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Particulate Matter Accumulation and Elemental Composition of Eight Roadside Plant Species

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Abstract: Particulate matter (PM) is the most dangerous air pollutant that adversely affects health. Increasing PM in urban areas is a big problem that must be solved. This study analyzed the amount of PM that accumulated on plant leaves, as well as the leaf traits that contribute to PM accumulation, to determine the plant's ability to accumulate PM and the impact of PM on the plants. Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis were used to quantitatively assess metal concentrations in the particles that had accumulated on the leaf samples. Eight common plant species that grow on the roadside were used to analyze leaf traits using leaf samples. Specific leaf areas (SLA), leaf extract pH (pH), relative leaf water content (RWC), chlorophyll (Chl), and carotenoids were analyzed. PM accumulation and leaf traits varied among plant species, and *Parthenocissus tricuspidata* showed the highest PM accumulation on its leaf surface. The leaf's elemental composition included C, O, Ca, K, Mg, S, P, Al, Si, Na, Cl, and Fe. Among these elements, Ca, K, and Cl made up a relatively large percentage. Fe was only detected in the leaves of *Pachysandra terminalis* and *P. tricuspidata*, while C and O were excluded as they are not relevant in determining PM metal content. Plants not only accumulate PM but also heavy metals from the atmosphere. This study found that plants with highly effective PM accumulation, such as *P. tricuspidate*, should be considered for optimizing the benefits of plants in improving air quality.

Keywords: air quality; leaf traits; urban area; elemental composition; particulate matter

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1. Introduction

Particulate matter (PM) is the most dangerous air pollution, and can enter the respiratory system and cause many adverse health effects for people, particularly for women and children [1]. Additionally, Mukherjee and Agrawal [2] showed that PM could lead to various diseases and lung cancer in people. The sources of PM are human activities or natural phenomena. In urban areas, traffic is the main source of PM [3]. The increasing traffic in urban areas has led to an increase in PM concentration levels. Reducing PM is a significant challenge that needs to be addressed to ensure residents' health. Plants have a role in reducing PM in urban areas [4]. Plants act as a green wall on the roadside, blocking PM. However, larger plants can obstruct traffic view [5]. Using smaller plants, such as shrubs or herbaceous plants, is a good alternative for roads in the city center. Although smaller plants are believed to be less efficient in reducing PM due to their smaller leaf surface area [6,7], they play an essential role in accumulating PM in the lower strata of plantings. While trees are the most effective in reducing PM in the atmosphere, smaller plants help reduce PM concentration at lower heights. Moreover, the amount of PM accumulation on the leaves of plant species varies [8,9]. The ability to accumulate PM in plants depends on leaf structure, such as leaf hair, roughness, leaf area, and the amount of wax on the leaves [10]. Additionally, the PM accumulation on the leaves depends on environmental conditions, such as PM concentration levels, rain, and wind [1]. Conversely, PM also has an impact on plants. The accumulation of PM on leaves reduces the absorption of light, which in turn affects plant growth [5]. Furthermore, heavy metals in air pollution affect plant growth and conduction [11]. In a polluted air environment, leaf traits will be changed to adapt to environmental stress. Accumulation of PM reduces the ability of plants to absorb light and blocks their pores, ultimately decreasing the rate of photosynthesis. This can lead to changes in the form of leaves and can cause leaf yellowing due to sulfurization [9]. PM also impacts other characteristics of plants, such as their relative water content (RWC), leaf extract pH (pH), and specific leaf area (SLA) [12]. Numerous studies have shown that exposure to PM decreases the RWC of plants, reducing their ability to tolerate stress [5,9]. Additionally, PM can reduce the water and nutrient uptake by plants, leading to stunted growth [13]. Acidic pollution can alter the pH of plants, which could reduce their ability to convert hexose sugars to ascorbic acid, ultimately decreasing their tolerance to stress [14]. However, the extent of these changes varies among different plant species and depends on their ability to tolerate stress from environmental conditions [15]. Therefore, it is crucial to assess the impact of PM on plants to identify tolerant species that can be used to improve air quality.

The aim of this study was to evaluate the accumulation of PM in the leaves of eight plant species planted along roadsides. The results of the study can be used to identify highly effective plants for PM accumulation, which can help to increase the removal of PM by plants in urban areas. The elemental composition of the particles accumulated on the leaf surface was also determined by using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). Furthermore, we also analyzed various leaf traits, including SLA, pH, RWC, total chlorophyll (TChl), and carotenoid, to determine the impact of PM on plants.

2. Materials and Methods

2.1. Study Area and Leaf Sampling

Plant samples were collected in mid-September 2021 from plant species that were planted under the overpass near Chungbuk National University, Cheongju, South Korea (36°38′0″ N, 127°29′0″ E). The sampling area is located on a five-way road with heavy car traffic (Figure 1). Eight different plant species were chosen for the study, consisting of four shrubs (*Euonymus japonicas* Thunb., *Buxus sinica* (Rehder & E.H.Wilson) M.Cheng var. *insularis* (Nakai) M.Cheng, *Pleioblastus fortunei* (Van Houtte) Nakai, and *Rhododendron yedoense* Maxim. f. *poukhanense* (H.Lév.) Sugim. ex T.Yamaz.), two herbaceous plants (*Liriope muscari* (Decne.) L.H.Bailey and *Pachysandra terminalis* Siebold & Zucc.), and two climbers (*Campsis grandiflora* (Thunb.) K.Schum. and *Parthenocissus tricuspidata* (Siebold & Zucc.) Planch.) (Table 1). Only leaves that were in good condition, free from pests, and healthy were selected for each plant species, and five different samples were collected from five plants of each species. All the samples were collected on the same day, which was 7 days after the last rainfall, and the leaves were cut from the same side. After cutting, the leaf samples were placed in separate paper bags and immediately transported to the laboratory for analysis.

Table 1. List of eight plants analyzed in this study.

	Plant Species	Habit	Height
Shrub	*Euonymus japonicas* Thunb.	Evergreen broad-leaved	1 m
	Buxus sinica (Rehder & E.H.Wilson) M.Cheng var. *insularis* (Nakai) M.Cheng	Evergreen broad-leaved	50 cm
	Pleioblastus fortunei (Van Houtte) Nakai	Evergreen broad-leaved	50 cm
	Rhododendron yedoense Maxim. f. *poukhanense* (H.Lév.) Sugim. ex T.Yamaz.	Deciduous broad-leaved	1 m

Table 1. *Cont.*

	Plant Species	Habit	Height
Herbaceous plant	*Liriope muscari* (Decne.) L.H.Bailey	Evergreen perennial	30 cm
	Pachysandra terminalis Siebold & Zucc.	Evergreen perennial	30 cm
Climber	*Campsis grandiflora* (Thunb.) K.Schum.	Deciduous broad-leaved	
	Parthenocissus tricuspidata (Siebold & Zucc.) Planch.	Deciduous broad-leaved	

Figure 1. Sampling site. Cheongju, South Korea (36°38′0′′ N, 127°29′0′′ E).

2.2. Analysis of Surface PM Accumulation

Following the wash-off method developed by Dzierzanowski et al. [16], leaf samples were washed with distilled water to collect particulate matter on the leaf surface. The leaf samples, measuring 300 cm^2, were placed in glass beakers containing 250 mL of distilled water and stirred for approximately 60 s. The beakers were then placed on an ultrasonic cleaner (WUC-A22H, Daihan Scientific, Wonju, Korea) for six minutes to ensure that all particles were washed off the leaf surface. A metal sieve with a 100 µm mesh diameter was used to filter out particles with a diameter over 100 µm. The collected water solution was further filtered using pre-weighed filter paper Type 91 (Whatman, Maidstone, UK) with a pore size of 10 µm to remove PM from the collected solution. The filter papers were then weighed again using a semi-micro balance (EX125D, Ohaus, Parsippany, NJ, USA). Based on the difference in weight of the filter paper before and after filtering, the amount of PM (100–10) on the leaf surface was determined. The leaf area of each sample was measured using an area meter (LI-3100C, LI-COR Biosciences, Lincoln, NE, USA).

2.3. Biochemical Characteristics of Leaves

2.3.1. Leaf Extract pH (pH)

To follow the method of Singh et al. [17], 1 g of fresh leaf samples were homogenized with 10 mL of distilled water. The resulting samples were then centrifuged at 2700 rpm for 3 min. The pH of the collected homogenate was measured using a pH meter (HI 8424, Hana Instruments, Woonsocket, RI, USA).

2.3.2. Relative Leaf Water Content (RWC)

Following the method of Turner [18], leaf samples were weighed to determine the fresh weight of each sample. The samples were then soaked in distilled water at 4 °C for 24 h and weighed again to determine the turgid weight. Finally, the dry weight of the leaves was determined after drying the samples in an oven at 80 °C for 24 h. The RWC was calculated using Equation (1):

$$\text{RWC (\%)} = [(\text{FW} - \text{DW})/(\text{TW} - \text{DW})] \times 100 \quad (1)$$

where FW = fresh weight, TW = turgid weight, and DW = dry weight.

2.3.3. Chlorophyll Contents

The method described by Lichtenthaler [19] was used to analyze the samples. To do this, 0.05 g of a fresh leaf was crushed with 10 mL of 100% acetone. The resulting liquid was then centrifuged at 2700 rpm for 10 min using a centrifuge (Cef-6, Daihan Scientific, Wonju, Korea). Next, 10 mL of the supernatant was taken, and the absorbance at 470 nm, 616.6 nm, and 644.8 nm was determined using a spectrophotometer (UV-1800, Shimadzu, Japan). The chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (TChl), and carotenoid contents were calculated using Equation (2).

$$\text{Chlorophyll a} = (11.24 \times A_{616.6}) - (2.04 \times A_{644.8})$$

$$\text{Chlorophyll b} = (20.13 \times A\ 6_{44.8}) - (4.19 \times A_{616.6}) \quad (2)$$

$$\text{Chlorophyll a + b} = (7.05 \times A_{616.6}) + (18.09 \times A_{644.8})$$

$$\text{Carotenoids} = (1000 \times A_{470}) - (1.90 \times \text{Chl a} - 63.14 \times \text{Chl b})/214$$

where $A_{616.6}$, $A_{644.8}$, and A_{470} are absorbance values at corresponding wavelengths.

2.3.4. Specific Leaf Area (SLA)

After collecting from plants, a part of the leaf samples was used to determine the SLA. Using the method of Chaturvedi et al. [20], the leaf areas of the samples were determined using an area meter (LI-3100C, LI-COR Biosciences, Lincoln, NE, USA). Afterward, the samples were dried in an oven at 80 °C for 24 h and weighed to determine the dry weight of each sample. SLA was then determined using Equation (3):

$$\text{SLA } (\text{cm}^{-2}\cdot\text{g}^{-1}) = \text{Leaf area}/\text{dry weight} \quad (3)$$

2.4. EDX Analysis

The analysis aimed to investigate the type of elemental compositions present in the PM collected from plants. Leaf samples of 5 × 5 mm were taken from the center of each leaf and then coated with gold in preparation for SEM analysis. EDX was used to quantitatively assess metal concentrations in the particles that had accumulated on the leaf sample. For each leaf sample, we used SEM to observe and mark the location of the accumulated particles. Then, three marked particles were randomly selected and analyzed with EDX to quantitatively assess the metal concentrations. The average metal concentration of the three particles was used to determine the ability of elemental compositions to accumulate on the leaves of each plant species.

3. Statistical Analysis

All data were analyzed using SAS software version 9.4 (SAS Institute, Cary, NC, USA) through two-way analysis of variance (ANOVA) with Duncan's multiple range test (DMRT). A significance level of 5% was established.

4. Result and Discussion

4.1. PM Accumulation of Plant Species

In this study, we observed significant differences in PM accumulation on leaves among eight plant species. The amount of PM accumulation ranged from 10.18 to 59.51 μg·cm^{-2} across the different plants studied. Among the eight plant species, *P. tricuspidata* showed the highest PM accumulation, followed by *R. yedoense* f. *poukhanense*, *L. Muscari*, and *P. terminalis*. The PM accumulation on the leaves of these plants was 29.60, 28.26, and 24.34 μg·cm^{-2}, respectively. In contrast, *C. grandiflora* showed the lowest PM accumulation (Figure 2).

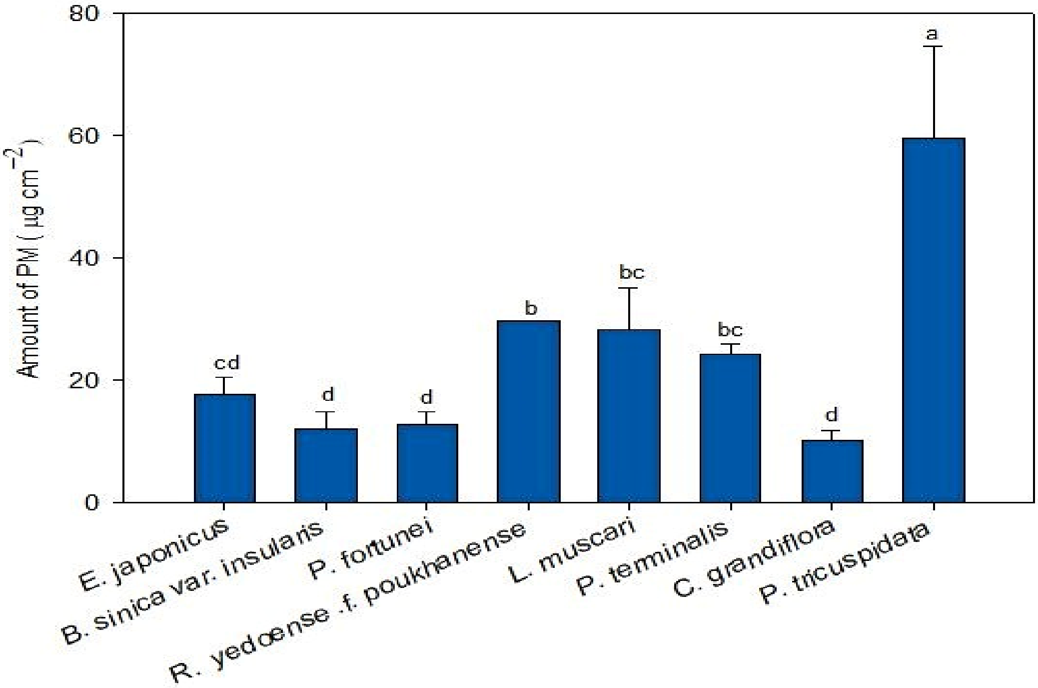

Figure 2. The amount of PM accumulation on the leaf surface of the eight plant species is presented in the figure. Different letters indicate significant differences in PM accumulation between various plant species according to DMRT.

The ability of plants to accumulate PM on their leaves depends on their leaf structure. Previous studies have shown that trees and shrubs with high leaf areas are effective PM accumulation plants [21,22]. However, planting tall shrubs and trees near roads and intersections may not be feasible for safety and space reasons. Therefore, herbaceous plants are a viable option to reduce PM and maintain safety in these areas. In this study, we found that herbaceous plants were highly effective in accumulating PM on their leaves. The low shrubs or herbaceous plants that grow near the ground are easily exposed to soil splash, leading to increased PM accumulation on their leaves. This can explain the high amount of PM accumulation on the leaves of *L. Muscari* and *P. terminals*. The PM accumulation on leaves also depends on the leaf structure, including leaf roughness, leaf area, and leaf hair [23]. In the case of *E. japonicus*, the leaf structure with curled leaf edges helped trap PM on the leaves, causing an increasing amount of PM accumulation on the leaf of this plant species [24]. Furthermore, plants with leaf hair accumulated PM more effectively compared to those without leaf hair [25]. For instance, we found the presence of leaf hair on the leaves of *R. yedoense* f. *poukhanense.* As leaf hair helped increase areas of PM deposition on the leaves of plants, it could be the reason for its increased effective accumulation of PM. Moreover, high leaf density helps to decrease PM wash from leaves due to rain or wind [10,26]. Among the eight plant species we studied, *P. tricuspidata* was the most effective in PM accumulation on its leaves. Its high leaf area and density likely contributed to the increased PM accumulation compared to other plants, as it can limit PM wash from the leaf surface under the influence of rain or wind. Additionally, the structural characteristics of leaves, such as shape and petiole length, influenced the movement of leaves on plants, which, in turn, affected the deposition of particles on the leaf surface [27]. Plants with long petioles showed less PM accumulation on the leaf [7]. This study found that *C. grandiflora* showed the lowest PM accumulation on the leaf. Our study suggests that the long petiole length of *C. grandiflora* may contribute to less effective PM accumulation compared to other plant species. We also found that smaller plants played a significant role in improving air pollution levels on the roadside. Leaf structures, such as leaf hair and area, influenced the ability of plants to accumulate PM. In addition, plants with lower heights exhibited more effective PM accumulation than taller plants.

4.2. Biochemical Characteristics of Leaves

All eight plant species studied showed a pH range of 5.46 to 5.83, with *P. fortunei* displaying the highest pH value. In this study, we did not observe any significant difference between the eight species (Table 2). pH is an indicator sensitive to air pollution [28], with acidic pollution leading to a reduction in pH. The degree of reduction depends on plant tolerance and other factors such as soil pH [1]. Furthermore, plants with a higher pH can increase the conversion of hexose sugar to ascorbic acid, which helps increase their tolerance to environmental stress [8].

Table 2. Leaf traits of eight plant species. Duncan's multiple range test was used to assess the significance of differences among each leaf traits. Different letters indicate significant differences between the eight plant species.

Species	SLA ($mg \cdot g^{-1}$)	pH	RWC (%)	Chl a ($mg \cdot g^{-1}$)	Chl b ($mg \cdot g^{-1}$)	TChl ($mg \cdot g^{-1}$)	Carotenoid ($mg \cdot g^{-1}$)
E. japonicus	87.61 ± 12.29 ed	5.56 ± 0.09 b	66.72 ± 10.02 b	0.16 ± 0.02 b	0.08 ± 0.01 b	0.25 ± 0.02 b	16.45 ± 1.51 b
B. sinica var. *insularis*	63.59 ± 5.51 ed	5.46 ± 0.03 b	80.85 ± 7.51 ab	0.06 ± 0.03 d	0.04 ± 0.01 c	0.10 ± 0.04 d	6.14 ± 2.95 d
P. fortunei	180.88 ± 28.73 b	5.83 ± 0.16 a	84.76 ± 5.51 a	0.18 ± 0.03 b	0.08 ± 0.01 b	0.26 ± 0.04 b	17.10 ± 2.79 b
R. yedoense f. *poukhanense*	147.31 ± 14.00 bc	5.58 ± 0.07 ab	77.73 ± 6.21 ab	0.15 ± 0.04 b	0.07 ± 0.01 b	0.23 ± 0.05 b	13.69 ± 3.21 b
L. muscari	128.64 ± 22.18 cd	5.69 ± 0.13 ab	81.82 ± 3.30 ab	0.16 ± 0.06 b	0.08 ± 0.02 b	0.24 ± 0.08 b	15.18 ± 5.31 b
P. terminalis	118.64 ± 1.69 cd	5.61 ± 0.07 ab	80.89 ± 3.70 ab	0.08 ± 0.02 cd	0.04 ± 0.01 c	0.13 ± 0.03 cd	7.19 ± 2.16 cd
C. grandiflora	247.44 ± 54.87 a	5.48 ± 0.28 b	78.55 ± 13.72 ab	0.26 ± 0.05 a	0.12 ± 0.02 a	0.37 ± 0.07 a	24.79 ± 4.84 a
P. tricuspidata	145.90 ± 2.72 bc	5.66 ± 0.06 ab	79.83 ± 10.51 ab	0.14 ± 0.00 bc	0.06 ± 0.00 bc	0.20 ± 0.00 bc	12.68 ± 0.52 bc
Significantly	***	ns	ns	***	***	***	***

SLA: specific leaf area; pH: leaf extract pH; RWC: relative leaf water content; Chl a: chlorophyll a; Chl b: chlorophyll b; TChl: total chlorophyll. ns, and ***, nonsignificant, and $p < 0.001$, respectively.

The chlorophyll and carotenoid content varied significantly among different plant species. The total chlorophyll content of the plants ranged from 0.10 to 0.37 $mg \cdot g^{-1}$, while chlorophyll a and chlorophyll b ranged from 0.06 to 0.26 $mg \cdot g^{-1}$ and from 0.04 to 0.12 $mg \cdot g^{-1}$, respectively. The carotenoid content ranged from 6.14 to 24.79 $mg \cdot g^{-1}$. Among the eight plant species studied, *C. grandiflora* had the highest chlorophyll and carotenoid content, while *B. sinica* var. *insularis* had the lowest content (Table 2). Chlorophyll is found in the chloroplasts of green plants and plays an essential role in plant metabolism [29]. Decreasing chlorophyll content directly affects plant growth, so determining the chlorophyll content of plants can be used to evaluate the effect of air pollution on them [30]. Several studies have shown that PM accumulated on leaves can lead to decreased light absorption and reduced plant chlorophyll content [16,31]. Additionally, PM accumulation can block the stomata, leading to a decrease in chlorophyll content [6]. Carotenoids are also important contents that play a critical role in the photosynthetic process and protect photosynthetic organisms against potentially harmful photooxidative processes [19]. A reduction in carotenoids can cause the yellowing of leaves due to environmental stress [16].

The RWC values of the eight plant species that were studied ranged from 66.72% to 84.76%. *P. fortunei* had the highest RWC, followed by *L. Muscari* and *P. terminalis*, while *E. japonicas* had the lowest RWC value. However, we did not find any significant differences among the plant species (Table 2). RWC represents the water status of plants and contributes to maintaining their physiological water balance [1]. High RWC helps plants adapt to environmental stresses such as air pollution or drought [9]. Therefore, plants with high RWC are more tolerant to air pollution than those with lower RWC.

The SLA values of the eight plant species studied ranged from 63.59 to 247.44, with *C. grandiflora* exhibiting the highest SLA among the species (Table 2). Conversely, *B. sinica* var. *insularis* had the lowest SLA value. SLA is a measure of leaf thickness [28]. High SLA helps increase plants' tolerance to environmental stress [29]. Air pollution can affect SLA, but the extent of this effect depends on the plant species and the protective or adaptive mechanisms of the plants [32,33].

4.3. Elemental Composition of Leaves

The EDX analysis of the plants showed the presence of various elements, such as C, O, Ca, K, Mg, S, P, Al, Si, Na, Cl, and Fe. Among them, C, and O were the most abundant elements detected. However, C and O elements were not relevant for determining the metal content of the deposited particles on the plant leaves, so they were excluded from the evaluation of PM metal content. In this study, Ca, K, and Cl were found in the EDX of all plant species, with values ranging from 9.56% to 49.60%, 7.79% to 30.65%, and 1.77% to 45.78%, respectively. Si was present in the EDX of all plants except *R. yedoense* f. *poukhanense*, and Mg was observed in all plants except E. japonicus. Al had a relatively high percentage in *P. terminalis* and *P. tricuspidata*, comprising 25.61% and 11.51%, respectively. Fe was only found in the EDX of *P. terminalis* and *P. tricuspidata*. Among the eight plants studied, *P. tricuspidata* and *P. terminalis* showed highly effective accumulation of metal elements (Table 3, Figure 3).

Si, Al, and Ca are emitted by non-exhaust road emissions found on the leaf surface of herbaceous plants and mosses. O, Al, Si, Fe, and K are emitted due to tires and other components of abrasive particles on paved roads created by wheels [34]. Additionally, Hozhabralsadat et al. [35] showed that C, O, Na, Mg, Al, Si, S, Cl, K, Ca, and Fe constitute fine particles from vehicle driving. In this study, we also found the same elemental composition of particles deposited on plant leaves using EDX analysis. Elemental air pollution comes from various sources, including vehicle exhaust, dust, and soil [35]. Plants play a role in reducing heavy metals in air pollution [36,37]. In this study, we found that the particles accumulated on the leaf surface of plants had different element compositions. The presence of these elements showed that plants are capable of accumulating heavy metals from their environment. However, we only analyzed the element composition of three particles on the leaf surface, so we cannot determine the complete range of elements accumulated by plants. Therefore, more advanced analytical techniques, such as inductively coupled plasma-mass spectrometry (ICP-MS), may be necessary in future studies to accurately determine the composition and amount of accumulated elements in plants.

Table 3. Energy-dispersive X-ray spectroscopy (EDX) atomic percentage of elements from particles on the leaf surface of eight plant species (excluding oxygen and carbon).

	E. japonicus	*B. sinica* var. *insularis*	*P. fortunei*	*R. yedoense* f. *poukhanense*	*L. muscari*	*P. terminalis*	*C. grandiflora*	*P. tricuspidata*
Ca	9.56	13.68	8.41	52.25	19.76	9.71	49.60	36.22
K	29.07	9.55	18.11	30.66	45.87	17.80	25.78	7.79
Mg	ND	0.99	2.78	10.05	3.41	3.19	6.47	6.35
S	ND	7.97	0.38	ND	2.66	0.42	3.66	0.31
P	ND	1.13	ND	ND	2.14	ND	1.50	ND
Al	ND	7.58	ND	ND	2.82	25.61	2.07	11.51
Si	15.59	14.66	53.02	ND	11.47	27.53	3.13	20.73
Na	ND	9.86	ND	ND	ND	3.50	6.02	1.64
Cl	45.78	34.58	17.30	7.03	11.87	3.11	1.77	3.76
Fe	ND	ND	ND	ND	ND	9.14	ND	11.70
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

ND: not detected.

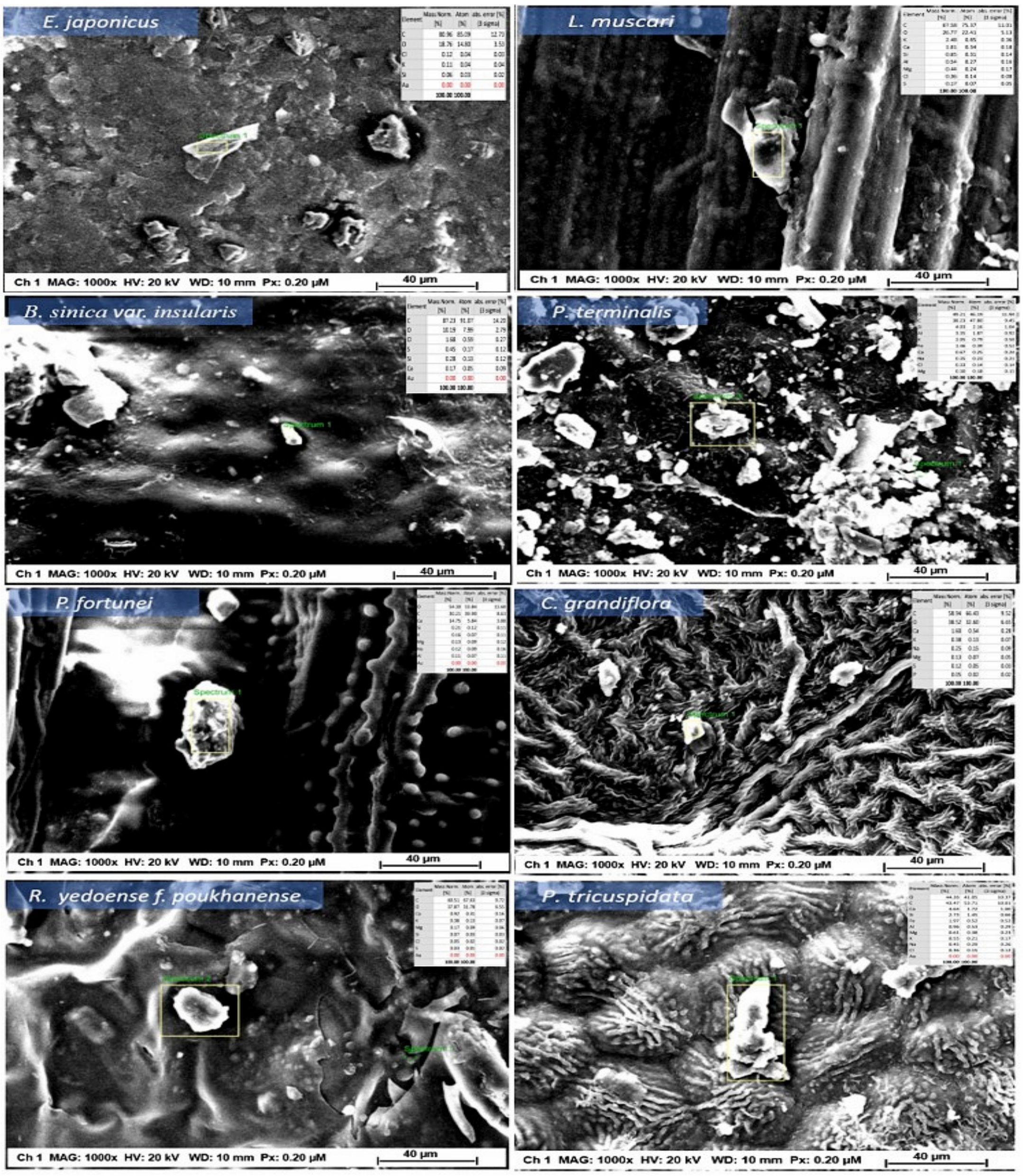

Figure 3. SEM images of plant leaves and EDX results of eight plant species.

5. Conclusions

The amount of large PM accumulated on the leaves differed between the eight plant species. Herbaceous plants showed a higher effective accumulation of PM than other plant types. Leaf density may influence a plant's ability to accumulate PM. Leaf hair helped to increase plants' ability to accumulate PM. The ability to accumulate PM depends on the structure of the leaf. In this study, we only determined the ability of large PM (10–100 μm) accumulation among eight plant species. Therefore, in future studies, it would be necessary to examine the accumulation of various types of PM in plants to compare their accumulation abilities across different plant species. The leaf traits also differed among the different plant species. The chlorophyll content of plants with high amounts of large PM on the leaf tended to be lower than others. SEM images showed significant PM accumulation on the leaves of the plants. The EDX analysis results revealed that the elemental composition of the particles on the leaves included C, O, Ca, K, Mg, S, P, Al, Si, Na, Cl, and Fe. Moreover, Ca, K, Cl, and Si were the most abundant elements in the PM deposited on the leaves of the eight plants. Plants play an essential role in accumulating PM and elemental composition in the atmosphere. Studying the ability of plants to reduce air pollution, such as PM and heavy metals, can help select suitable plant species to optimize the benefits of plants in improving air quality.

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