, the analysis of the PM composition is needed to identify the exact path of air pollutants.

O₃ only showed a negative correlation with PM, which might be related to the organic PM generation process through oxidation of volatile organic compounds (VOCs) by O₃ [41]. However, Bell et al. [42] observed a positive correlation between PM and O₃, as PM and O₃ are produced by photochemical reactions. These contradictory results indicate that PM and O₃ levels are driven by a combination of the chemical reactions of their precursors and meteorological factors. Therefore, it is necessary to analyze the correlation between PM and O₃ by identifying the environmental factors affecting these occurrences. In addition, measuring O₃ in urban green areas and analyzing PM formation and extinction data should be conducted to understand the real correlation between O₃ and PM in urban green areas.

5. Conclusions

This study investigated the PM-reducing effect of an urban green area in the Sihwa Industrial Complex. Monthly PM reduction was related to the atmospheric mixing height and west wind blowing. Hourly PM reduction was affected by the speed and direction of wind and the vehicle traffic volumes. Thus, the reduction of PM by the urban green area was associated with PM absorption, adsorption and deposition on leaves, monthly mixing height, and the large scale of air current movement affecting air stagnation and PM dispersion. Our results suggest that an urban green area will reduce PM concentration if the forest layer of the urban green area is planted at a proper location,

with changes made as necessary, and the operation of industries and vehicles is managed. However, this study only identified the PM-reducing effect of an urban green area based in a limited space, namely Sihwa Industrial Complex, and analyzed the measured data just for a short period of time. Furthermore, we did not measure PM without an urban green area to confirm the real PM reduction effect of the urban green area. Further research on PM measurement at a control site is required, and it is necessary to identify the overall seasonal PM reduction characteristics through long-term monitoring. Moreover, as the wind condition significantly influences the urban green area's PM reduction effect, further research of prevailing wind field modeling at spatial boundaries on a city level should be carried out to address local solutions for reducing PM concentration.

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