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Particulate Matter Removal Ability of Ten Evergreen Trees Planted in Korea Urban Greening

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Abstract: Broad-leaved evergreen trees create urban forests for mitigation of climate warming and adsorption of particulate matter (PM). This study was performed to identify the species suitable for urban greening by examining the adsorption capacity of the evergreen species in urban areas in Korea, the adsorption points and the elemental composition of PM in the adsorbed tree. Leaf sampling was carried out four times (period of seven months from October 2017 to May 2018) and used after drying (period 28 to 37 days). Particulate matter (PM) was classified and measured according to size $PM_{2.5}$ (0.2–2.5 μm), PM_{10} (2.5–10 μm), PM_{100} (10–100 μm). The total amount of PM adsorbed on the leaf surface was highest in *Pinus densiflora* (24.6 μg·cm^{-2}), followed by *Quercus salicina* (47.4 μg·cm^{-2}). The composition of PM adsorbed by *P. densiflora* is 4.0% $PM_{2.5}$, 39.5% PM_{10} and 56.5% PM_{100}, while those adsorbed by *Q. salicina* are evergreen at 25.7% $PM_{2.5}$, 27.4% PM_{10} and 46.9% PM_{100}. When the amount of PM adsorbed on the leaf was calculated by LAI, the species that adsorbed PM the most was *P. densiflora*, followed by *Q. salicina*, followed by *Q. salicina* in the wax layer, then *P. densiflora*. As a result of this study, the amount of PM adsorbed per unit area of leaves, and the amount of PM calculated by LAI, showed a simpler pattern. The hardwoods had a high adsorption rate of $PM_{2.5}$. The adsorption ratio of ultra-fine $PM_{2.5}$ by evergreen broad-leaved trees was greater than that of coniferous trees. Therefore, broad-leaved evergreens such as *Q. salicina* are considered very suitable as species for adsorbing PM in the city. $PM_{2.5}$ has been shown to be adsorbed through the pores and leaves of trees, indicating that the plant plays an important role in alleviating PM in the atmosphere. As a result of analyzing the elemental components of PM accumulated on leaf leaves by scanning electron microscopy (SEM)/ energy dispersive x-ray spectroscopy (EDXS) analysis, it was composed of O, C, Si, and N, and was found to be mainly generated by human activities around the road. The results of this study provide basic data regarding the selection of evergreen species that can effectively remove aerial PM. It also highlights the importance of evergreen plants for managing PM pollution during the winter and provides insights into planning additional green infrastructure to improve urban air quality.

Keywords: adsorption; broad-leaved tree; evergreen; particulate matter; SEM-energy dispersive X-ray

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1. Introduction

Air pollution is now recognized as a major environmental risk for respiratory and systemic diseases. According to data from over 3000 cities, provided by the World Health Organization, outdoor air pollution has grown 8% globally in the last five years, with billions of people around the world now exposed to dangerous air [1]. Human populations in fast-growing cities in the Middle East, Southeast Asia and the Western Pacific Region in particular are exposed to pollution levels that are five to 10 times above World Health Organization-recommended levels of micrometer-size PM. This could be a public health emergency with huge future medical and social costs. For this reason, there is a global need to address growing environmental and clinical problems related to air pollution [2]. $PM_{2.5}$ is defined as a material with a particle diameter of less than 2.5 μm and is the relatively small portion of PM overall. Compared to other air pollutants, $PM_{2.5}$ potentially has the most significant impact on human health, related to respiratory and cardiovascular disease and mortality [3]. In particular, it is deposited in the alveoli and has a greater effect on the respiratory system than other PM [4].

Korea has been experiencing air pollution caused by an increase of various industrial facilities, a rapid increase in the number of a private car and a vehicle driven by fossil fuel engines due to urbanization. In recent years, one of the most important issues is particulate matter (PM), since collectively, it is a major source of air pollution and one of the fastest growing types of environmental pollution [5].

As PM accumulates in the leaves of trees, it has been shown to decrease photosynthetic efficiency, reduce the normal function of plants, increase the wax layer [6], and decrease the survival rate and performance of insects [7]. It has been shown that leaves adsorb PM like nanoparticles more quickly than other tree parts [8]. Adsorption of PM reduces terrestrial biomass growth, and eliminates oxidative stress, leaf and root bacteria and fungi [9]. Therefore, it is necessary to prepare for this as PM can affect, not only humans, but also ecosystems in the long term.

The ability to effectively capture PM is an important consideration in choosing the optimal plant species to use for urban greening [10], thus, it is important to investigate the PM capture ability of different plant species to optimize their use in various urban environments [11]. Although some plant species are known to remove airborne contaminants in urban environments, little is known about how effectively other species can capture PM in urban areas [12].

Urban green spaces are becoming increasingly important due to their positive effects such as reduced air pollution, landscape functions, noise reduction, and heat island mitigation. Various woody and herbaceous plants are used to create urban green spaces and are the main materials for urban greening [13]. Among them, broad-leaved evergreen trees in warm temperate zones are moving northward, due to climate change. Among them, broad-leaved evergreen trees in temperate regions have four-season leaves, so they are highly valued as landscape trees and street trees and are of increasing importance in the creation of urban forests in Korea. However, their PM reduction effect and adsorption mechanism are not known. This study was conducted to investigate the characteristics of PM adsorption in eight evergreen broadleaf trees and two coniferous trees that grow in Korea, and select aquatic species with highly fine PM adsorption, based on this data. The characteristics of PM adsorption in research species were examined for PM adsorption ability, adsorption tissue, and elements of PM adsorption in trees. The adsorption content of $PM_{2.5}$, which is more harmful to humans, was selected for urban greening in Korea.

2. Materials and Methods

2.1. Site Selection

This study was conducted on trees planted in an industrial area (N 35°18′03″, E 128°11′95″) in Jinju, Gyeongnam Province, Republic of Korea (Figure 1). Trees on the 8-lane roads running around the site were investigated. These tree species were mainly exposed to urban road dust and pollution sources. In this area, a data logger (SELCO HE-170, China) was installed to measure temperature and relative humidity, and a precipitation meter (LABDIA, NAVIMRO, Korea) was installed to measure precipitation. The average annual precipitation is 1812.7 mm, and the average temperature, wind speed, and relative humidity are 14.4 °C, 1.12 $m \cdot s^{-1}$, and 56.6%, respectively. The concentrations of PM_{10} and $PM_{2.5}$ measured by β-ray aspiration at a measuring station 500 m away from this research site represent 44 μg/m^3 per year of PM_{10} in 2017 and 41 μg/m^3/year in 2018. $PM_{2.5}$ was 21 μg/m^3/year in 2017 and 18 μg/m^3/year in 2018 (http://www.jinju.go.kr/). These values correspond to Korea's air quality standards; that is, the average annual PM_{10} and $PM_{2.5}$ are 50 μg/m^3 or less 15 μg/m^3 or less, respectively. In addition to the metal and machinery industries, the complex also has a mix of various industries, such as paper and silk.

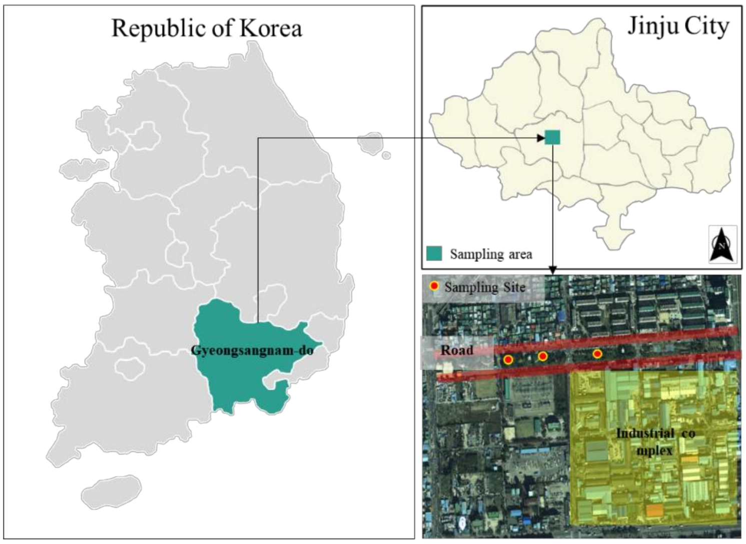

Figure 1. Location of sampling area (Google Maps).

The traffic density of this industrial area is 1200 vehicles/h within a 500 m radius (http://www.jinju.go.kr/). The test was conducted in late autumn to winter. The reason for this is the low temperature in Korea and the dry season. Due to the nature of the industrial complex, there are few seasonal pollutants. In addition, the experimental site is a traffic pollution monitoring and evaluation point designated by the Korea Environment Corporation.

During the measurement period, the average wind speed was 8–15 km/h. North of the industrial complex is a residential area and green space [14].

2.2. Species and Sampling

Trees were sampled by randomly selecting trees within 100 m to reduce environmental influences such as temperature and relative humidity. This study had an average height of 7.0 ± 0.5 m, average diameter at breast height of 21.1 ± 4.2 cm, average crown width of 2.6 ± 0.4 m. The morphological characteristics of the leaves of the different tree species are shown in Table 1 and Figure 2. Among the species, *Ginkgo biloba* L. was included in conifers considering taxonomic aspects.

Samples for this study were taken over a period of 7 months from October 2017 to May 2018. Whole leaves, without any damage from insects, were picked by using 2 scissors from all 4 sides of a tree. Since PM is susceptible to static electricity, the collected leaves were placed in labeled paper bags and transferred to the laboratory. The samples were stored in a refrigerator at 5 °C until they were used for analysis.

Leaves were sampled from 3 trees in each of the 4 directions (east, west, south, and north). The height on the tree for sampling was 1.5 m. The reason for measuring 1.5 m is that the adsorption of PM in the upper and lower parts of trees 0–20 m away from the main road was reported to be higher in the lower part [15], which is closely related to human activity. This is because trees in urban forests were judged to be more affected by PM than the upper ones.

Table 1. Habit, shape, surface characteristics, mean area, and phyllotaxy of leaves studied in this research.

Species	Family	Leaf			Phyllotaxy
		Shape	Surface Characteristics	Mean Area (cm^2)	
Broad-Leaved Species					
Camellia japonica L.	Theaceae	Elliptical	Smooth	35.0 ± 2.1	Alternate
Rhaphiolepis indica (L.) Lindl. var. *umbellata* (Thunb. ex Murray) H.Ohashi	Rosaceae	Oval	Smooth	18.6 ± 0.1	Alternate
Dendropanax morbiferus H.Lév.	Araliaceae	Elliptical	Smooth	24.4 ± 2.5	Alternate
Machilus thunbergia Siebold & Zucc. ex Meisn.	Lauraceae	Oblong	Smooth	28.4 ± 0.7	Alternate
Illicium anisatum L.	Illiciaceae	Oblong	Smooth	16.5 ± 0.4	Alternate
Daphniphyllum macropodum Miq.	Euphorbiaceae	Elliptical	Smooth	49.8 ± 3.7	Alternate
Quercus glauca Thub.	Fagaceae	Elliptical	Mature leaves with trichomes	33.2 ± 0.4	Alternate
Quercus salicina Blume	Fagaceae	Oblong	Mature leaves with trichomes	14.0 ± 3.1	Alternate
Conifer Species					
Ginkgo biloba L.	Ginkgoaceae	Crescent-shaped	Smooth	28.0 ± 2.9	Fascicled
Pinus densiflora Siebold & Zucc.	Pinaceae	Needle	Smooth	0.5 ± 0.0	Fascicled

Sampling was carried out 4 times, and the dry period without precipitation prior to each sampling was 28 to 37 days (Table 2). The PM on leaf surface and wax layer was analyzed. According to one report [16], leaves can reach maximum saturation 26 days after PM is adsorbed. The leaves used for analysis (30 leaves, fresh weight 50 g) were collected, and leaves collected in the same sampling area were mixed together.

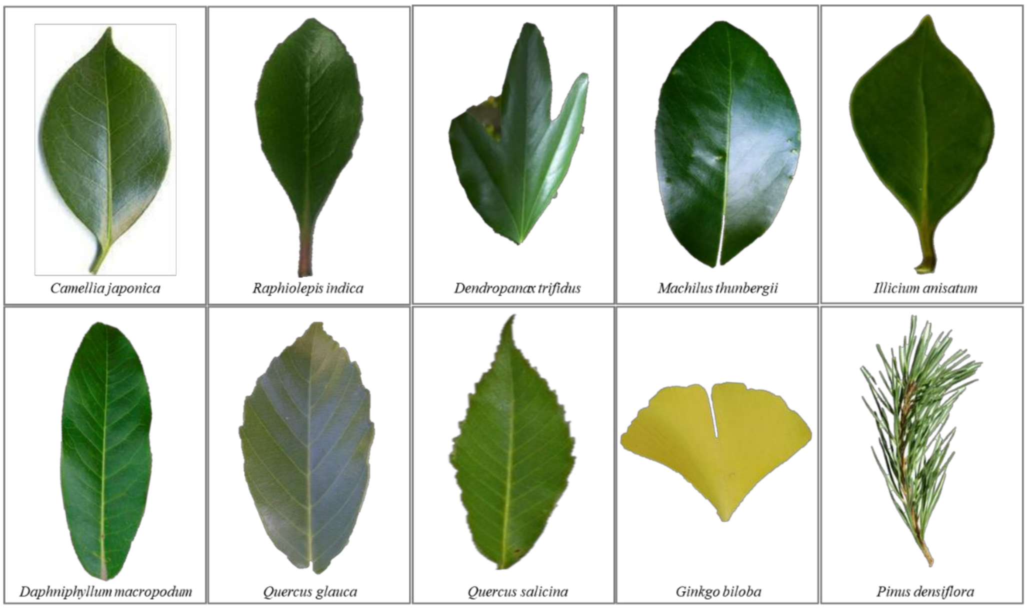

Figure 2. Pictures of representative leaves of 8 broad-leaved evergreen and 2 conifer species plant species taken from sampling sites and used in this study.

Table 2. Sampling dates, duration of dry period before collecting leaf samples, atmospheric PM_{10} concentration on sampling day, and analytical measurements taken for this study.

Analysis	Date of Sampling			
	31 October 2017	**10 January 2018**	**25 March 2018**	**15 May 2018**
Dry period before sampling (without precipitation) (days)	37	29	31	28
Atmospheric concentration of PM_{10} measured at 10:00	44	95	92	73
SEM and EDXS	√			
PM on surface	√	√	√	√
PM in wax	√	√	√	√

√ indicates measurement was taken on specified sampling date.

2.3. Determination of Amount of PM Adsorbed on Leaf Surfaces

The amount of PM adsorbed on the leaf surface and stoma was analyzed according to the method of Dzierżanowski et al. [17]. PM attached to the surface of leaves was completely washed off using distilled water. The water was filtered in order of decreasing filter pore size (Merck Millipore membrane filters, Carrigtwohill, Ireland) with pore diameters of 100, 10, 3.0, and 0.2 µm. The filters were dried in a dryer at 60 °C for 2 h before being used [15]. After filtering the PM, the weight was measured with an electronic scale (PAG214, Ohaus, Parsippany-Troy Hills, NJ, USA).

The area of each leaf was measured using a leaf area analyzer (LI-3000c and LI-3050c, Soldan Inc., Lincoln, NE, USA) to calculate the amount of adsorbed PM per unit leaf area. All analyses were repeated 3 times. The PM adsorption experiment of needle leaves confirmed that the experimental error was very small through the previous experiment.

2.4. Determination of Amount of PM Adsorbed in Wax Layer

The PM adsorbed in the wax layer was measured in a similar manner as the PM adsorbed on the leaf surface. However, chloroform was used instead of distilled water to decompose the wax layer. After rinsing with water, each sample leaf was washed with 150 mL of chloroform (Daejung, Seoul, Korea) for 40 s, in order to dissolve the epicuticular wax layer from the leaf tissues and wash out particles trapped in the wax (in-wax PM). The filtration procedure was the same as that for analyzing PM adsorbed on the leaf surface.

2.5. Determination of Amount of PM by LAI (Leaf Area Index)

The amount of PM adsorption by the LAI was investigated by referring to the method of Kim et al. [18]. As a divided value, it was measured using a leaf area index measuring instrument LAI-2000 Plant Canopy Analyzer (Li-Cor). The LAI is expressed as the ratio of the sum of leaf area per unit ground surface area (m^2/m^2), and the equation is as follows:

$$\mathrm{LAI} = \frac{\text{leaf area } \left(\mathrm{m}^2\right)}{\text{Ground surface area } \left(\mathrm{m}^2\right)}$$

After the leaf area index was measured, the amount of PM adsorption was calculated by multiplying the amount of PM adsorption per unit area of the leaf (mg/cm^2).

2.6. Analysis of PM Adsorption Location in Leaves

The location where the PM was adsorbed was analyzed using an electron optical microscope (S4800, Hitachi, Tokyo, Japan). The evergreen leaves were cut into 1 cm^2 pieces that could be observed with a microscope, avoiding the veins from the midpoint, and the coniferous leaves were prepared by cutting a 1 cm long piece at the middle point of the leaf. The ends of the leaves were attached to the microscope with double-sided adhesive tape. The samples were gold-coated for improved electrical conductivity, and then randomly selected samples were observed using an electron optical microscope (Genesis-1000, Emcrafts, Seoul, Korea).

2.7. Analysis of PM Using SEM-Energy Dispersive X-ray

The PM composition was measured using energy dispersive x-ray (SEM/EDX; Horiba, EX-220SE, Singapore). As discussed, all the leaves of test l species were washed with distilled water and filtered, and the collected dust was used for analysis. In order to prepare suitable samples for analysis, the collected waste was stored in a desiccator (D01-96-120, Seoul, Korea) for a minimum of 48 h before and after collecting the specimens. The specimens were cut into 10 mm $\times$ 10 mm samples and adhered to the carbon mount to prepare for SEM/EDX analysis. The samples were coated with 20 nm thick Pt. To analyze the images of individual particles, a field emission scanning electron microscope (JSM-6700F, JEOL Ltd., Tokyo, Japan) was used. The working distance was less than 25 mm, the acceleration voltage was 20 keV, and the magnification factor of the SEM images was fixed at 5000$\times$.

The EDX used for chemical analysis of individual particles was an auxiliary device connected to the SEM (JSK-6510, JEOL Ltd., Tokyo, Japan). The working distance was 15 mm, the acceleration voltage was 15 keV, and the magnification was fixed at 3000$\times$. A total of 20 elements (Al, Br, C, Ca, Cl, Co, Cu, F, Fe, K, Mg, Mn, Na, Nb, O, P, S, Si, Ti and Zn) were analyzed. The elemental composition of PM was analyzed 3 times, and the sources of PM particles were identified by classifying them based on morphological characteristics [19,20].

2.8. Statistical Analysis

A one-way ANOVA model was used to compare the Amount of PM adsorbed on leaf surfaces, the PM adsorption in the wax layer, rate of the elemental composition of adsorbed PM. Duncan multiple range test test (p = 0.05) was employed to assess the significance of differences among variants. Before all analyses, normal distribution was verified with the Shapiro-Wilk test. The data are given as means with standard errors of the mean (±SE). Bold values indicate statistical significance ($p < 0.05$). Statistical analyses were conducted in SPSS software 25.0 (SPSS Inc., Chicago, IL, USA).

3. Results and Discussion

3.1. Amount of PM Adsorbed on Leaf Surfaces

The analysis of the amount of PM adsorption on leaf surfaces revealed that there was a significant difference between broad-leaved evergreen trees and coniferous species in PM deposition (Figure 3). The total amount of PM was calculated by the amount of PM adsorbed by the leaves of the test species for 26–37 days without rain. The results showed that the leaf shape characteristics of broad-leaved evergreen trees and coniferous species made notable differences among the species, in terms of their PM capturing capacity. The amount of PM adsorbed on the surface of *P. densiflora* leaves was 74.89 $\mu g \cdot cm^{-2}$ per leaf area (PLA), which was significantly higher than that of other species. PM adsorption on deciduous leaf surfaces was 47.42 $\mu g \cdot cm^{-2}$ PLA in *Q. salicina*, 27.76 $\mu g \cdot cm^{-2}$ PLA in *Q. glauca*, 22.94 $\mu g \cdot cm^{-2}$ PLA in *R. indica*, 13.72 $\mu g \cdot cm^{-2}$ PLA in *I. anisatum*, 13.64 $\mu g \cdot cm^{-2}$ PLA in *M. thunbergii*, and 23.58 $\mu g \cdot cm^{-2}$ PLA in *G. biloba*.

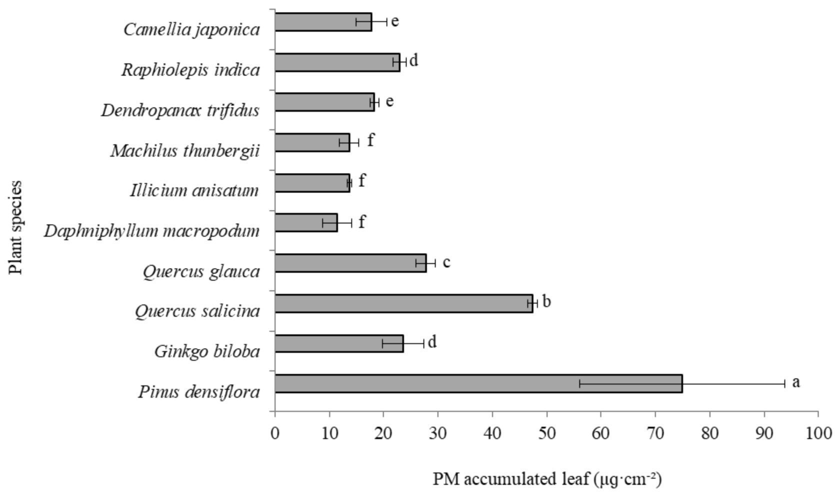

Figure 3. Total amount of particulate matter (PM) accumulated on leaves of eight evergreen and two coniferous species. Data presented as mean ± standard deviation (SD), with 5 replicates of 30 leaves each. Bars marked with different letters are significantly different by Duncan multiple test ($p < 0.05$).

Pollution may also affect the long-term accumulation of PM through the responses of plants. Freer-Smith et al. [21] attributed differences in PM accumulation to the differences in leaf structure between conifers and broad-leaved species. Our results show that pine species had particularly high accumulation, in spite of their leaves having no hairs or rough surfaces. However, the long, narrow needles may be more easily hit by particles in the air than large and flat leaves, which have thicker boundary layers. In a computer simulation study, twice as much PM accumulation on pine species was predicted compared to actual observations [22,23], but both ranked the conifers highest in accumulated PM on foliage. Although high PM accumulation by conifers has been noted by several authors [24], the authors also mention the sensitivity of these species to pollution. Therefore, it is important to evaluate the resistance of selected species to pollutants in urban areas.

Table 3 shows the differences among species in PM accumulation on leaf surfaces categorized by the PM size observed in this study. $PM_{2.5}$ attached to leaf surfaces accounted for 15.0% of total PM by weight; this accumulation is an important indicator, because $PM_{2.5}$ is the most harmful to human health. $PM_{2.5}$ accumulated on leaf surface was the highest value of 25.71 $\mu g \cdot cm^{-2}$ PLA at *Q. salicina* and the lowest value of 0.61 $\mu g \cdot cm^{-2}$ PLA at *D. macropodum*.

Table 3. Total amount of particulate matter (PM) accumulated on leaf surface of eight evergreen and two coniferous tree species by PM size. Data are mean ± SD with 5 replicates of 30 leaves each. Species marked with different letters are significantly different by Duncan multiple test ($p < 0.05$).

Leaf Morphology	Plant Species	Amount of PM on Leaf (μg·cm^{-2})				Proportion (%)		
		$PM_{2.5}$ (0.2–2.5 μm)	PM_{10} (2.5–10 μm)	PM_{100} (10–100 μm)	Total	$PM_{2.5}$ (0.2–2.5 μm)	PM_{10} (2.5–10 μm)	PM_{100} (10–100 μm)
Broad-leaved	*C. japonica*	1.06 ± 0.12 e	6.88 ± 0.22 d	9.85 ± 0.16 cd	17.79 e	5.9	38.7	55.4
	R.indica	3.98 ± 0.18 c	6.97 ± 0.17 d	11.99 ± 0.12 cd	22.94 d	26.9	26.9	52.3
	D.trifidus	4.35 ± 0.11 c	5.69 ± 0.22 d	8.25 ± 0.06 d	18.29 e	23.8	31.1	45.1
	M. thunbergii	1.07 ± 0.07 e	5.58 ± 0.16 d	6.99 ± 0.06 d	13.64 f	7.8	40.9	51.2
	I. anisatum	3.85 ± 0.17 c	3.05 ± 0.21 e	6.82 ± 0.04 d	13.72 f	28.0	22.2	49.7
	D. macropodum	0.07 ± 0.01 f	4.67 ± 0.06 de	6.72 ± 0.14 d	11.46 f	0.6	40.8	58.6
	Q. glauca	6.83 ± 0.18 b	6.44 ± 0.23 d	14.49 ± 0.20 c	27.76 c	24.6	23.2	52.2
	Q. salicina	12.19 ± 0.04 a	12.98 ± 0.06 b	22.25 ± 0.24 b	47.42 b	25.7	27.4	46.9
Conifer-leaved	*G. biloba*	0.52 ± 0.22 ef	9.54 ± 0.15 c	13.52 ± 0.07 c	23.58 d	2.2	40.5	57.3
	P. densiflora	2.97 ± 0.89 d	29.60 ± 4.35 a	42.32 ± 8.74 a	74.89 a	4.0	39.5	56.5

Note: All values are means of three replicates ± SD.

PM_{10} accumulated on leaf surfaces was the highest value of 29.60 $\mu g \cdot cm^{-2}$ PLA at *P. densiflora*, which accounted for 39.5% of total PM attached to leaf surfaces and was significantly higher than that of other species ($p < 0.05$). The lowest amount of PM_{10} accumulated on leaf surfaces value at 3.05 $\mu g \cdot cm^{-2}$ PLA at *I. anisatum*.

PM_{100} accumulated on leaf surface was the highest value 42.32 $\mu g \cdot cm^{-2}$ PLA *at P. densiflora*, which accounted for 56.5% of total accumulated PM and was about four times more than that on leaves of *R. indica*. $PM_{2.5}$ and PM_{10} accounted for 3.9%, and 39.5%, respectively, of a total PM accumulation on leaves of *P. densiflora*, indicating that the species is much more effective in accumulating large PM particles. Based on atmospheric PM_{10} concentration of 80.0 ± 23.8 $\mu g \cdot cm^{-2}$ and $PM_{2.5}$ concentration of 40.8 ± 13.8 $\mu g \cdot cm^{-2}$, *P. densiflora* was the most effective in adsorbing atmospheric PM_{10}, accounting for 37.0%, while *Q. salicina* was the most effective in adsorbing $PM_{2.5}$, adsorbing 25.7%. The other tree species used in this study displayed about 22.2–41.1% adsorption rates of PM_{10} and 2.2–28.1% adsorption rates of $PM_{2.5}$.

The fact that different plant species secrete different amounts of wax also leads to differences in the amount of in-wax PM that plants accumulate. Dzierżanowski et al. [17] studied the accumulation of PM on leaf surfaces and wax layers of suburban plant species. Leaf surfaces adsorbed more PM_{100} than $PM_{2.5}$ or PM_{10}. PM ranging in size from 0.2 to 10 µm was found to be similar to that detected in wax layers in some plants. Popek et al. [25] observed that the amount of adsorbed PM, from lowest to highest by weight, were $PM_{2.5}$ (14%), PM_{10} (21%), and PM_{100} (65%). In terms of quantity, $PM_{2.5}$ was the least adsorbed, but it is significant because it poses the greatest threat to human health. It is reasonable to deduce that even at a low weight, the amount of adsorbed $PM_{2.5}$ particles could still be large because the particles weigh little compared to PM_{10} and PM_{100}. These results are explained by the atmospheric concentration of differently sized PM particles, and the leaves and structural characteristics of the plant species studied. Broad-leaved evergreen and coniferous trees purify the air by removing atmospheric PM, but PM which contained heavy metal particles is toxic and destroys leaf cell tissues. It is considered that plants should be selected appropriately through additional experiments, related to atmospheric PM concentration, PM removal using plants, and the physiological and biochemical effects of PM on plants.

3.2. PM Adsorption in the Wax Layer

Broad-leaved evergreen trees and coniferous species notable differences existed among the species, in terms of their PM capturing capacity (Figure 4, Table 4). The species that greatest amount of $PM_{2.5}$ and PM_{100} in the wax layer was deposited *P. densiflora* (3.16 $\mu g \cdot cm^{-2}$ PLA and 18.17 $\mu g \cdot cm^{-2}$ PLA) *and Q. salicina* (3.14 $\mu g \cdot cm^{-2}$ PLA and 17.47 $\mu g \cdot cm^{-2}$ PLA). *P. densiflora* deposited the highest total mass of PM in the wax layer at 24.58 $\mu g \cdot cm^{-2}$ PLA. There was no significant difference in the total amount of PM adsorbed by the wax layers of *P. densiflora* and *Q. salicina* (0.75 $\mu g \cdot cm^{-2}$ PLA). While *P. densiflora* displayed the greatest effectiveness in adsorbing PM with its wax layer, it has low resistance to pollutants, generated by vehicle exhaust, and thus, is not suitable as a roadside species [20].

PM accumulated of wax layer was the lowest value of 8.14 $\mu g \cdot cm^{-2}$ PLA at *I. anisatum*. The particles fixed in the wax layer accounted for approximately 35.4% of total PM on the leaf (on the surface and in the wax layer). According to a study, there is a positive correlation between the amount of leaf wax and the amount of PM accumulation on the leaf. It is also suggested that the chemical composition and structure of the leaf wax can play a role in PM accumulation efficiency [19].

Table 4. Total amount of particulate matter (PM) accumulated in wax layer of leaves of the eight evergreen and two coniferous species by particle size. Data are mean ± SD with 5 replicates of 30 leaves each. Species marked with different letters are significantly different by Duncan multiple test (p < 0.05).

Leaf Morphology	Plant Species	Amount of PM in Wax Layer (μg·cm^2)				Proportion (%)		
		$PM_{2.5}$ (0.2–2.5 μm)	PM_{10} (2.5–10 μm)	PM_{100} (10–100 μm)	Total	$PM_{2.5}$ (0.2–2.5 μm)	PM_{10} (2.5–10 μm)	PM_{100} (10–100 μm)
Broad-leaved	*C. japonica*	0.17 ± 0.05 c	0.18 ± 0.09 c	12.76 ± 0.97 ab	13.11 bc	1.30	1.38	97.32
	R. indica	0.37 ± 0.12 bc	3.40 ± 1.24 ab	10.91 ± 1.71 ab	14.68 bc	2.52	23.18	74.30
	D. trifidus	1.88 ± 1.04 abc	1.90 ± 0.08 abc	6.35 ± 2.80 b	10.13 c	18.56	18.76	62.69
	M. thunbergii	1.78 ± 1.02 abc	2.80 ± 1.26 ab	7.15 ± 3.88 b	11.73 c	15.17	23.87	60.95
	I. anisatum	0.10 ± 0.06 c	0.13 ± 0.05 c	7.91 ± 2.47 b	8.14 c	1.23	1.60	97.17
	D. macropodum	2.03 ± 0.74 ab	2.07 ± 0.97 ab	9.59 ± 3.41 b	13.69 bc	14.83	15.12	70.05
	Q. glauca	2.76 ± 1.45 a	3.78 ± 1.21 a	13.74 ± 5.76 ab	20.28 ab	13.61	18.64	67.75
	Q. salicina	3.14 ± 1.37 a	3.22 ± 1.59 ab	17.47 ± 6.85 a	23.83 a	13.18	13.51	73.31
Softwood-leaved	*G. biloba*	1.48 ± 1.06 abc	1.49 ± 0.97 bc	5.89 ± 2.41 b	8.86 c	16.70	16.82	66.48
	P. densiflora	3.16 ± 1.24 a	3.25 ± 1.21 ab	18.17 ± 6.21 a	24.59 a	12.89	13.26	73.85

Note: All values are means of three replicates ± SD.

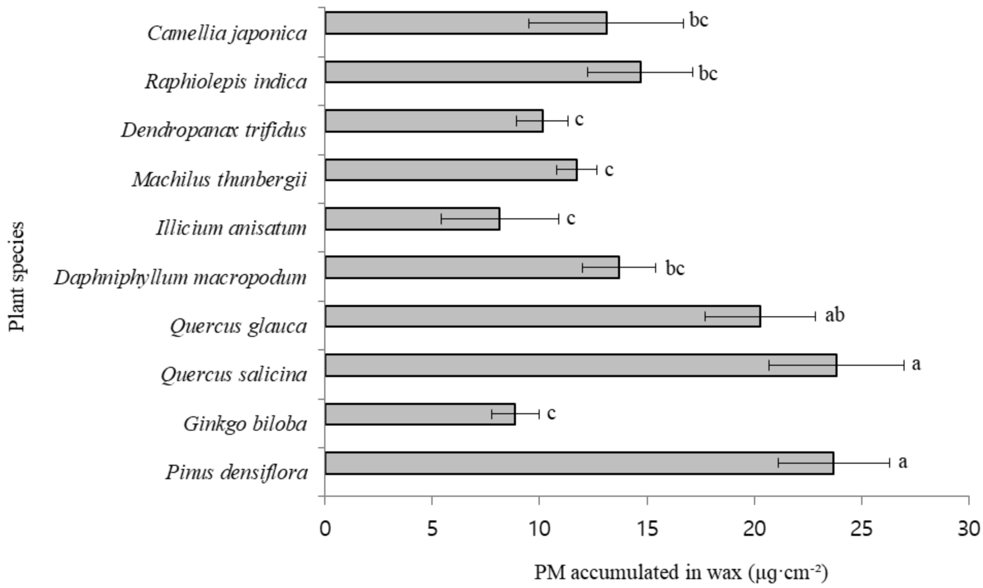

Figure 4. Total particulate matter (PM) accumulated in wax layer of leaves of eight evergreen and two coniferous species. Data presented as mean ± SD, n = 30. Bars marked with different letters are significantly different by Duncan multiple test ($p < 0.05$).

3.3. PM Accumulation Amount Calculated by LAI

The amount of PM adsorption converted to LAI showed a difference between species (Table 5). LAI also showed a difference for each species and ranged from 0.57 to 1.78. The species with the largest LAI was *G. biloba* (1.78), and *Q. salicina*, followed by *Q. glauca*. On the other hand, it was the smallest *D. macropodum*. When the amount of PM adsorbed on the leaf surface was calculated by LAI, the species that adsorbed the most PM were *P. densiflora*, *Q. salicina*, *G. biloba*, and *Q. glauca*. On the other hand, *D. macropodum* was the least adsorbing PM on the leaf surface. As the amount of PM, adsorbed on the wax layer, was calculated by LAI, the species that adsorbed PM the most was *Q. salicina*, followed by *P. densiflora*.

Table 5. PM accumulation amount calculated by LAI as particulate matter (PM) accumulated on the leaf surface and wax layer of 8 evergreen trees and 2 conifers.

Plant Species	LAI	Leaf Surface PM (μg·cm^2)	Wax Layer PM (μg·cm^2)	PM of Leaf Surface by LAI	PM of Wax Layer by LAI
C. japonica	0.79	17.79	13.11	14.05	10.35
R. indica	1.18	22.94	14.68	27.06	17.32
D. trifidus	0.94	18.29	10.13	17.19	9.52
M. thunbergii	0.57	13.64	11.73	7.77	6.68
I. anisatum	0.66	13.72	8.14	9.05	5.37
D. macropodum	0.49	11.46	13.69	5.61	6.70
Q. glauca	1.45	27.76	20.28	40.2	29.40
Q. salicina	1.61	47.42	23.83	76.34	38.36
G. biloba	1.78	23.58	8.86	41.97	15.77
P. densiflora	1.36	74.89	24.59	101.85	33.44

Note: The amount of PM adsorption by the leaf area index was investigated. Using the method of Kim et al. (2018) As a divided value, it was measured using a leaf area index measuring instrument LAI-2000 Plant Canopy Analyzer (Li-Cor). The leaf area index is expressed as the ratio of the sum of leaf area per unit ground surface area (m^2/m^2), and the equation.

As a result of this study, the amount of PM adsorbed per unit area of leaves and the amount of PM calculated by LAI showed a simpler pattern. In other words, it could be established that a species with a large leaf area absorbs a lot of PM.

For the analysis of PM adsorption amount by tree, the amount of PM adsorption per unit area (mg/cm^2) is also important. However, since the size and leaf area of trees are different from each other, it is difficult to analyze only with the adsorption amount of leaves. This is because even if the amount of PM adsorption per unit area is high, the amount of PM adsorption per tree can be relatively high. This is true, even if the amount of PM adsorption per unit area is low, and the amount of PM adsorption per tree is relatively high because the amount of PM adsorption per unit area is low. Therefore, two measurement methods, such as measuring the amount of PM absorption by calculating the unit leaf area and LAI, as in this study, are considered to be very good methods for measuring the amount of PM absorption.

3.4. PM Adsorption Location on Leaves

An analysis of PM adsorption on the leaf surface revealed that the adsorbed PM was concentrated in the stomata, the corrugated areas around the stomata (Figure 5A–D), and the leaf hairs (Figure 5E,F). As shown in Figure 5A,B, PM up to 2 µm could enter or block the stomata. Several researchers have reported that more PM could be deposited on rough leaf surfaces [17,26,27]. In particular, when PM (Ag–NP) is adsorbed through the leaves of woody plants, such as poplar. However, it quickly migrates to the stem, increasing the leaves' O_2-, reducing bio-mass, and affecting bacterial and fungal growth [27]. In addition, the presence of more PM in the leaves reduced the efficiency of the photosynthetic device, lowered the ratio of photosynthesis and chlorophyll, and lowered energy efficiency. In addition, it is said that it varies according to species, such as invasive species and indigenous species [28]. Therefore, biochemical studies on PM adsorption by the leaves of the species, examined in this study, are required in the future.

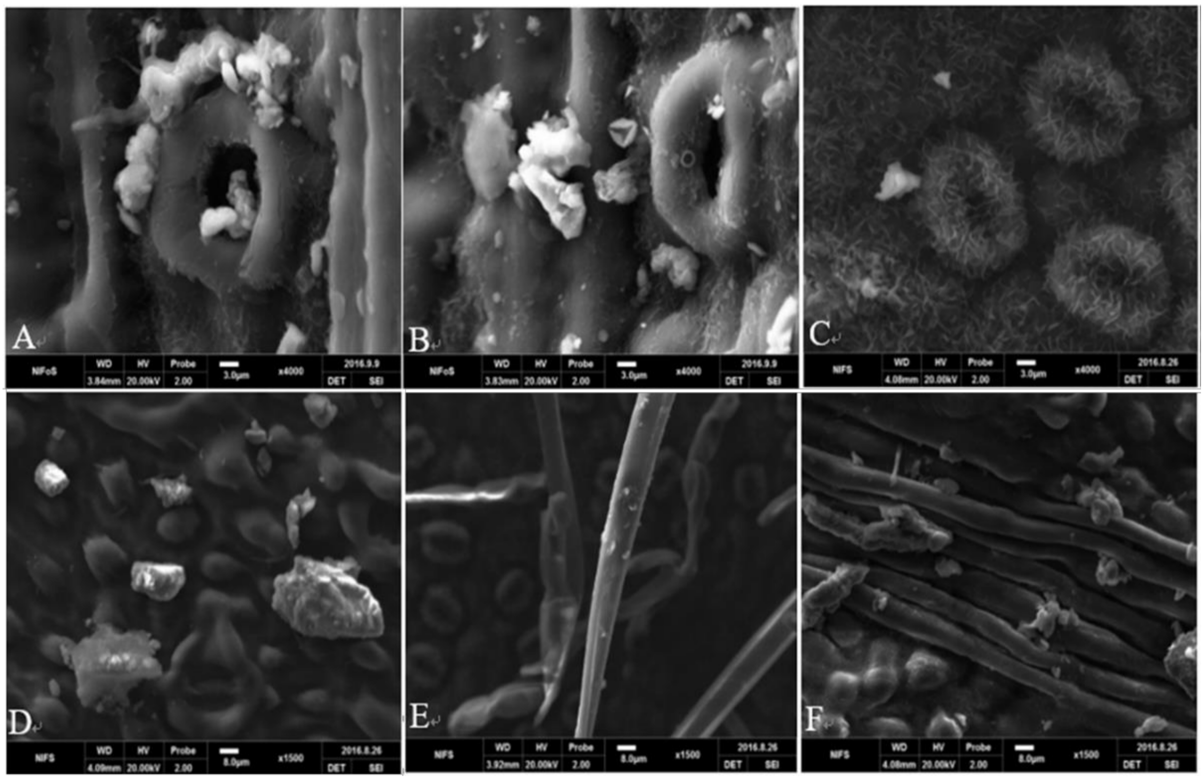

Figure 5. Scanning electron micrographs of particulate matter (PM) adsorbed on leaf surface. All dusty leaves of experimental species were collected, washed with water, filtered, and used for analysis. (**A**,**B**) PM in and around stomata; (**C**,**D**) PM in furrowed areas; (**E**,**F**) PM around trichomes.

Figure 5A,B demonstrates the locations where PM is deposited on the leaf surface. Previous studies showed that PM can be adsorbed through the stomata, suggesting that particles smaller than 0.1 μm in size can pass through the stomata [19,29]. Our results directly demonstrated the specific location of PM deposition on leaf surfaces. Previous studies demonstrated that particles can be adsorbed through stomata and indicated that a particle less than 0.1 mm can pass through the stomata [29,30]. However, we found that particles less than $PM_{2.5}$ can pass through the stomata, which is a conclusion of similar studies [20,31].

3.5. Elemental Composition of Adsorbed PM

The environmental scanning electron microscope (ESEM) was used to analyze the morphology of the PM particles adsorbed on the leaves and the elemental composition of the adsorbed PM and deduce the origin of the particles. The PM was found to be made up of C, O, Na, Mg, Al, Si, K, Ca, Ti, Fe, Cl, Nb, S, F, P, and Mn (Table 6). O (46.7%), C (35.9%), Si (7.0%), and N (5.3%) accounted for the majority of components. The high O, C, and Si content in PM is reported to be derived from soil and industrial activities [20]. This PM had an irregular shape with edges, as shown in Figures 5 and 6. On the other hand, PM with high O, C, and Ca content (Figure 6A,B,G,I), and PM containing a lot of H and N with irregular shapes (Figure 6C–F,H) were judged to be produced by human activity (Table 6).

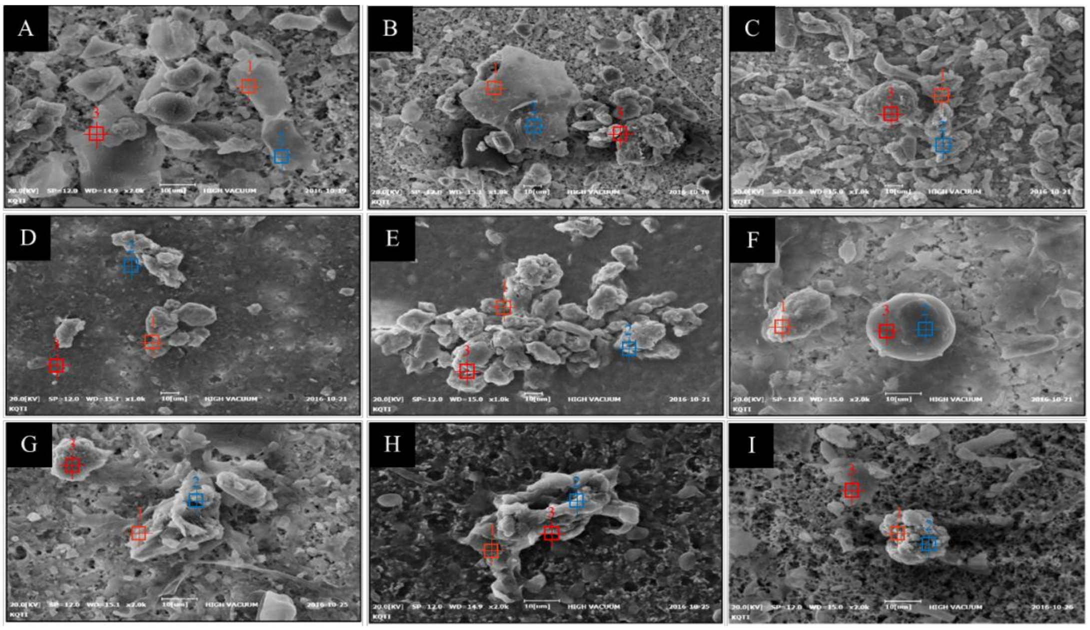

Figure 6. Size and morphology of particulate matter (PM) adsorbed on leaf surfaces, used to determine the elemental composition of PM shown in Table 3. Analytical images were taken randomly from all leaf samples of tree species used in the study. PM with high O, C, and Ca content (**A**,**B**,**G**,**I**), and PM containing a lot of H and N with irregular shapes (**C**–**F**,**H**).

The source of PM can be estimated by analyzing the elemental composition of PM adsorbed on leaves. The detection of O, C, Si and Ca in PM reveals that they originated from human activity [32]. Fe, Cl, S and Ti were higher than other elements, which can be assumed to have been released from automotive exhaust [33]. That is, PMs with Fe, Cl, and S were artificially produced, but were mainly found to be the result of human activities [34]. Most of the analyzed PM particles contained more than 10 elements, including C, O, Na, Mg, Al, Si, K, Ca, Ti, Fe, Cl, Nb and S. The elements also showed a slight difference depending on the form of PM. A, B, C, D, E, and I were overwhelmingly rich in C and O, and also contained Si. In addition, F, G, H contained a lot of N other than C, O. Overall, PM was overwhelmingly high in C and O, and contained a lot of Si and N.

Table 6. Mean elemental composition (%, *w*/*w*) of the three particles marked in red and blue in Figure 6. The analysis compared the elemental composition ratio of the morphology of particulate matter (A–I). Data are mean ± SD with 3 replicates of 30 leaves each. Species marked with different letters are significantly different by Duncan multiple test ($p < 0.05$).

Element	**Labels of EDX Images in Figure 6**									**Total (%)**
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	
C	37.6 ± 0.1 bc	29.3 ± 0.91 f	30.9 ± 0.3 e	38.0 ± 0.3 b	41.4 ± 1.0 a	35.3 ± 1.0 d	38.9 ± 1.0 b	35.6 ± 1.0 d	36.5 ± 1.0 cd	35.9 ± 0.7
N	4.0 ± 0.1 e	2.7 ± 0.2 f	4.4 ± 0.1 de	5.2 ± 0.1 d	2.9 ± 0.0 f	7.7 ± 1.0 b	6.6 ± 1.0 c	9.6 ± 0.2 a	4.9 ± 0.0 d	5.3 ± 0.3
O	44.8 ± 0.4 d	44.7 ± 1.0 d	47.0 ± 0.6 bc	48.1 ± 1.0 ab	46.1 ± 1.0 cd	47.9 ± 1.0 ab	45.7 ± 1.0 cd	48.9 ± 1.0 a	46.6 ± 1.0 bc	46.7 ± 0.7
Na	0.3 ± 0.0 d	0.7 ± 0.0 b	1.4 ± 0.1 a	0.3 ± 0.0 d	0.1 ± 0.0 e	0.3 ± 0.0 d	0.3 ± 0.0 d	0.1 ± 0.0 e	0.5 ± 0.0 c	0.4 ± 0.0
Mg	0.5 ± 0.0 c	0.8 ± 0.0 a	0.7 ± 0.0 b	0.4 ± 0.0 d	0.4 ± 0.1 d	0.4 ± 0.0 d	0.4 ± 0.0 d	0.2 ± 0.0 e	0.5 ± 0.0 c	0.5 ± 0.0
Al	3.6 ± 0.1 b	4.6 ± 0.1 a	2.9 ± 0.1 c	2.1 ± 0.2 f	2.1 ± 0.1 f	1.7 ± 0.2 g	2.4 ± 0.1 e	1.1 ± 0.0 h	2.6 ± 0.1 d	2.5 ± 0.0
Si	5.1 ± 0.1 f	11.6 ± 0.6 a	9.7 ± 0.2 b	6.1 ± 0.1 e	6.1 ± 0.1 e	6.6 ± 0.3 d	6.4 ± 0.1 de	5.4 ± 0.0 f	7.2 ± 0.1 c	7.0 ± 0.1
K	1.7 ± 0.0 b	1.9 ± 0.1 a	0.9 ± 0.0 c	0.5 ± 0.1 d	0.5 ± 0.0 de	0.4 ± 0.0 e	0.5 ± 0.0 d	0.2 ± 0.0 f	0.9 ± 0.0 c	0.8 ± 0.3
Ca	0.9 ± 0.0 c	1.0 ± 0.1 b	0.4 ± 0.0 e	1.2 ± 0.1 a	1.2 ± 0.0 a	0.2 ± 0.0 f	0.3 ± 0.0 e	1.2 ± 0.1 a	0.6 ± 0.0 d	0.8 ± 0.0
Ti	0.4 ± 0.0 b	0.3 ± 0.0 b	0.1 ± 0.0 b	0.1 ± 0.0 b	0.1 ± 0.0 b	0.5 ± 0.0 b	0.1 ± 0.0 b	6.4 ± 1.0 a	0.2 ± 0.0 b	0.9 ± 0.1
Fe	0.6 ± 0.0 f	0.7 ± 0.0 e	1.9 ± 0.0 b	1.5 ± 0.1 c	1.4 ± 0.0 c	2.8 ± 0.0 a	0.7 ± 0.0 e	0.2 ± 0.0 g	1.2 ± 0.0 d	1.2 ± 0.3
Cl	0.1 ± 0.0 c	0.0 ± 0.0 c	0.2 ± 0.2 b	0.0 ± 0.0 c	0.0 ± 0.0 c	0.6 ± 0.1 a	0.0 ± 0.0 c	0.1 ± 0.0 bc	0.1 ± 0.0 c	0.1 ± 0.0
Nb	0.4 ± 0.0 a	0.3 ± 0.0 b	0.0 ± 0.0 c	0.0 ± 0.0 c	0.0 ± 0.0 c	0.0 ± 0.0 c	0.0 ± 0.0 c	0.0 ± 0.0 c	0.0 ± 0.0 c	0.1 ± 0.0
S	0.1 ± 0.2 ef	0.3 ± 0.0 de	0.0 ± 0.0 f	0.0 ± 0.0 f	0.0 ± 0.0 f	2.3 ± 0.2 a	0.5 ± 0.0 c	0.8 ± 0.0 b	0.3 ± 0.0 d	0.4 ± 0.0
F	0.2 ± 0.1 a	0.1 ± 0.0 a	0.1 ± 0.0 a	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.1 ± 0.0 a	0.0 ± 0.0
P	0.0 ± 0.0 de	0.3 ± 0.0 a	0.1 ± 0.0 c	0.0 ± 0.0 e	0.0 ± 0.0 de	0.0 ± 0.0 de	0.0 ± 0.0 d	0.0 ± 0.0 e	0.2 ± 0.0 b	0.0 ± 0.0
Mn	0.2 ± 0.1 a	0.1 ± 0.1 ab	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0
Total (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

PM with high O, C, and Ca content (Figure 6A,B,G,I), and PM containing a lot of H and N with irregular shapes (Figure 6C–F,H).

This is because the PM particles adsorbed on leaves are produced by natural and artificial elements. Fe, which is negative for human health, is easily found in roadside trees [26]. It has been reported that ultrafine PM originated mainly from artificial causes [30,35]. It has been found that the composition of atmospheric $PM_{2.5}$ on the campus of the Chinese Academy of Sciences, includes dust and dirt from soil and construction, while atmospheric $PM_{2.5}$ and PM_{100} are adsorbed on the leaves [36]. Fe and S, which showed the highest elemental content other than O and C, can be estimated from diesel exhaust and coal dust.

Urban PMs are reported to be different depending on the characteristics of biomass, season, and urban environment and spatial variations [37]. In Thessaloniki, Greece, $PM_{0.49}$, a very fine dust, was said to be the main vehicle exhaust in urban traffic and wood burning in the outskirts of the city [38]. The PM components, identified by the DTT (dithiothreitol) activation method are quinones, humic-like substances (HULIS), and dissolved transition metals [39–41].

Pollution resistance and landscaping are important for urban greening but selecting species with high adsorption of ultrafine dust is very important. The adsorption capacity of $PM_{2.5}$ was found to be higher in leaves covered with fine hairs, since the leaves are rough with many protrusions and fillers on the surface [42]. Tree species with smooth leaf surfaces, low pore density and pore opening are known to poorly adsorb $PM_{2.5}$. In our study, the amount of $PM_{2.5}$ adsorbed showed that the leaf surface adsorbed more than the wax layer. The species that adsorbed the most $PM_{2.5}$ on the leaf surface were *D. trifidus*, *Q. glauca*, and *Q. salicina*, and conifer species showed very low adsorption. It should be noted that total PM and $PM_{2.5}$ adsorption rates differ. Until now, the total PM adsorption rate has been the main factor in selecting species for urban greening, but from now on, it will be necessary to select species with high adsorption capacity of ultrafine particulates.

4. Conclusions

This study was conducted to select broad-leaved evergreen tree species with high PM adsorption capacity for urban areas of Korea. This study investigated the PM adsorption capacity of eight broad-leaved evergreen trees and two coniferous species of increasing importance as a result of climate change. Through the study of PM, we made the following conclusions. First, it is necessary to consider urban forest planting species. In the meantime, urban greening has focused on tree species that are well-adapted to urban environments and trees with excellent landscapes. However, our study showed that each species has very different adsorption capacities for particulate matters. In the future, the PM adsorption capacity of candidate species for urban greening should be investigated. Second, selection of $PM_{2.5}$ adsorbing species should be carried out. The result of our research is that a species with high PM_{10} adsorption capacity does not adsorb much $PM_{2.5}$. That is, the $PM_{2.5}$ adsorption capacity for candidate species for urban greening should be investigated. Third, it is necessary to predict the source of PM in advance when selecting a tree species for urban greening. That is, it would be good to elementally analyze the PM adsorbed through the environmental scanning electron microscope (ESEM) method and identify the source of the PM, and then select the appropriate species.

The key point of this study is $PM_{2.5}$ adsorption capacity of evergreen species. $PM_{2.5}$ adsorption capacity depends on leaf shape, stomata and LAI. Based on the above results, it is judged that *P. densiflora* and the evergreen oak tree species *Q. glauca* and *Q. salicina* and *P. densiflora* are suitable for urban greening in Korea. This is because *P. densiflora* has the highest total amount of PM adsorption, and *Q. glauca* and *Q. salicina* have the highest total amount of PM adsorption among broad-leaved trees, as well as the highest adsorption of ultrafine dust such as $PM_{2.5}$. The results of this study were conducted in a limited area for a short period of time, so an additional long-term monitoring experiment should be performed. The results of this study can broaden our understanding of the role of urban landscape patterns and provide useful information for urban planning.

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