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Seasonal Variations in the Particulate Matter Accumulation and Leaf Traits of 24 Plant Species in Urban Green Space

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Abstract: Particulate matter (PM), an extremely serious type of air pollution, leads to numerous human diseases. Mitigating PM in the urban city, where resident density has been increasing, has been a major challenge. The increase in residents leads to increasing traffic, the primary source of PM in urban areas. Plants play an important role in reducing PM and maintaining an ecological balance. For some Asian countries, such as Korea, with differing seasons and environmental conditions, PM accumulation and plant survival are greatly impacted by environmental conditions. In this study, we analyzed the amount of PM accumulation on the leaf surfaces and wax layers of 24 plant species during four seasons (spring, summer, autumn, and winter) to determine the PM accumulation in plants under different environmental conditions. The leaf traits of plant chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (TChl), relative water content (RWC), leaf extract pH (pH), and leaf specific area (SLA) were analyzed to determine the influence of PM on plants and the relationship between PM and leaf traits. In this study, we found that the amount of PM accumulation differed among plants and seasons. Among the 24 plant species, plants *Pinus strobus*, *P. parviflora*, *P. densiflora*, *Euonymus japonicus*, and *Acer palmatum* were most adept at PM accumulation. Leaf structure, environmental conditions, such as PM concentration, and rainfall may be the main factors that impact the ability of plant leaves to accumulate PM. The plant leaf traits differed among the four seasons. PM accumulation on the leaf was negatively correlated with SLA (in all four seasons) and pH (in spring, summer, and autumn). PM was negatively correlated with Chl a, Chl b, and TChl in summer.

Keywords: air pollution; environmental conditions; large PM; coarse PM; wax layer

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1. Introduction

Air pollution has increased over the past 50 years and is considered the world's largest environmental health problem [1]. Air pollution causes numerous diseases ranging from asthma to cancer, pulmonary illnesses, and heart disease that kill an estimated 7 million people worldwide every year, of which 4.2 million die from stroke, heart disease, lung cancer, and acute and chronic respiratory disease [2]. Particulate matter (PM) is the most dangerous type of air pollution and is a primary concern worldwide, particularly in developing countries. PM with a small diameter that can penetrate the lung alveoli negatively affects the respiratory system [3]. Particulate matter can originate from either anthropogenic or natural sources, such as agriculture or industrial activities, volcanic eruptions, soil erosion, sea salt, or desert sand. According to the aerodynamic diameter, PM can be classified as large PM (>10 µm), coarse (2.5–10 µm), fine (0.1–2.5 µm), and ultrafine (≤0.1 µm), as reported by Sæbø et al. [4].

Plants play a vital role in mitigating urban pollution by accumulating PM on their leaves [5–9]. Plants that grow in urban environments improve air quality and act as a natural filter for PM. In Beijing, China, plants in the city center removed 774 tons of PM10 in one year [10]. However, species differ in their ability to accumulate PM. Plants accumulate PM on their leaf surfaces and epicuticular waxes, so the amount of PM accumulation depends on the macrostructure (plant height, petiole length) and microstructure of the leaf (leaf hairs, thickness wax layer, and stomatal density) [4,11]. Trees with large total leaf areas were considered the most effective type of plants for reducing PM [12]. Other studies have shown that plants growing low to the ground, such as shrubs, can accumulate more PM on the leaf because of exposed soil splash [13]. Several studies have demonstrated that the PM accumulation of needleleaf species is greater than that of broadleaf trees [14,15]. Additionally, the thickness of the wax layer is a factor that can influence the amount of PM accumulated on leaves [16]. Plants with thick wax accumulated more PM than those with thin wax layers. The long petiole length could increase the amount of PM removal from leaves via rain or wind. In addition, the plant's capacity to capture PM is influenced by several other factors, including environmental variables, such as wind and rain [17]. Wind and rain can wash PM from leaves, decreasing leaf PM accumulation [18]. However, the amount of PM washed from the leaf depends on the leaf structures, density, and area. Plants with a high density of leaves are less influenced by rain [19,20]. Furthermore, the concentration of PM in the atmosphere can directly influence the amount of PM accumulation on the leaf [21]. Under a high PM concentration, plants can accumulate more PM than plants grown in a lower PM concentration environment [22]. However, PM adversely affects plant life [23]. PM impacts plants' physical and biochemical characteristics [24]. PM influences the structural components of leaves, such as leaf area, leaf thickness, and wax amounts [19,25]. In addition, PM also impacts photosynthesis, leaf extract pH (pH), specific leaf area (SLA), and plant relative water content (RWC) [26]. Popek et al. [27] showed that the effectiveness of photosynthesis was reduced because of PM accumulation on the leaf surface. PM accumulation on the leaf leads to prevention of light absorption or blocking of stomata by reducing the total chlorophyll (TChl) of plants [28]. Therefore, PM also impacts the growth and productivity of plants. However, the impact of PM on plants depends greatly on plant responses [29]. Under different environmental conditions, the ability of PM to accumulate and the influence of PM on individual plant species can differ. The ability of PM accumulation and the tolerance to air pollution are important in selecting suitable plant species for improving urban air quality. However, a few researchers have addressed the correlation between PM accumulation on leaf and leaf traits in common plant species in Korea. Therefore, analyzing PM accumulation on plant leaves and the correlation between PM and leaf trait conditions can inform plant selections designed to improve air quality. Analyzing the complex correlation during different seasons helps to comprehensively determine the correlations among PM, plants, and the environment, which is a premise for selecting plant species to optimize the benefit of the plants in improving air quality in Korea.

2. Materials and Methods

2.1. Study Area and Sample Collection

The study site was located in Chungbuk National University in Cheong-Ju, South Korea, which is located at 36.6290° N, 127.4563° E (Figure 1). Twenty-four plant species that are commonly used for urban greening in Korea were selected for leaf sample collection. Leaf samples were collected from spring 2020 to winter 2021 in four time periods: at the beginning of June (late spring), at the beginning of August (summer), in October (autumn), and in February (late winter). These consisted of 11 evergreen species and 13 deciduous tree species in good condition (healthy and free from disease, insects, and pests) (Table 1). In winter, only the evergreen tree samples were collected because the leaves had fallen from the deciduous trees. For each plant species, we put a tag on the selected plant to ensure that the samples were collected from the same plant. Following each collection, the leaf samples were stored in paper bags and immediately transferred to the laboratory for analysis. The samples were collected after two weeks without heavy rain and between 8 am and 12 noon.

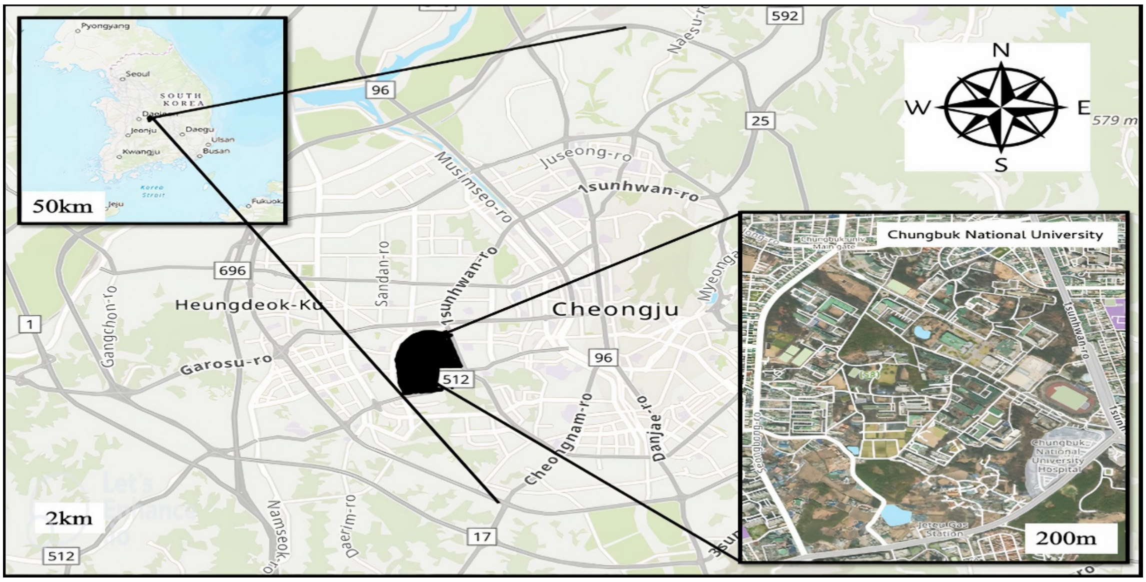

Figure 1. The location map of the sampling sites. Chungbuk National University, Cheongju City, Korea.

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

Species	Family	Habit	Type
Juniperus chinensis L.	Cupressaceae	Tree	Evergreen
Juniperus chinensis var. kaizuka Hort.	Cupressaceae	Tree	Evergreen
Pinus parviflora Siebold & Zucc.	Pinaceae	Tree	Evergreen
Pinus densiflora Siebold & Zucc.	Pinaceae	Tree	Evergreen
Chamaecyparis pisifera Siebold & Zucc.	Cupressaceae	Tree	Evergreen
Taxus cuspidata Siebold & Zucc.	Taxaceae	Tree	Evergreen
Abies holophylla Maxim.	Pinaceae	Tree	Evergreen
Picea abies (L.) H.Karst.	Pinaceae	Tree	Evergreen
Pinus strobus L.	Pinaceae	Tree	Evergreen
Platycladus orientalis (L.) Franco	Cupressaceae	Tree	Evergreen
Euonymus japonica Thunb.	Celastraceae	Shrub	Evergreen
Magnolia denudata Desr.	Magnoliaceae	Tree	Deciduous
Aesculus turbinata Blume	Hippocastanaceae	Tree	Deciduous
Rhododendron yedoense Maxim	Ericaceae	Shrub	Deciduous
Hibiscus syriacus L.	Malvaceae	Shrub	Deciduous
Acer palmatum Thunb.	Aceraceae	Tree	Deciduous
Cercis chinensis Bunge	Fabaceae	Shrub	Deciduous
Cornus officinalis Siebold&Zucc.	Cornaceae	Tree	Deciduous
Acer triflorum Kom.	Aceraceae	Tree	Deciduous
Zelkova serrata (Thunb.) Makino	Ulmaceae	Tree	Deciduous
Ginkgo biloba L.	Ginkgoaceae	Tree	Deciduous
Ligustrum obtusifolium Siebold & Zucc.	Oleaceae	Shrub	Deciduous
Prunus x *yedoensis* Matsum.	Rosaceae	Tree	Deciduous
Viburnum dilatatum Thunb.	Adoxaceae	Shrub	Deciduous

2.2. Leaf Surface PM (sPM) and Epicuticular Wax (wPM) Analysis

According to the method developed by Dzierzanowski et al. [30], leaf samples were washed with distilled water to collect PM on the leaf surface (sPM) and washed with chloroform to collect PM in wax (wPM). Approximately 300 cm^2 leaves of each plant species were put in a glass beaker and washed with 250 mL distilled water for 60 s. The glass beaker was placed on an ultrasonic cleaner (WUC-A22H, Daihan Scientific, Wonju, Korea) for 6 min to ensure that all the PM was washed from the leaf surface. Then, the collected solution was passed through a metal sieve (diameter 100 µm mesh) to remove all particles with a diameter over 100 µm. After that, the solution water was filtered with two types of paper filters, type 91 and type 42, with pore sizes of 10 μm and 2.5 μm, respectively. Before filtering, paper filters were placed in a desiccator (DH. DeBG1K, Daihan Scientific, Wonju, Korea) for 48 h to control humidity, and then the filter papers were weighed. Following filtering, the PM was divided into two types: large PM (100–10 μm) and coarse PM (10–2.5 μm). The same method was used to evaluate the weight of the paper filter after filtration. After washing with water, the leaf area was measured by using a leaf area meter (LI-3100C, LI-COR Biosciences, Lincoln, NE, USA). Then, the leaf sample was washed with chloroform and filtered with filter paper by the same filtration methods to determine the amount of wPM. The amount of PM accumulation on the leaves of plants was evaluated using Equation (1):

$$PM = W_2 - W_1/A \tag{1}$$

where W_2 is the weight after filtration (g), W_1 is the weight before filtration (g), and A is the leaf area (cm^2).

2.3. *Analysis of Leaf Traits*

2.3.1. Chlorophyll (Chl a, Chl b, Total Chlorophyll (Tchl))

The concentration of chlorophyll (Chl a, Chl b, Tchl) was measured according to Lichtenthaler [31]. For each plant species, 0.05 g of fresh weight was placed on the different mortars. Liquid nitrogen was added and crushed. Approximately 10 mL of 100% acetone was added to the mortar, and the sample liquid was collected. A centrifuge (Cef-6, Daihan Scientific, Wonju, Korea) was used to homogenize the samples for 10 m at 4900 rpm. Ten milliliters of supernatant were collected, and the absorbance was analyzed at wavelengths of 470 nm, 616.6 nm, and 644.8 nm by using a spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan). Chl a, Chl b, and TChl were calculated using Equation (2):

$$\begin{gathered}\text{Chlorophyll a} = (11.24 \times A_{616.6}) - (2.04 \times A_{644.8}) \\ \text{Chlorophyll b} = (20.13 \times A\ 6_{44.8}) - (4.19 \times A_{616.6}) \\ \text{Chlorophyll a + b} = (7.05 \times A_{616.6}) + (18.09 \times A_{644.8})\end{gathered} \tag{2}$$

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

2.3.2. Specific Leaf Area (SLA)

The SLA, which denotes the area per dry mass of the leaf, was measured following Ref. [20]. The leaf area was divided by leaf weight (indirectly indicating leaf thickness) and measured by an LI-3100C (LI-COR Biosciences, Lincoln, NE, USA). Then, the selected leaves were dried using a dry oven (HB-502S, Hanbaek Scientific, Bucheon, Korea) at 70 °C for 48 h to estimate their dry weights. SLA was determined using Equation (3):

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

2.3.3. Leaf Extract pH (pH)

The pH was measured using the method developed by Singh et al. [32]. For each plant species, 1.0 g of fresh leaves was placed in a test tube with 10 mL distilled water and homogenized at 2500 rpm for 3 min. Then, the pH value was measured by using a pH meter (HI 8424, Hana Instruments, Woonsocket, RI, USA).

2.3.4. Relative Water Content (RWC)

The RWC was determined according to the method developed by Turner [33]. The leaves were cut to a similar size (5 × 5 cm), and their fresh weight (FW) was immediately measured. After floating them in distilled water at 4 °C for 24 h, their turgid weight (TW) was determined. Finally, they were dried in an oven at 80 °C for 48 h and weighed to measure dry weight (DW). The RWC value was determined using Equation (4):

$$\text{RWC (\%)} = [(\text{FW} - \text{DW})/(\text{TW} - \text{DW})] \times 100 \quad (4)$$

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

3. Statistical Analysis

All data were analyzed using SAS software version 9.4 (SAS Institute, Cary, NC, USA) for analysis of variance (ANOVA) with Duncan's multiple range test (DMRT). The significance level was set at 5%. Variations in the accumulated PM on different plant species and leaf traits in the four seasons were determined using a two-way ANOVA. The relationships between the amount of PM accumulation on the leaf and leaf traits were identified by using Pearson's correlation analysis. The presented data are given as the means with standard error (±SE).

4. Results and Discussion

4.1. PM Accumulation of Plant Species

In this study, we found that the amount of PM accumulation on leaf surfaces and wax layers differed among various plant species and sampling seasons. The amount of total PM accumulation on leaf surfaces of 24 plant species in the four seasons ranged from 8.32 to 148.43 $\mu g \cdot cm^{-2}$ in spring, 7.65 to 137.02 $\mu g \cdot cm^{-2}$ in summer, 3.65 to 122.84 $\mu g \cdot cm^{-2}$ in autumn, and 21.02 to 264.44 $\mu g \cdot cm^{-2}$ in winter (only on the evergreen plants). The amount of total PM accumulation on the wax layer of 24 plant species in spring, summer, autumn, and winter (only on the evergreen plants) ranged from 5.74 to 103.6 $\mu g \cdot cm^{-2}$, 4.12 to 116.67 $\mu g \cdot cm^{-2}$, 3.81 to 77.22 $\mu g \cdot cm^{-2}$, and 17.74 to 236.46 $\mu g \cdot cm^{-2}$, respectively. When comparing the amount of PM accumulation on leaves in the four seasons, we found that PM was highest in winter (needleleaf) and spring (broadleaf); conversely, the amount of PM was lowest in autumn. When comparing PM accumulation between needleleaf and broadleaf, the average PM accumulation on leaf surfaces and wax layers was higher on needleleaf than on broadleaf. In spring, the amount of PM accumulation on the leaf surfaces and the wax layers of 10 needleleaf ranged from 148.43 to 14.53 $\mu g \cdot cm^{-2}$ and from 103.63 to 16.62 $\mu g \cdot cm^{-2}$, respectively. Among the ten needleleaf plants, *P. strobus* showed the highest PM accumulation, followed by *P. parviflora* and *P. densiflora*. In contrast, the amount of PM accumulation in *J. chinensis* was the lowest. The amount of PM accumulation on the leaf surfaces and the wax layers of 14 broadleaf ranged from 23.75 to 8.32 $\mu g \cdot cm^{-2}$ and from 22.89 to 5.74 $\mu g \cdot cm^{-2}$, respectively. The plant species that showed the highest PM accumulation on leaf surfaces were *A. palmatum* followed by *E. japonicus* and *C. chinensis*, while *G. biloba* showed the lowest PM accumulation. The highest PM accumulations on the wax layers were the species *E. japonicus*, *P.* × *yedoensis*, and *C. officinalis*. Additionally, the plant species with the lowest PM accumulation was *V. dilatatum*. The amount of PM accumulation in needleleaf was higher than that in all the broadleaf plants except *J. chinensis* and *P. orientalis*. In summer, the amount of PM accumulation on the leaf surface and the wax layer of *P. strobus* was still the highest among needleleaf plants, with PM accumulations of 137.02 and 116.67 $\mu g \cdot cm^{-2}$ on the leaf surface and wax layer, respectively. Among the ten needleleaf, *P. orientalis* showed the lowest PM accumulation on both the leaf surfaces and the wax layer. For broadleaf plants, the amount of PM accumulation on the leaf surfaces ranged from 7.65 to 23.22 $\mu g \cdot cm^{-2}$, while the PM accumulation on the wax layer ranged from 4.25 to 13.83 $\mu g \cdot cm^{-2}$. Among 13 broadleaf, *A. palmatum* showed the highest PM accumulation on the leaf surface, and *P.* × *yedoensis* showed the highest accumulation on the wax layer. Conversely, *G. biloba* and *R. yedoense* showed the lowest PM accumulation on leaf surfaces and wax layers, respectively. In autumn, the amount of PM accumulation on the leaves of 10 needleleaf plants ranged from 8.86 to 122.84 $\mu g \cdot cm^{-2}$ on the leaf surfaces and from 8.52 to 77.22 $\mu g \cdot cm^{-2}$ on the wax layers, while, in summer, the highest and lowest PM accumulation on both the leaf surfaces and the wax layers were observed for *P. strobus* and *P. orientalis*, respectively. These plant species had higher PM accumulation than the other needleleaf plants, followed by *P. strobus*, *P. parviflora*, and *P. densiflora*. For broadleaf, the PM accumulation on the leaf surfaces ranged from 3.65 to 13.62 $\mu g \cdot cm^{-2}$ and on the wax layers ranged from 3.81 to 13.39 $\mu g \cdot cm^{-2}$. *H. syriacus* had the highest PM accumulation on the leaf surface, while *P.* × *yedoensis* had the highest PM accumulation on the wax layer, followed by *E. japonicus* and *C. officinalis*. Conversely, *G. biloba* and *R. yedoense* had the lowest PM accumulation on the leaf surface and the wax layer, respectively. In winter, leaf samples of eleven evergreens (ten needleleaf and one broadleaf) were collected. The amount of PM accumulation on the leaf surfaces ranged from 21.02 to 264.44 $\mu g \cdot cm^{-2}$ and on the wax layers ranged from 17.74 to 236.46 $\mu g \cdot cm^{-2}$. Among the 11 plant species, *P. strobus* showed the highest PM accumulation on the leaf surface, and *T. cuspidata* and *E. japonicus* showed the lowest PM accumulation on the leaf surface and the wax layer, respectively. Among the 24 plant species, *P. strobus* showed the highest PM accumulation, followed by *P. parviflora* and *P. densiflora*. The average PM accumulation on needleleaf was higher than the average PM accumulation on broadleaf by approximately three to over four times. Among broadleaf, *A. palmatum* and *E. japonicus* accumulated PM more effectively than other broadleaf (Table 2, Figure 2).

Table 2. The total PM accumulation on the leaf surface and the wax layer of 24 plant species in four seasons (spring, summer, autumn, and winter).

Species	Total sPM ($\mu g \cdot cm^{-2}$)				Total wPM ($\mu g \cdot cm^{-2}$)			
	Spring	**Summer**	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**
J. chinensis	14.5 ± 4.1	12.5 ± 2.1	12.6 ± 1.7	26.5 ± 1.1	16.6 ± 0.9	13.6 ± 3.4	12.2 ± 4.7	30.3 ± 1.2
J. chinensis var. *kaizuka*	26.5 ± 1.6	12.8 ± 1.1	10.9 ± 1.5	31.3 ± 0.2	28.7 ± 1.8	13.3 ± 2.8	19.4 ± 6.8	38.1 ± 1.3
P. parviflora	113.9 ± 26.4	65.6 ± 7.1	54.1 ± 11.8	138.8 ± 7.5	40.4 ± 7.5	29.3 ± 6.6	56.8 ± 8.7	71.8 ± 8.4
P. densiflora	72.9 ± 2.7	75.1 ± 11.4	56.8 ± 6.0	72.7 ± 6.8	52.1 ± 5.6	47.8 ± 1.7	51.0 ± 10.2	81.3 ± 3.2
C. pisifera	24.8 ± 2.7	31.1 ± 7.5	11.5 ± 0.6	31.5 ± 0.9	23.5 ± 1.3	11.3 ± 0.6	16.5 ± 9.5	24.8 ± 3.2
T. cuspidata	25.7 ± 4.5	40.1 ± 5.0	9.0 ± 0.5	21.0 ± 0.7	24.3 ± 2.3	12.8 ± 1.3	10.4 ± 0.2	20.7 ± 0.5
A. holophylla	43.8 ± 3.6	17.5 ± 3.4	15.5 ± 0.3	67.5 ± 10.8	34.7 ± 11.1	35.3 ± 3.8	16.6 ± 2.5	46.0 ± 3.4
P. abies	30.7 ± 1.2	20.1 ± 0.5	22.7 ± 2.2	55.8 ± 4.9	28.4 ± 4.3	20.8 ± 0.7	23.3 ± 1.8	32.7 ± 3.3
P. strobus	148.4 ± 23.0	137.0 ± 31.8	122.8 ± 25.8	264.4 ± 31.1	103.6 ± 22.2	116.7 ± 5.4	77.2 ± 27.5	236.5 ± 23.1
P. orientalis	22.0 ± 2.3	11.6 ± 1.1	8.9 ± 0.9	28.7 ± 2.1	25.3 ± 1.3	9.3 ± 1.4	8.5 ± 0.8	28.8 ± 1.7
E. japonicus	23.7 ± 3.4	17.9 ± 0.3	12.9 ± 1.0	27.7 ± 3.2	22.9 ± 5.2	8.7 ± 0.5	10.7 ± 1.4	17.7 ± 1.6
M. denudata	10.9 ± 1.0	11.5 ± 0.8	9.0 ± 0.4	-	9.8 ± 0.7	6.7 ± 0.4	6.2 ± 0.8	-
A. turbinata	12.9 ± 0.8	9.9 ± 0.7	6.8 ± 1.1	-	9.2 ± 1.0	9.0 ± 0.5	4.5 ± 0.5	-
R. yedoense	16.0 ± 2.3	9.8 ± 0.2	9.8 ± 0.7	-	11.0 ± 0.2	4.1 ± 0.9	3.8 ± 0.7	-
H. syriacus	16.9 ± 0.4	16.6 ± 1.2	13.6 ± 1.9	-	12.0 ± 0.1	6.0 ± 0.3	6.3 ± 1.9	-
A. palmatum	23.8 ± 2.4	23.2 ± 9.9	12.6 ± 0.7	-	9.2 ± 0.6	6.6 ± 1.3	8.1 ± 1.3	-
C. chinensis	17.6 ± 2.1	10.8 ± 0.0	4.8 ± 0.7	-	10.3 ± 0.6	5.1 ± 0.1	7.3 ± 2.2	-
C. officinalis	16.2 ± 0.6	17.6 ± 0.9	12.7 ± 0.4	-	15.8 ± 1.3	5.2 ± 0.4	12.2 ± 1.2	-
A. triflorum	15.3 ± 0.8	13.5 ± 1.3	10.0 ± 0.1	-	13.5 ± 6.3	8.0 ± 2.1	6.3 ± 1.1	-
Z. serrata	10.0 ± 0.5	9.6 ± 0.6	3.7 ± 0.2	-	8.9 ± 06	4.3 ± 1.0	5.5 ± 0.0	-
G. biloba	8.3 ± 1.1	7.7 ± 2.4	7.2 ± 0.3	-	9.5 ± 1.5	6.3 ± 0.8	5.8 ± 0.5	-
L. obtusifolium	9.4 ± 0.9	16.2 ± 2.8	4.0 ± 0.3	-	11.1 ± 2.0	7.2 ± 0.5	7.7 ± 0.5	-
P. × *yedoensis*	15.4 ± 0.6	13.0 ± 1.0	5.7 ± 1.6	-	17.5 ± 2.9	13.8 ± 1.8	13.4 ± 1.4	-
V. dilatatum	10.6 ± 1.3	13.3 ± 1.5	7.0 ± 1.3	-	5.7 ± 1.1	4.9 ± 0.6	8.1 ± 1.1	-

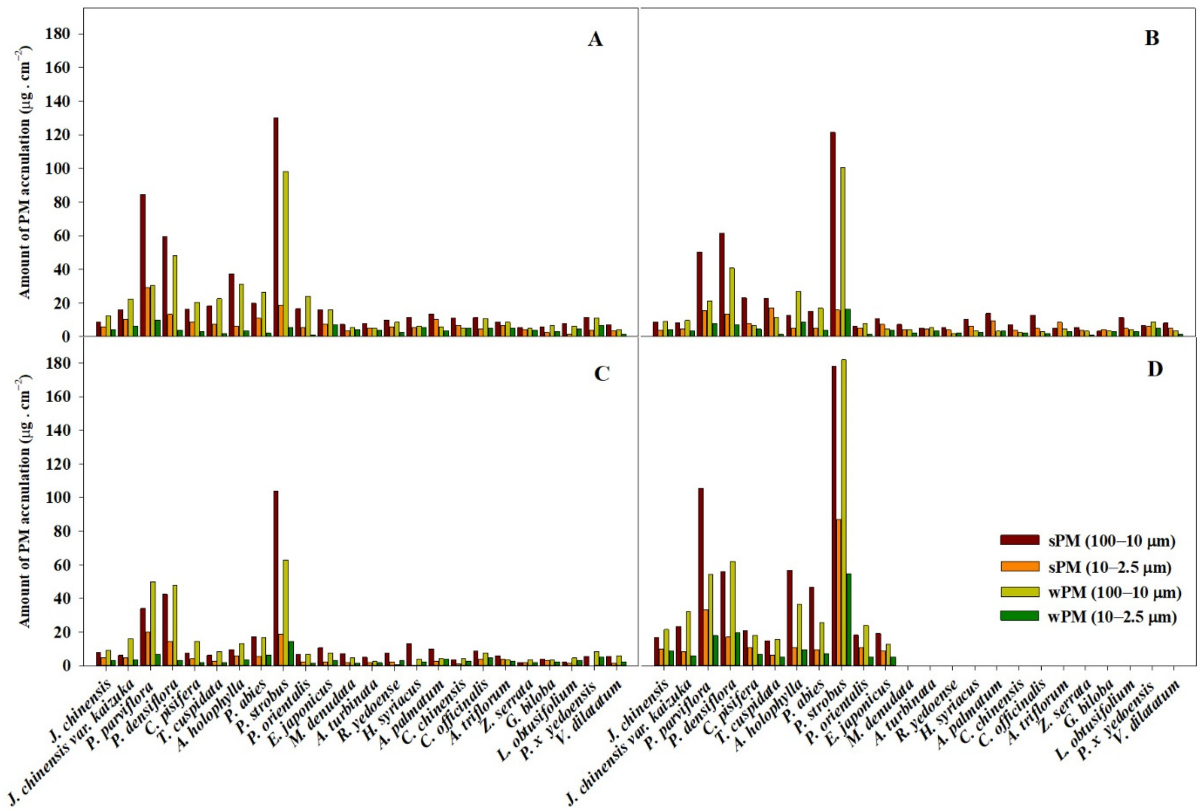

Figure 2. The amount of PM accumulation on the leaf surface and wax of 24 plant species. (**A**): Spring, (**B**): summer, (**C**): autumn, (**D**): winter.

The amount of wax on the leaves of the 24 plant species differed among both plant species and seasons. The amount of wax on the ten needleleaf during four seasons ranged from 81.20 to 755.04 μg·cm^{-2}, 55.95 to 1066.92 μg·cm^{-2}, 51.55 to 910.55 μg·cm^{-2}, and 106.74 to 3793.19 μg·cm^{-2} in spring, summer, autumn, and winter, respectively. In all the seasons, the amount of wax on *P. strobus* was the highest, followed by *P. densiflora*, while *T. cuspidata* showed the lowest amount of wax among the ten needleleaf. The wax on 13 broadleaf ranged from 15.68 to 95.41 μg·cm^{-2}, 15.76 to 191.50 μg·cm^{-2}, and 14.91 to 149.12 μg·cm^{-2} in spring, summer, and autumn, respectively. The amount of wax on *E. japonicus* was highest in spring, and the amount of wax on *V. dilatatum* was highest in summer and autumn. In winter, the amount of wax on *E. japonicus* was 160.86 μg·cm^{-2}. When comparing the amount of wax on needleleaf and broadleaf, we found that the amount of wax on all the needleleaf plants in spring, autumn, and summer was higher than that on broadleaf except for *T. cuspidata*. Among the 24 plant species, the amount of wax on *P. strobus* was higher than that of the other plant species (Figure 3).

Total sPM: (sPM (10–100 μm) + sPM2.5 (2.5–10 μm)), total wPM: (wPM (10–100 μm) + wPM2.5 (2.5–10 μm)).

Plant accumulation of PM occurs directly on leaves, so the leaf structure contributes to the ability of plants to accumulate PM. In this study, we found that the amount of PM accumulation on the leaves of 24 plant species was different among plant species and the four seasons. The amount of PM accumulation on the leaves of plants depends on leaf structures and environmental conditions [34]. The increasing PM concentration in the environment could lead to an increase in the amount of PM accumulation on the leaves of plants [35]. In this study, the PM concentration level was highest in winter, which could cause the highest PM accumulation on the needleleaf [36]. For the broadleaf, the PM accumulation on the leaf surface was higher in spring than in the other seasons due to the PM concentration in this season being higher than in summer and autumn. Under different environments, the PM concentration level, rainfall, and wind impact the amount of PM accumulation on leaves [37,38]. The high rainfall in summer and autumn could wash PM from a leaf, causing decreasing PM accumulation on the leaves of plants in the two seasons. The amount of PM accumulation in the 24 plant species tended to be higher in needleleaf than in broadleaf. Numerous studies have also shown that needleleaf are more effective in PM accumulation than broadleaf because of their high stomatal concentration and large amount of leaf wax [39,40]. The needleleaf secrete mucus oils on their leaf surfaces, reducing the amount of PM washed from leaves [41]. The trees, with their large leaf area, were considered the most effective PM accumulation plants. Although the crowns of the shrubs were much lower than the trees, nearing the ground helped shrubs accumulate PM closer to the ground [4]. In this study, the shrubs *E. japonicus* and *R. yedoense* showed more effective PM accumulation on the leaf surface than others.

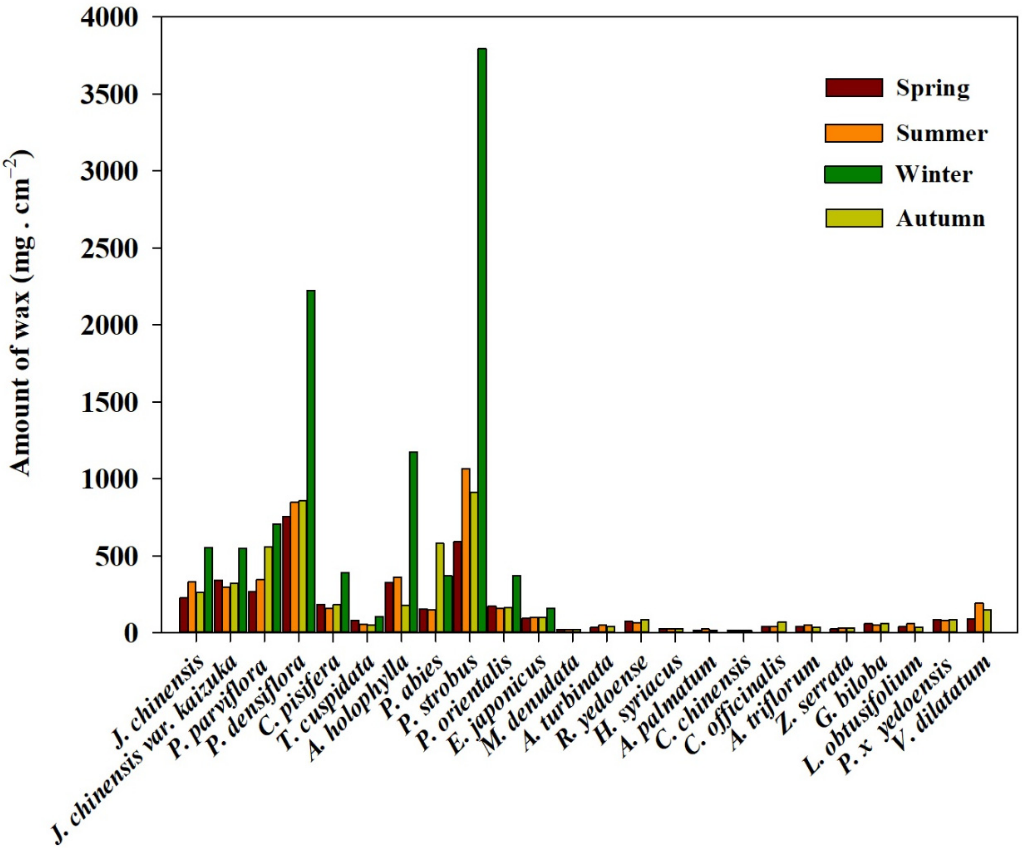

Figure 3. The amount of wax on 24 plant species in four seasons (spring, summer, autumn, and winter).

Among the ten needleleaf, *P. strobus* showed the highest PM accumulation on the leaf surface. The high stomatal concentration on the leaf could increase the PM accumulation on the leaf of *P. strobus*. Additionally, the amount of wax on *P. strobus* was the highest, causing an increasingly large amount of PM accumulation in this plant species. Other studies also showed that *P. parviflora* and *P. densiflora* were able to accumulate more PM than other plant species, which was the same as our result. Among the 14 broadleaf, the plant species that showed the most effective PM accumulation were *A. palmatum* and *E. japonicus* because of their leaf structures. Leaf structures, such as heave, groove, vein, chambers, bumps, glands, and secretions, impact PM deposition on leaves [42]. Many studies have shown that plants with rough leaves can accumulate more PM than plants with smooth leaves [39]. However, *E. japonicus* with smooth leaves showed high effective accumulation on leaves because of the plant's curled leaf edges, which could keep PM on the leaf apices despite the washing effect of rainfall. Moreover, the glands and secretions of the leaves were related to increasing PM accumulation in *E. japonicus*. For *A. palmatum*, the leaf fold structure led to increased PM accumulation. Conversely, *G. biloba*, with a rough leaf and high leaf area, showed the lowest PM accumulation. The long leaf petiole increased the wind's effective removal of PM from its leaves [43]. The ridged microstructure and dense wax tubules, due to the high self-cleaning ability of *G. biloba,* reduced the effective accumulation of PM in *G. bibola* [44]. The water repellency of the leaf prevented PM deposition on the leaf, which was also one of the reasons that led to decreasing PM accumulation on the leaf of *G. bibola*. The amount of wax on 24 plants differed due to their structural differences. The amount of wax in winter increased in response to the increasing PM in the atmosphere. The PM concentration level is positively correlated with the amount of wax in plants [45]. Leaf structures impacted the ability of PM to accumulate in the plants. However, other factors, such as leaf shape, canopy shape, and leaf height, need to be studied to better understand the complex relationships of plant species and PM accumulation.

4.2. The Leaf Traits of 24 Plant Species

In this study, the leaf traits of 24 plant species were analyzed. Among the leaf traits, the Chl a, Chl b, TChl, carotenoid, and RWC were different among plant species and seasons. We did not find any seasonal tendencies when comparing the Chl a and carotenoid contents of the 24 plant species. For the Chl b of 24 plant species, we found that Chl b tended to be lower in autumn than in summer; the species not following this trend were *P. strobus*, *Z. serrata*, and *L. obtusifolium*. The TChl of 24 plant species showed the same tendency as the Chl b, but *T. cuspidata*, *A. holophylla, P. strobus*, *Z. serrata*, and *L. obtusifolium* did not follow this trend. The RWC of the 24 plant species differed among the plants. In this study, the RWC of broadleaf did not show any seasonal tendencies. However, the RWC of needleleaf increased in autumn compared with summer. When comparing the RWC of needleleaf between autumn and winter, the RWC decreased in winter except in *P. strobus*. The pH differed among plant species. We found that the pH increased in autumn compared with summer for all plant species except *J. chinensis* and *P. parviflora*. The pH of 11 plant species was higher in winter than in other seasons. Additionally, the SLA of 24 plants differed among plant species. Among the four seasons, we found that the SLA of 11 plant species, except for *A. holophylla* and *P. strobus,* was lowest in winter. When comparing the SLA among the three seasons (spring, summer, and autumn), we did not find any seasonal tendencies (Tables 3 and 4).

Table 3. The leaf traits of 24 plant species in four different seasons (spring, summer, autumn, and winter).

	Seasons	**Chl a ($mg \cdot g^{-1}$ FW)**	**Chl b ($mg \cdot g^{-1}$ FW)**	**TChl ($mg \cdot g^{-1}$ FW)**	**RWC (%)**	**pH**	**SLA ($cm^2 \cdot g^{-1}$)**
J. chinensis	Spring	0.056 ± 0.001	0.024 ± 0.001	0.080 ± 0.001	74.66 ± 1.15	5.08 ± 0.05	19.06 ± 0.60
	Summer	0.090 ± 0.003	0.030 ± 0.003	0.124 ± 0.004	73.45 ± 0.15	5.04 ± 0.02	24.87 ± 0.51
	Autumn	0.049 ± 0.001	0.020 ± 0.000	0.069 ± 0.002	79.28 ± 0.18	4.88 ± 0.03	20.97 ± 0.65
	Winter	0.066 ± 0.002	0.027 ± 0.002	0.094 ± 0.004	74.14 ± 0.58	5.70 ± 0.01	16.25 ± 0.32
J. chinensis var. *kaizuka*	Spring	0.052 ± 0.003	0.022 ± 0.002	0.078 ± 0.006	78.65 ± 0.04	4.75 ± 0.01	19.72 ± 0.96
	Summer	0.058 ± 0.001	0.026 ± 0.000	0.084 ± 0.001	77.93 ± 0.99	4.75 ± 0.01	18.77 ± 0.48
	Autumn	0.053 ± 0.002	0.023 ± 0.001	0.076 ± 0.004	91.87 ± 0.59	4.93 ± 0.05	19.40 ± 0.16
	Winter	0.055 ± 0.001	0.023 ± 0.002	0.078 ± 0.002	83.36 ± 1.12	5.77 ± 0.08	17.02 ± 0.60
P. parviflora	Spring	0.189 ± 0.007	0.060 ± 0.008	0.249 ± 0.015	71.99 ± 1.08	5.00 ± 0.03	9.65 ± 1.36
	Summer	0.117 ± 0.000	0.048 ± 0.000	0.166 ± 0.001	79.69 ± 1.47	5.09 ± 0.05	9.06 ± 0.97
	Autumn	0.119 ± 0.001	0.045 ± 0.000	0.165 ± 0.002	81.71 ± 0.49	4.93 ± 0.02	13.12 ± 0.70
	Winter	0.088 ± 0.000	0.039 ± 0.000	0.128 ± 0.000	76.85 ± 0.28	5.85 ± 0.04	9.02 ± 0.30

Table 3. *Cont.*

	Seasons	Chl a ($mg \cdot g^{-1}$ FW)	Chl b ($mg \cdot g^{-1}$ FW)	TChl ($mg \cdot g^{-1}$ FW)	RWC (%)	pH	SLA ($cm^2 \cdot g^{-1}$)
P. densiflora	Spring	0.178 ± 0.004	0.075 ± 0.001	0.250 ± 0.007	77.58 ± 1.13	4.62 ± 0.03	14.34 ± 0.52
	Summer	0.122 ± 0.001	0.047 ± 0.001	0.184 ± 0.014	86.58 ± 1.26	4.59 ± 0.02	11.11 ± 0.67
	Autumn	0.106 ± 0.001	0.041 ± 0.001	0.146 ± 0.001	96.52 ± 1.10	4.85 ± 0.01	13.08 ± 1.24
	Winter	0.075 ± 0.004	0.032 ± 0.003	0.108 ± 0.007	93.19 ± 0.50	6.07 ± 0.05	9.23 ± 0.12
C. pisifera	Spring	0.157 ± 0.003	0.059 ± 0.001	0.216 ± 0.004	81.78 ± 0.80	4.90 ± 0.05	39.54 ± 2.07
	Summer	0.139 ± 0.007	0.056 ± 0.002	0.195 ± 0.009	80.96 ± 0.53	4.94 ± 0.03	58.19 ± 0.28
	Autumn	0.131 ± 0.001	0.051 ± 0.001	0.183 ± 0.001	84.92 ± 0.31	5.03 ± 0.01	42.99 ± 0.35
	Winter	0.089 ± 0.001	0.038 ± 0.001	0.127 ± 0.001	80.65 ± 1.66	6.04 ± 0.10	32.61 ± 0.43
T. cuspidata	Spring	0.124 ± 0.020	0.053 ± 0.008	0.140 ± 0.024	75.52 ± 0.54	5.21 ± 0.14	63.01 ± 1.89
	Summer	0.105 ± 0.005	0.045 ± 0.002	0.141 ± 0.006	77.25 ± 0.98	4.84 ± 0.07	55.18 ± 1.69
	Autumn	0.111 ± 0.003	0.042 ± 0.001	0.148 ± 0.005	79.31 ± 0.36	5.24 ± 0.01	58.30 ± 2.69
	Winter	0.105 ± 0.004	0.051 ± 0.002	0.156 ± 0.005	73.02 ± 1.14	5.69 ± 0.04	42.38 ± 0.77
A. holophylla	Spring	0.105 ± 0.009	0.044 ± 0.003	0.135 ± 0.011	74.88 ± 1.25	4.74 ± 0.03	28.94 ± 0.58
	Summer	0.113 ± 0.001	0.042 ± 0.000	0.156 ± 0.001	73.96 ± 0.24	4.74 ± 0.03	33.90 ± 1.49
	Autumn	0.114 ± 0.004	0.042 ± 0.001	0.157 ± 0.005	88.70 ± 0.57	4.93 ± 0.02	27.12 ± 0.59
	Winter	0.062 ± 0.002	0.030 ± 0.001	0.092 ± 0.002	77.56 ± 1.18	6.28 ± 0.07	28.10 ± 0.55
P. abies	Spring	0.103 ± 0.004	0.042 ± 0.003	0.128 ± 0.002	79.12 ± 1.07	4.19 ± 0.09	27.62 ± 1.04
	Summer	0.122 ± 0.003	0.046 ± 0.001	0.168 ± 0.004	73.40 ± 0.35	4.19 ± 0.09	31.79 ± 0.93
	Autumn	0.087 ± 0.001	0.033 ± 0.001	0.120 ± 0.002	83.60 ± 0.81	5.06 ± 0.04	33.57 ± 0.41
	Winter	0.101 ± 0.000	0.042 ± 0.002	0.142 ± 0.002	80.702 ± 0.35	5.84 ± 0.07	21.70 ± 0.41
P. strobus	Spring	0.094 ± 0.007	0.037 ± 0.003	0.147 ± 0.012	62.41 ± 0.53	4.84 ± 0.04	7.80 ± 0.86
	Summer	0.083 ± 0.001	0.035 ± 0.001	0.120 ± 0.003	72.78 ± 0.31	4.84 ± 0.04	3.78 ± 0.91
	Autumn	0.101 ± 0.004	0.042 ± 0.002	0.143 ± 0.006	73.44 ± 0.77	5.05 ± 0.02	1.27 ± 0.11
	Winter	0.084 ± 0.002	0.040 ± 0.000	0.124 ± 0.002	78.97 ± 0.46	5.54 ± 0.03	4.85 ± 0.52
P. orientalis	Spring	0.094 ± 0.002	0.040 ± 0.001	0.139 ± 0.003	78.17 ± 2.58	4.84 ± 0.02	49.33 ± 1.98
	Summer	0.105 ± 0.002	0.045 ± 0.001	0.150 ± 0.002	76.43 ± 0.20	4.84 ± 0.02	46.32 ± 1.88
	Autumn	0.096 ± 0.003	0.039 ± 0.001	0.135 ± 0.003	85.22 ± 1.06	5.38 ± 0.02	51.76 ± 0.49
	Winter	0.065 ± 0.005	0.029 ± 0.002	0.094 ± 0.008	75.84 ± 1.28	6.16 ± 0.15	39.36 ± 1.72
E. japonica	Spring	0.048 ± 0.003	0.024 ± 0.001	0.072 ± 0.002	67.96 ± 1.40	5.16 ± 0.01	81.74 ± 1.51
	Summer	0.071 ± 0.004	0.033 ± 0.001	0.103 ± 0.004	70.75 ± 0.85	5.16 ± 0.01	82.66 ± 4.59
	Autumn	0.039 ± 0.002	0.018 ± 0.001	0.057 ± 0.002	74.41 ± 0.59	5.31 ± 0.03	91.05 ± 2.82
	Winter	0.044 ± 0.006	0.021 ± 0.003	0.065 ± 0.009	60.96 ± 1.07	6.14 ± 0.03	77.15 ± 1.44
M. denudata	Spring	0.096 ± 0.005	0.038 ± 0.004	0.145 ± 0.014	67.29 ± 0.85	5.47 ± 0.01	179.51 ± 7.27
	Summer	0.111 ± 0.003	0.046 ± 0.002	0.156 ± 0.004	77.87 ± 0.31	5.47 ± 0.01	168.66 ± 6.71
	Autumn	0.086 ± 0.002	0.036 ± 0.001	0.122 ± 0.003	84.80 ± 0.13	6.14 ± 0.03	177.88 ± 10.6
	Winter	0	0	0	0	0	0
A. turbinata	Spring	0.214 ± 0.015	0.043 ± 0.005	0.271 ± 0.021	69.42 ± 0.35	5.17 ± 0.03	131.94 ± 2.31
	Summer	0.172 ± 0.000	0.073 ± 0.001	0.245 ± 0.001	72.26 ± 0.32	5.17 ± 0.03	145.68 ± 6.54
	Autumn	0.122 ± 0.003	0.047 ± 0.001	0.172 ± 0.005	80.75 ± 1.09	5.56 ± 0.05	123.81 ± 2.56
	Winter	0	0	0	0	0	0
R. yedoense	Spring	0.119 ± 0.026	0.029 ± 0.012	0.148 ± 0.037	77.55 ± 0.41	5.21 ± 0.04	165.65 ± 1.17
	Summer	0.165 ± 0.006	0.076 ± 0.005	0.261 ± 0.018	87.68 ± 1.78	5.18 ± 0.07	163.55 ± 2.48
	Autumn	0.165 ± 0.004	0.066 ± 0.001	0.230 ± 0.006	86.44 ± 0.40	5.47 ± 0.03	151.35 ± 1.82
	Winter	0	0	0	0	0	0
H. syriacus	Spring	0.128 ± 0.013	0.026 ± 0.004	0.154 ± 0.013	80.34 ± 0.65	5.63 ± 0.03	160.35 ± 4.51
	Summer	0.173 ± 0.012	0.071 ± 0.006	0.244 ± 0.017	78.41 ± 0.79	5.63 ± 0.03	147.46 ± 4.12
	Autumn	0.157 ± 0.002	0.071 ± 0.002	0.228 ± 0.003	81.45 ± 0.88	6.15 ± 0.02	151.61 ± 3.38
	Winter	0	0	0	0	0	0

Table 3. *Cont.*

	Seasons	Chl a ($mg \cdot g^{-1}$ FW)	Chl b ($mg \cdot g^{-1}$ FW)	TChl ($mg \cdot g^{-1}$ FW)	RWC (%)	pH	SLA ($cm^2 \cdot g^{-1}$)
A. palmatum	Spring	0.075 ± 0.007	0.026 ± 0.012	0.070 ± 0.007	85.26 ± 0.19	4.71 ± 0.02	152.04 ± 5.05
	Summer	0.164 ± 0.015	0.071 ± 0.002	0.242 ± 0.012	91.30 ± 0.27	4.71 ± 0.02	193.06 ± 5.44
	Autumn	0.168 ± 0.003	0.068 ± 0.001	0.237 ± 0.003	92.00 ± 0.47	4.99 ± 0.09	201.17 ± 6.55
	Winter	0	0	0	0	0	0
C. chinensis	Spring	0.193 ± 0.008	0.054 ± 0.007	0.269 ± 0.015	61.45 ± 1.75	4.31 ± 0.05	159.38 ± 13.53
	Summer	0.191 ± 0.004	0.085 ± 0.002	0.274 ± 0.006	65.69 ± 0.34	4.42 ± 0.06	156.05 ± 17.76
	Autumn	0.166 ± 0.000	0.070 ± 0.001	0.234 ± 0.001	75.35 ± 0.50	5.44 ± 0.01	253.01 ± 21.21
	Winter	0	0	0	0	0	0
C. officinalis	Spring	0.127 ± 0.029	0.055 ± 0.014	0.182 ± 0.042	64.92 ± 0.16	5.84 ± 0.02	156.65 ± 2.40
	Summer	0.150 ± 0.005	0.065 ± 0.001	0.209 ± 0.003	73.81 ± 0.77	5.84 ± 0.02	210.40 ± 21.70
	Autumn	0.081 ± 0.006	0.036 ± 0.002	0.117 ± 0.008	73.75 ± 0.86	6.25 ± 0.04	121.68 ± 3.91
	Winter	0	0	0	0	0	0
A. triflorum	Spring	0.194 ± 0.019	0.070 ± 0.015	0.287 ± 0.035	68.34 ± 4.52	4.41 ± 0.02	214.34 ± 7.11
	Summer	0.217 ± 0.023	0.100 ± 0.009	0.317 ± 0.031	75.56 ± 0.85	4.39 ± 0.04	238.45 ± 9.92
	Autumn	0.152 ± 0.005	0.063 ± 0.002	0.212 ± 0.008	71.01 ± 0.31	5.81 ± 0.01	205.55 ± 8.00
	Winter	0	0	0	0	0	0
Z. serrata	Spring	0.177 ± 0.005	0.061 ± 0.002	0.237 ± 0.006	52.93 ± 3.92	5.15 ± 0.01	203.19 ± 0.53
	Summer	0.192 ± 0.018	0.078 ± 0.006	0.269 ± 0.023	61.44 ± 0.93	5.15 ± 0.01	174.44 ± 2.83
	Autumn	0.233 ± 0.030	0.102 ± 0.010	0.374 ± 0.035	56.92 ± 0.40	5.86 ± 0.02	224.08 ± 3.65
	Winter	0	0	0	0	0	0
G. biloba	Spring	0.093 ± 0.003	0.029 ± 0.002	0.122 ± 0.003	75.00 ± 0.06	5.00 ± 0.09	129.80 ± 5.15
	Summer	0.074 ± 0.004	0.034 ± 0.003	0.107 ± 0.006	72.13 ± 0.05	5.00 ± 0.09	131.70 ± 1.51
	Autumn	0.053 ± 0.002	0.024 ± 0.000	0.074 ± 0.001	80.03 ± 0.67	5.69 ± 0.03	156.01 ± 1.22
	Winter	0	0	0	0	0	0
L. obtusifolium	Spring	0.203 ± 0.005	0.070 ± 0.003	0.257 ± 0.017	69.74 ± 2.66	5.14 ± 0.02	122.36 ± 2.48
	Summer	0.174 ± 0.004	0.063 ± 0.002	0.237 ± 0.005	66.93 ± 0.71	5.14 ± 0.02	157.87 ± 13.67
	Autumn	0.156 ± 0.011	0.065 ± 0.003	0.240 ± 0.013	72.35 ± 3.70	5.34 ± 0.02	207.37 ± 3.50
	Winter	0	0	0	0	0	0
P. × yedoensis	Spring	0.137 ± 0.002	0.049 ± 0.002	0.186 ± 0.004	75.81 ± 0.22	5.03 ± 0.00	95.33 ± 1.98
	Summer	0.134 ± 0.005	0.055 ± 0.004	0.189 ± 0.008	76.55 ± 0.80	5.03 ± 0.00	110.75 ± 3.71
	Autumn	0.124 ± 0.019	0.042 ± 0.001	0.146 ± 0.004	81.83 ± 0.43	5.38 ± 0.01	120.18 ± 3.51
	Winter	0	0	0	0	0	0
V. dilatatum	Spring	0.164 ± 0.021	0.039 ± 0.006	0.203 ± 0.028	46.36 ± 1.82	5.60 ± 0.01	216.28 ± 11.07
	Summer	0.212 ± 0.010	0.091 ± 0.004	0.303 ± 0.014	64.15 ± 1.48	5.60 ± 0.01	251.32 ± 1.95
	Autumn	0.146 ± 0.007	0.063 ± 0.003	0.209 ± 0.010	62.67 ± 0.78	5.68 ± 0.01	302.54 ± 4.60
	Winter	0	0	0	0	0	0

Chl a: chlorophyll a concentration, Chl b: chlorophyll b concentration, TChl: total chlorophyll concentration, RWC: relative leaf water content, pH: leaf extract pH, and SLA: specific leaf area.

PM impacts plant growth and production by impacting its physiology and biological activities. Under stress from the environment, numerous changes in plants can be observed. However, the level of change depends on the response of the plants to the environment [26]. In this study, the leaf traits (chlorophyll, pH, RWC, and SLA) were analyzed to determine the influence of PM on the plant while the plant responded to environmental stress. Chlorophyll content signifies the photosynthesis process that determines plant growth and production [46]. PM accumulation on the leaf could block the stomata, leading to reduced stomatal conductance, which leads to reduced chlorophyll content in the plants [17]. Moreover, PM accumulation on the leaf prevented light absorption due to the decreasing effectiveness of photosynthesis [47]. PM could even lead to chlorosis (yellowing) in plants. In this study, the decreasing chlorophyll content of broadleaf caused them to change from green to yellow at the end of the growing season. We did not find any patterns among the chlorophyll content of the plants, but we suggest that the chlorophyll reduction in some plants caused PM to accumulate on the leaves. The increase in the chlorophyll content of other plants during the high PM concentration season showed plant tolerance to environmental stress [48]. In this study, we also found that the large sPM (10–100 µm), wPM (10–100 µm), and coarse wPM (2.5–10 µm) showed negative correlations with plant chlorophyll and carotenoid in summer, but, in winter, we found positive correlations between coarse wPM (2.5–10) and chlorophyll and carotenoid. In winter, the needleleaf and one broadleaf (*E. japonica*) were collected and analyzed.

Table 4. ANOVA analysis of PM accumulation on the leaf and leaf traits of 24 plant species in the four seasons (spring, summer, autumn, and winter).

	Species ($F_{23,192}$)	**Seasons ($F_{3,192}$)**	**Species × Season ($F_{69,192}$)**
sPM (10–100)	155.44 ***	20.46 ***	5.77 ***
sPM (2.5–10)	149.94 ***	47.48 ***	38.04 ***
wPM (10–100)	229.74 ***	34.54 ***	13.88 ***
wPM (2.5–10)	27.95 ***	9.71 ***	9.39 ***
Chl a	47.32 ***	750.56 ***	23.66 ***
Chl b	29.11 ***	498.36 ***	20.88 ***
TChl	48.89 ***	747.12 ***	27.2 ***
RWC	576.54 ***	8009.28 ***	297.33 ***
pH	882.41 ***	19134.2 ***	1415.78 ***
SLA	465.06 ***	2098.27 ***	84.38 **

Levels of significance: ** $p < 0.01$, *** $p < 0.001$. PM (10–100): particulate matter with diameter 10–100 µm, PM (2.5–10): particulate matter with diameter 2.5–10 µm, sPM: particulate matter on the leaf surface, wPM: particulate matter in the wax layer, Chl a: chlorophyll a concentration, Chl b: chlorophyll b concentration, TChl: total chlorophyll concentration, RWC: leaf relative water content, pH: leaf extract pH, SLA: specific leaf area.

The RWC reflected the status of water of plants, which plays a significant role in maintaining plant physiological balance. Plants with a high RWC could be more tolerant to stress from the environment, such as drought or air pollution [49]. PM locked on stomata led to a decreasing transpiration rate, which decreased the water pulled from plant roots and was a reason why minerals could not translate from plant roots for biosynthesis [6]. In this study, we suggested that the increase in PM concentration in winter caused a decrease in the RWC of needleleaf. In contrast, the increasing RWC of a plant in the high PM concentration season showed the high tolerance level of the plants to air pollution.

Further, pH is a sensitive indicator of stress in plant environments. Moreover, low pH reduces conversion of hexose sugar to ascorbic acid, which plays an important role in the tolerance level of plants [30]. Therefore, plants with a high pH have a greater ability to tolerate air pollution than plants with a low pH. Air pollutants lead to decreasing pH, which causes sensitive stomata due to reduced plant photosynthesis rates. Furthermore, acidic pollution, such as SO_2 and NO_2, is one reason for the decreasing pH of plants [50]. In this study, the increasing pH of needleleaf (in winter) and broadleaf (in autumn) may have caused the plants to respond to air pollution. We found a negative correlation between PM accumulation on leaves and pH in spring, summer, and autumn. Other factors, such as environmental soil pH, that could impact plant pH need to be studied to determine the correlation between pH and these factors.

SLA measures the thickness of the leaf. The changes in SLA mirror the changes in leaf structure and nutritional content. The thickness of leaves can help to increase effective light absorption [33]. However, PM accumulation on the leaf surface may increase the leaf's shape area and cause changes in the SLA of plants. Based on plant protective or adaptive mechanisms, SLA fluctuation levels vary [51]. In this study, we found that the SLA of the plant was different among species. Moreover, the SLA of needleleaf was lowest in winter, which caused a large amount of PM accumulation on the leaf surface of needleleaf during this season. We also found that PM accumulation was negatively correlated with plant SLA (Table 5).

Table 5. Pearson correlation analysis of the accumulation of different fractions of particulate matter on leaf and leaf traits of 24 plant species in the four seasons.

	PM Size	Chl a		Chl b		TChl		RWC		pH		SLA	
Spring	sPM (10–100)	−0.012		0.106		0.046		−0.037		−0.204		−0.554	***
	sPM (2.5–10)	0.035		0.110		0.069		0.141		−0.284	*	−0.548	***
	wPM (10–100)	−0.148		0.066		−0.070		0.047		−0.269	*	−0.633	***
	wPM (2.5–10)	0.087		0.095		0.127		−0.007		0.016		−0.154	
Summer	sPM (10–100)	−0.285	*	−0.295	*	−0.266	*	0.155		−0.148		−0.484	***
	sPM (2.5–10)	−0.196		−0.168		−0.183		0.314	*	−0.200		−0.381	***
	wPM (10–100)	−0.344	**	−0.359	**	−0.332	**	0.062		−0.244	*	−0.537	***
	wPM (2.5–10)	−0.306	**	−0.329	**	−0.300	*	0.138		−0.165		−0.471	***
Autumn	sPM (10–100)	−0.123		−0.136		−0.131		0.055		−0.313	**	−0.445	***
	sPM (2.5–10)	−0.175		−0.210		−0.181		0.182		−0.479	***	−0.579	***
	wPM (10–100)	−0.177		−0.214		−0.189		0.190		−0.477	***	−0.577	***
	wPM (2.5–10)	−0.134		−0.139		−0.137		−0.025		−0.258	*	−0.331	**
Winter	sPM (10–100)	0.231		0.287		0.252		0.200		−0.360		−0.559	***
	sPM (2.5–10)	0.177		0.250		0.202		0.107		−0.459		−0.472	**
	wPM (10–100)	0.142		0.209		0.165		0.269		−0.423		−0.545	***
	wPM (2.5–10)	0.149	***	0.217	***	0.172	***	0.214		−0.413		−0.492	**

Levels of significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. PM (10–100): particulate matter with diameter 10–100 μm, PM (2.5–10): particulate matter with diameter 2.5–10 μm, sPM: particulate matter on the leaf surface, wPM: particulate matter in the wax layer, Chl a: chlorophyll a concentration, Chl b: chlorophyll b concentration, TChl: total chlorophyll concentration, RWC: leaf relative water content, pH: leaf extract pH, SLA: specific leaf area.

5. Conclusions

In this study, we found that the amount of PM accumulation on the leaves of 24 plant species differed among the four seasons. In winter, the amount of PM accumulation increased with increasing PM concentration in the atmosphere. In summer and autumn, the low PM concentration and the high rainfall may have led to a reduction in the amount of PM accumulation on the plant leaves. In this study, needleleaf was more effective than broadleaf in accumulating PM. The shrubs demonstrated to be highly effective at reducing PM. Using both trees and shrubs can increase the effective PM accumulation in the urban area. The *P. strobus*, *P. parviflora*, *P. densiflora*, *E. japonicus*, and *A. palmatum* showed more effective PM accumulation than other plant species. The leaf traits differed regarding plant species and seasons. PM had a negative correlation with plant SLA. In summer, PM was negatively correlated with chlorophyll and carotenoids. Further, pH had a negative correlation with PM accumulation on the leaves in spring, summer, and autumn. PM accumulation impacted the leaf traits of the plant, but numerous other factors, such as temperature and soil, also impact leaf traits. More studies on the complex correlations among leaf PM accumulation, leaf traits, and environmental conditions are needed to effectively increase the use of plants to improve air quality.

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