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A Study on the Leaf Retention Capacity and Mechanism of Nine Greening Tree Species in Central Tropical Asia Regarding Various Atmospheric Particulate Matter Values

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Abstract: With the rapid advancement of the global economy, there has been a noticeable escalation in the level of inhalable particulate matter (PM) pollution in the atmosphere. The utilization of plants has been recognized as an effective means to mitigate the escalation in the atmospheric PM concentration through the capture and retention of this particulate matter on their leaves. This research focuses on investigating the PM retention capacity of nine commonly found greening plant species in Changsha, China, located in the country's mid-subtropical region. In this study, we employed an air aerosol generator (QRJZFSQ-II) and a portable leaf area meter (LI-3000C) to systematically evaluate the PM retention in unit leaf area for different PM values. In addition, the leaf surface structure was observed via scanning electron microscopy, and the relationship between the leaf microstructure and the retained particles was quantitatively analyzed. The results showed that (1) there were significant differences in the retention of TSP, PM_{10}, and $PM_{2.5}$ per unit leaf area among the nine greening tree species analyzed. *Rosa saturata* was found to have the best retention effect regarding TSP and $PM_{2.5}$, and *Rhododendron simsii* was found to have the best retention effect regarding PM_{10}. (2) There were significant differences in the contents of TSP and $PM_{2.5}$ per leaf area among the different tree species with different life forms ($p < 0.05$), with the order of retention being shrub > arbor (needle leaves) > arbor (broad leaves). (3) Coniferous plants have a deep leaf surface texture, which is conducive to capturing more particles on their leaf surface, and (4) the long stomata diameter was significantly negatively correlated with PM retention, and the stomata density was significantly positively correlated with PM retention. However, the short diameter and small area of stomata demonstrated no significant correlation with PM retention ($p < 0.05$). Considering the selection of suitable tree species for greening in urban air pollution control, we suggest that *Osmanthus fragrans*, *Pseudolarix amabilis*, *Rosa saturata*, and *Rhododendron simsii* be used more frequently in urban areas affected by severe air pollution.

Keywords: accumulation on leaves; particulate matter; green plants; microstructure of leaf surfaces

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1. Introduction

Air pollution is a global problem and has adverse effects on human health, vegetation, and animal growth [1]. Particulate matter (PM) consists of solid and liquid particles suspended in the air; PM pollutants can be classified into three groups according to their diameter PM_{10} (consisting of a diameter less or equal to 10 μm), $PM_{2.5}$ (consisting of a diameter less or equal to 2.5 μm), and PM_1 (consisting of a diameter less or equal to 1 μm) [2]. $PM_{2.5}$ can be inhaled directly into the alveoli, leading to the development of lung diseases [3]. Excessive total suspended particles (TSP) in the air can reduce visibility, leading to the occurrence of haze and photochemical smog. Particles with a diameter of ≤10 μm (PM_{10}) provide the conditions for atmospheric chemical reactions. Particulate matter with a diameter of ≤2.5 μm ($PM_{2.5}$) can remain in the atmosphere for a long time due to its small particle size, light weight, and difficulty in settling [4]. Aerosol particles such as $PM_{2.5}$ cause changes to the climate, mainly through the alteration of air temperature and precipitation patterns. Studies have shown that $PM_{2.5}$ contributes to global warming to some extent [5]. Therefore, reducing the concentration of PM in the air is beneficial to public life and health and is of great significance.

Inhalable particulate matter (PM) in the atmosphere is one of the main components of haze, and it makes a significant contribution to air pollution [6]. The harmful PM in the air is mainly man-made and is composed of heavy metals, black carbon, and polycyclic aromatic hydrocarbons suspended in the atmosphere [7]. Many studies have demonstrated that plants have large leaf surface areas and a complex leaf microstructure which can effectively retain dust and reduce the concentration of atmospheric particles [8–11]. Therefore, the use of urban green plants and forests to reduce and control PM pollution has attracted increasing attention around the world in recent years [12–14].

As natural biological filters or sinks, plants can mitigate PM in the air [15]. Particles can be transferred via gravity, diffusion (Brownian motion), or turbulence to increase the deposition of particles on the leaf blade surface [16]. The structure of the tree crown induces the turbulent motion of air, which increases the deposition of particulate matter on the leaf surface [17]. The leaves of different plants have different morphological features; thus, the ability of leaves to adsorb and retain PM varies significantly among plants [18,19]. In addition, significant disparities have been observed in the amount of PM retained by different types of plants, such as arbors, shrubs, and herbs [20,21]. The branches, leaves, trunks, and particular organs of plants can retain particles, while the leaves stand out in their ability to block and absorb PM as they possess the largest total surface area of all plant parts [22].

Due to appendages such as the stoma, villus, glandular oil, and so forth, the leaf surface of green plants can effectively settle and absorb airborne particles, and the leaf surface area is much larger than its footprint, with these characteristics providing a significant advantage with regard to atmospheric particle retention. The use of green plants to retain dust has become one of the most effective methods of alleviating urban air pollution [23]. Scanning electron microscopy (SEM) and image analysis software can be used to observe the surface microstructure, particle count, particle size, and particle distribution of plant leaves [24]. Quantitative and comprehensive assessment of PM retained by plant leaves is of great significance for accurately assessing the air purification capacity of urban forests at different scales (leaf, individual tree, and stand) and screening tree species with a higher PM retention capacity [25].

With the rapid economic development and improved quality of life in China and worldwide, air pollution has become a formidable challenge. Plants can not only make our environment more attractive but also reduce atmospheric particulate pollution, which is the most economical and environmentally friendly solution to control atmospheric particulate pollution to date [26]. Therefore, our study on the dust retention capacity of common greening tree species in Changsha can make up for the deficiency of research in central tropical Asia and provide a scientific basis for regions with a similar climate and plant distribution.

2. Materials and Methods

2.1. Sampling Location

The sampling area is located in Hunan Botanical Garden, Yuhua District, Changsha, China. The geographical location is positioned at 28°3′36″ N and 113°1′35″ E. There are no highly polluting factories within 5 km of the botanical garden, such as cement plants or coal-fired power plants. Hunan Botanical Garden covers an area of 113.5 ha, and its vegetation cover stands at over 90%. It belongs to the subtropical monsoon humid climate area, with an annual average temperature of 16.9 °C, an average annual precipitation of 1400.6 mm, and an annual average relative temperature of 80%; in this location, the average annual sunshine duration is 1726 h [27]. The location boasts good air quality and limited automobile traffic. The nine sampling points are located about 3 m away from the roads. All of the leaf samples were collected in the botanical garden, and the habitat was considered equivalent for each sample. The specific sampling points are shown in Figure 1.

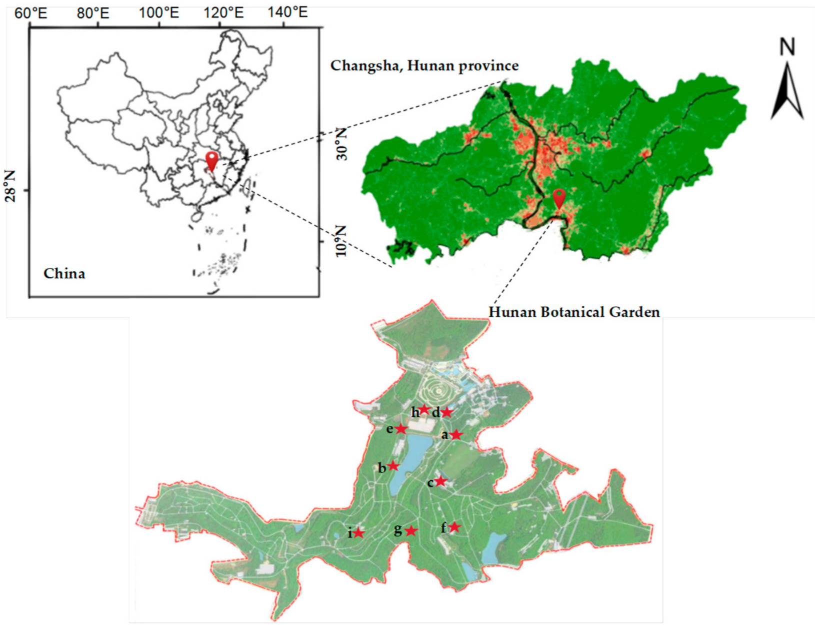

Figure 1. Sampling point diagram: (a) *Cinnamomum camphora*; (b) *Osmanthus fragrans*; (c) *Magnolia grandiflora*; (d) *Pseudolarix amabilis*; (e) *Pinus massoniana*; (f) *Taxodium distichum*; (g) *Photinia serratifolia*; (h) *Rosa saturata*; (i) *Rhododendron simsii*. The "📍" represents the sampling area, and the "★" represents the sampling points.

2.2. Sampling Collection

Nine typical green plant species in Changsha, mid-subtropical China, were selected in this study, and the names and growth characteristics of each plant species are shown in Table 1. In this study, our focus was on investigating the particulate retention capacity of leaves from common green plants and exploring the correlation between leaf microstructure and particulate retention capacity. Studies have shown that when the precipitation rate in an area is greater than 15 mm, this can result in the dust that falls on plant leaves being washed away [28]. To reduce the influence of different rainfall rates during the sampling period on the number of retained particles on the leaf surface, a state of no precipitation was required one week before sampling to ensure that a specific number of particles were retained on the leaf surface. The leaves were collected on 12 July 2023, and all samples were collected on that specific day. According to the actual characteristics of each tree species at the sampling site, the sampling height of the arbors was determined to be 2 to 6 m [29] and that of shrubs was determined to be 1 to 1.5 m. At least 5 sample trees were selected for each arbor species, and 3 to 4 sample trees with no arbor cover were selected for shrubs. Approximately 100 to 200 g of well-grown leaves were collected from the east, south, west, and north directions. The leaves of the same tree species were collected and mixed, numbered and put in a sealed bag, and put in a 4 °C refrigerator as soon as possible after being brought back to the laboratory.

Table 1. The basic status of the investigated green plants (mean ± SD).

Species	Family	Foliage	Habit	Height (m)	Crown Width (m)
Cinnamomum camphora	Lauraceae	Evergreen broad	Arbor	6.73 ± 0.68	4.20 ± 0.36
Osmanthus fragrans	Oleaceae	Evergreen broad	Arbor	5.47 ± 0.25	5.10 ± 0.36
Magnolia grandiflora	Magnoliaceae	Evergreen broad	Arbor	7.17 ± 0.35	6.23 ± 0.25
Pseudolarix amabilis	Pinaceae	Deciduous needle	Arbor	16.60 ± 0.56	7.17 ± 0.35
Pinus massoniana	Pinaceae	Deciduous needle	Arbor	15.57 ± 0.40	5.30 ± 0.44
Taxodium distichum	Cupressaceae	Deciduous needle	Arbor	19.33 ± 0.76	4.17 ± 0.35
Photinia serratifolia	Rosaceae	Deciduous	Shrub	—	1.43 ± 0.21
Rosa saturata	Rosaceae	Evergreen	Shrub	—	1.43 ± 0.21
Rhododendron simsii	Ericaceae	Deciduous	Shrub	—	1.53 ± 0.25

2.3. Mass Measurement of the PM on the Leaves

The retained particles (TSP, PM_{10}, and $PM_{2.5}$) of different plant leaves were measured using an aerosol generator (QRJZFSQ-II), and the plant leaf area was measured using a portable leaf area meter (LI-3000C). Considering the individuality of the leaves of coniferous tree species, the calculation method of leaf area of these tree species in this study referred to the method of Hwang [30]. The specific operation steps are as follows: first, take coniferous leaves as a truncated cone, take 100 leaf samples, measure the diameters and lengths with a vernier caliper, record the average value, and calculate the average surface area of the leaf as shown in Equation (1).

$$S = \frac{1}{2}\pi \cdot (D_1 + D_2) \cdot [\frac{1}{4} \cdot (D_2 - D_1)^2 + L^2]^{\frac{1}{2}} \quad (1)$$

Here, S was the average surface area of pine needles (m^2), D_1 was the average diameter of the upper tip (m), D_2 was the average diameter of the bottom end (m), and L was the average length lengths (m). Thus, the total surface area of pine needles was calculated by multiplying the number of pine needles by the average surface area of pine needles. The total leaf area of each tested tree species is shown in Table 2. The number of particles retained per unit leaf area was calculated as in Equation (2).

$$M = \frac{m}{S_t} \quad (2)$$

Table 2. The means (±SD) of the total leaf area of each tested tree species (m^2).

Species	Total Leaf Area	Species	Total Leaf Area
Cinnamomum camphora	0.34 ± 0.01	*Taxodium distichum*	0.09 ± 0.02
Osmanthus fragrans	0.18 ± 0.01	*Photinia serratifolia*	0.11 ± 0.01
Magnolia grandiflora	0.22 ± 0.02	*Rosa saturata*	0.07 ± 0.01
Pseudolarix amabilis	0.11 ± 0.01	*Rhododendron simsii*	0.08 ± 0.01
Pinus massoniana	0.15 ± 0.01		

Here, M is the retained particulate matter in the unit area (g·m^{-2}), m is the lag of leaf particulate matter in the aerosol regenerator (g), and S_t is the leaf area of all leaves in the aerosol regenerator (m^2).

2.4. Observation of Foliar Microstructure

The collected leaves were made into 3 mm × 3 mm sections, with avoidance of the veins. Six pieces were taken from each sample, one leaf section was randomly selected to observe the upper surface, and the other section was used to observe the lower surface. The samples were placed in an oven at 50 °C for 48 h until the leaves were completely dry.

The square leaf sections were glued on a sample stage with conductive adhesive and then sputter-coated with gold using an ion sputter coater. SEM (Japan Electronics Corporation, JSM-6380LV, Tokyo, Japan) was carried out to observe the stomatal characteristics, roughness, and other microscopic indicators of the surface of the leaves, and the images obtained were adjusted to 1000 magnification for photo preservation. This procedure was repeated at least three times.

2.5. Data Analysis

In this study, the data were organized and analyzed using SPSS 26.0 software, statistical analysis was carried out by applying one-way analysis of variance (ANOVA) and post hoc Tukey HSD multiple comparisons, and the data were expressed in the form of the mean and standard deviation. Most of the charts were created with Excel 2003 (Microsoft Corp., Redmond, WA, USA) and R language. The heat map was generated using the pheatmap package, and structural equation modeling (SEM) analyses were performed in R using the "Lavaan" package. The standardized effects are the sum of standardized path coefficients for the relationships between different variables and particle retention. A given effect was assumed to be significant at $p < 0.05$.

3. Results

3.1. Dust Retention Ability Analysis

The comparison of dust retention on the unit leaf area of nine common green plants is shown in Table 3. The comparison showed that the retention of TSP, PM_{10}, and $PM_{2.5}$ on the leaf surface of different green tree species was quite different, with the ranges of 2.10–12.69, 1.13–6.80, and 0.24–1.65 $g \cdot m^{-2}$, respectively. The highest accumulation of TSP on the leaf surface was found in *Rosa saturata* with a retention rate of (12.69 ± 1.87) $g \cdot m^{-2}$, followed by *Rhododendron simsii*, *Pseudolarix amabilis*, and *Osmanthus fragrans* with rates of TSP accumulation of (11.04 ± 0.47), (8.18 ± 0.72), and (5.59 ± 1.22) $g \cdot m^{-2}$, respectively, whereas the lowest accumulation of TSP on the leaf surface was found in *Magnolia grandiflora* with a retention rate of (2.10 ± 0.08) $g \cdot m^{-2}$. The retention capacity of TSP and $PM_{2.5}$ of *Rosa saturata* was the strongest but ranked second for PM_{10} among the nine tested green plants. *Osmanthus fragrans* ranked fourth in the retention capacity of TSP and PM_{10} but seventh in the retention capacity of $PM_{2.5}$. The worst retention effect of different particle sizes was found for *Magnolia grandiflora*. It can be seen that the retention ability of green plants to particles with different particle sizes is also different due to their different characteristics. The retention ability of green plants to TSP was not completely consistent with that of PM_{10} and $PM_{2.5}$. The retention ability of TSP per unit leaf area could not completely determine its retention ability to particles with different sizes, which is closely related to leaf surface microstructure. The dust retention amount of each tree species was quite different due to various factors, which provides a favorable basis for the selection of tree species with excellent dust retention ability for greening.

Table 3. Comparison of PM with different sizes captured on the unit leaf area of nine green tree species ($g \cdot m^{-2}$).

Species	TSP (Mean ± SD)	PM_{10} (Mean ± SD)	$PM_{2.5}$ (Mean ± SD)
Cinnamomum camphora	2.15 ± 0.44 e	1.34 ± 0.03 e	0.35 ± 0.04 e
Osmanthus fragrans	5.59 ± 1.22 d	3.44 ± 0.76 c	0.60 ± 0.04 d
Magnolia grandiflora	2.10 ± 0.08 e	1.13 ± 0.16 e	0.24 ± 0.04 e
Pseudolarix amabilis	8.18 ± 0.72 c	3.94 ± 0.24 c	0.98 ± 0.09 c
Pinus massoniana	5.01 ± 0.66 d	3.03 ± 0.44 c	0.86 ± 0.20 c
Taxodium distichum	4.82 ± 0.99 d	2.24 ± 0.24 d	0.68 ± 0.07 d
Photinia serratifolia	5.29 ± 0.57 d	3.35 ± 0.24 c	1.02 ± 0.10 c
Rosa saturata	12.69 ± 1.87 a	4.96 ± 0.53 b	1.65 ± 0.05 a
Rhododendron simsii	11.04 ± 0.47 b	6.80 ± 0.52 a	1.39 ± 0.10 b

Note: Different letters represent significant differences in the same index among different tree species ($p < 0.05$).

The mass–particle size distribution can reflect the size of the particulate retention capacity of different tree species; the proportion of particulates with different particle sizes in the total particulate matter is shown in Figure 2. Among the particles trapped on the leaf surface, PM_{10} accounted for 39.10–63.26% of the TSP and $PM_{2.5}$ accounted for 10.67–19.28% of the TSP. The amount of retarded coarse particulate matter (PM_{10}) on the leaf surface contributed more to TSP among the nine selected tree species, especially *Photinia serratifolia*, *Cinnamomum camphora*, and *Osmanthus fragrans*, which were up to 63.26%, 32.48%, and 61.48%, respectively. The contribution rate of fine particles ($PM_{2.5}$) on the leaf surface to TSP was relatively small, and the fine particles on the leaves of the highest *Photinia serratifolia* accounted for 19.28% of TSP. In *Osmanthus fragrans*, fine particulate matter ($PM_{2.5}$) accounted for only 10.67% of TSP.

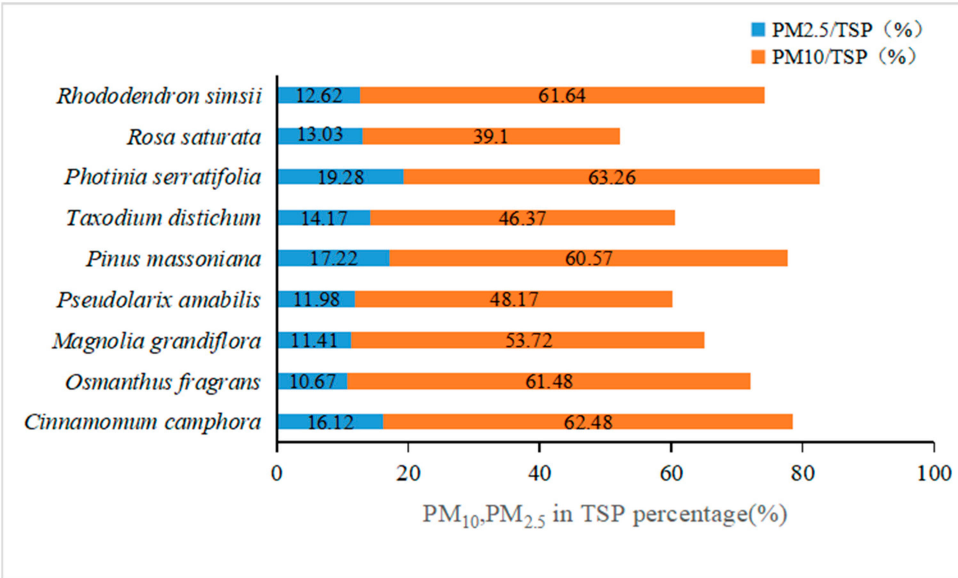

Figure 2. The proportion of particulates with different particle sizes in the total particulate matter.

3.2. Characteristics of the per Leaf Area Accumulation and Retention of TSP, PM_{10}, and $PM_{2.5}$ in Different Living Types

Nine green plants were divided into trees and shrubs according to their life forms, in which the trees were divided into needle-leaved and broad-leaved types. The analysis of the retention of different particle sizes per unit leaf area of plants with different life forms is shown in Figure 3. There were significant differences in TSP and $PM_{2.5}$ retention per unit leaf area of plants with different life forms ($p < 0.05$). There were significant differences in PM_{10} retention between shrubs and conifers ($p < 0.05$), and this same observation was made for shrubs and broadleaved trees. However, there were no significant differences in PM_{10} retention between conifers and broadleaved trees ($p < 0.05$). The retention of TSP, PM_{10}, and $PM_{2.5}$ per leaf area in different life forms followed the order of shrub > arbor (needle leaves) > arbor (broad leaves).

The average dust retention of coniferous species was higher than that of broad-leaved species, which might be closely related to their microstructure. The dust retention effect of shrubs was better than that of trees, probably due to the low height of shrubs and the high concentration of airborne particles near the ground due to secondary dust rising. Some particles will directly fall onto shrubs of low height and increase the retention of particles on their leaves. The results of a study by Wang et al. showed that, due to the influence of ground dust, the particles attached to the low leaves were larger than those found on the high leaves, which also confirmed the hypothesis that shrub plants have particular positional advantages in blocking the adsorption of particles [9]. Tall trees mainly blocked the adsorption of airborne dust and drifting dust, while shrubs mainly blocked the adsorption of ground dust. In addition, the height of trees was greater than that of shrubs, and the dispersion of fine particles in the air will slow down when the airflow is blocked by the leaves in the diffusion process and settle on the leaves of shrubs of lower height.

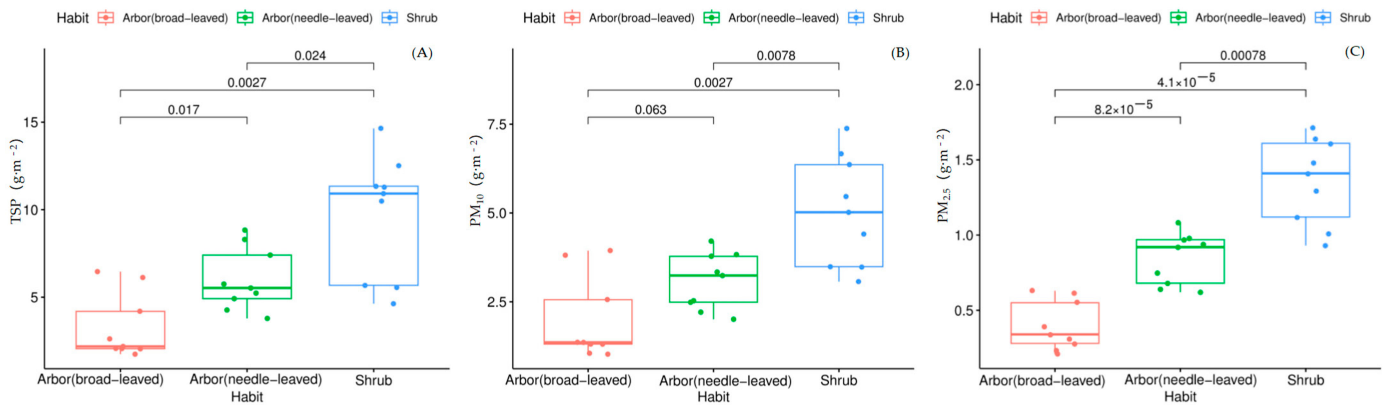

Figure 3. Comparison of PM retention per unit leaf area in different life forms of greening tree species. (**A**) Comparison of TSP retention in different life forms of greening tree species. (**B**) Comparison of PM_{10} retention in different life forms of greening tree species. (**C**) Comparison of $PM_{2.5}$ retention in different life forms of greening tree species. The numbers above the brackets mean the *p*-values.

3.3. Electron Microscope Scanning of the Leaf Surface of Different Green Plants

Leaf microstructure, such as stomatal density, waxy layer thickness, villus length, and texture groove depth, can directly affect the particulate retention ability of the leaf surface. Plant leaves are the main carriers for trapping atmospheric particles; individual differences in leaf surface characteristics lead to different retention capacities for particles with different particle sizes. The leaf microstructure includes waxy layer thickness, stomatal density, furrow depth, and villus length. By observing the scanning micrographs of the upper and lower surfaces of the representative leaves of each tested plant, it was found that the roughness of the leaf surface of different plants was different, and the leaf surface morphology was also found to be different (Figure 4). Through analysis of the microstructure pictures, it can be seen that *Rosa saturata*, with the greatest dust-trapping ability, has a large stomatal density, and this characteristic makes it easier for particles to gather around the stomatal aperture, resulting in the depression of the stomatal aperture and a semi-blocking shape [31]. It can also be observed that there is dense dust on the upper and lower surfaces of the leaves of *Rosa saturata*, which provides an additional surface for particulate retention and significantly improves the plant's particulate retention capacity. The surface texture of coniferous plants', such as *Pseudolarix amabilis* and *Pinus massoniana*, leaves is wavy with a deep texture. Oil is often secreted between the texture, and the wax layer is thick, which is conducive to the trapping of more particles on the leaf surface. Compared with the coniferous leaf surface, the leaf texture of broad-leaved tree species such as *Cinnamomum camphora* and *Magnolia magnolia* is irregular, and the leaf surface is relatively smooth, with less oil secretion, which is not conducive to the retention of particles.

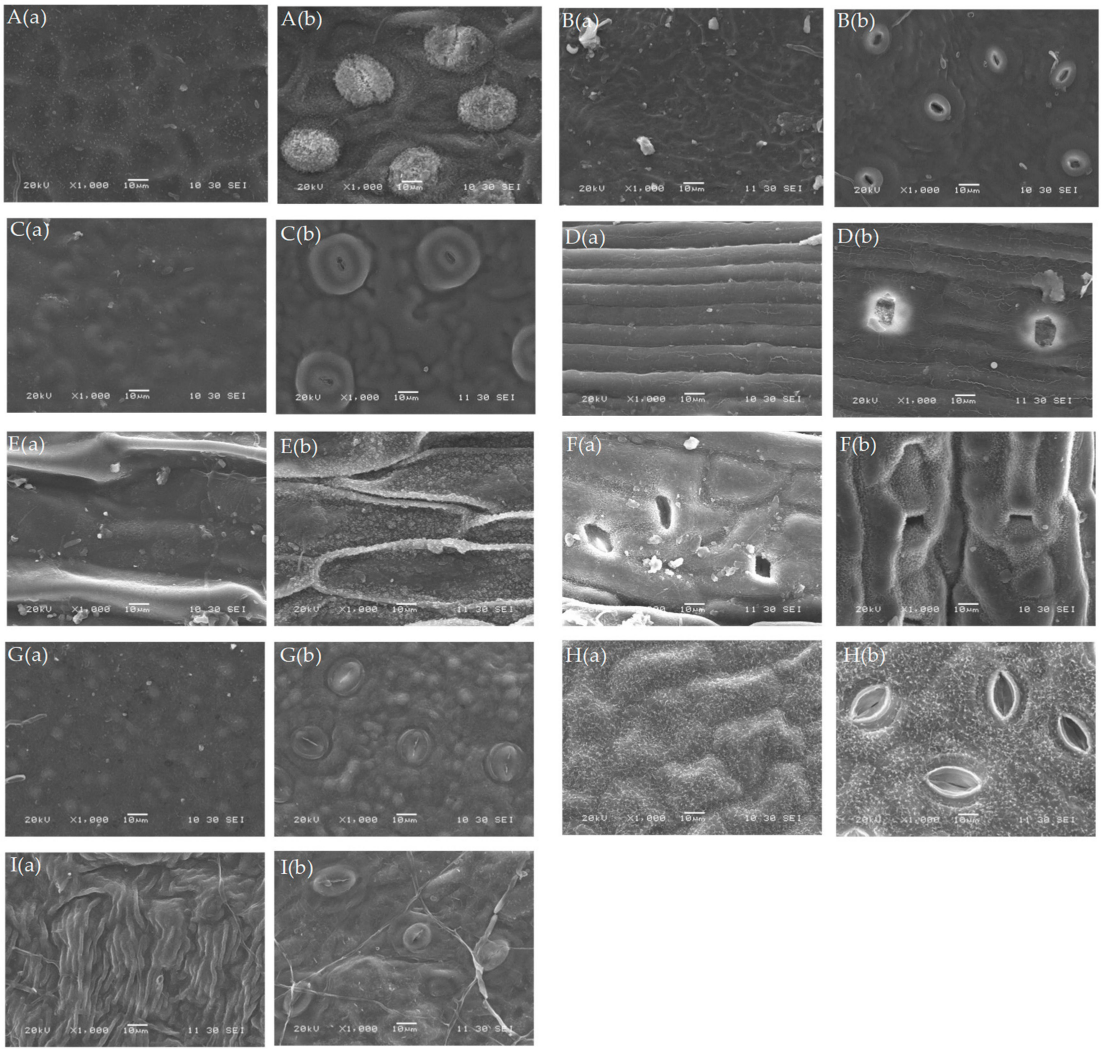

Figure 4. Scanning electron micrographs of the leaf surfaces of nine green plant species (1000× magnification): (**A**) *Cinnamomum camphora*; (**B**) *Osmanthus fragrans*; (**C**) *Magnolia grandiflora*; (**D**) *Pseudolarix amabilis*; (**E**) *Pinus massoniana*; (**F**) *Taxodium distichum*; (**G**) *Photinia serratifolia*; (**H**) *Rosa saturata*; (**I**) *Rhododendron simsii*. (**a**) Upper surface of the leaf and (**b**) lower surfaces of the leaf.

3.4. Relationship between Foliar Microstructure and Dust Retention Ability

Different leaf microstructure characteristics could directly affect the ability of the leaf to adsorb particles. According to the results listed in Table 4 and Figure 5, the short diameter and area of stomata were correlated with the PM retention per unit leaf area. However, this correlation was not significant ($p > 0.05$). Stomatal density was positively correlated with the retention of TSP ($R = 0.87$), PM_{10} ($R = 0.83$), and $PM_{2.5}$ ($R = 0.96$) ($p < 0.01$). Zhang et al. found that the number and density of stomata were significantly positively correlated with the retention of TSP and $PM_{1–3}$ ($p < 0.05$) [32,33], which is consistent with the results of the present study. In addition, leaf stomatal length was significantly inversely associated with the retention of TSP ($R = -0.40$), PM_{10} ($R = -0.43$), and $PM_{2.5}$ ($R = -0.44$). In conclusion, the short diameter and small area of the stomata did not directly affect the retention of particles, while a longer stomatal diameter would make the retention of particles more difficult. The stomatal density was significantly positively correlated with the retention of particles, indicating that stomatal density was one of the main factors for the retention of particles on leaves, which might be related to the respiration of plants through their leaves.

Table 4. The microstructural characteristics of the investigated green plants.

Species	Stomata (μm)		Stomatal Density (mm^{-2})	Stomatal Area (mm^2)
	Stomatal Length	Stomatal Width		
Cinnamomum camphora	26.69 ± 0.82 a	25.69 ± 0.88 c	175.17 ± 6.69 h	25.26 ± 1.38 b
Osmanthus fragrans	12.54 ± 0.90 b	15.66 ± 0.82 d	349.77 ± 7.26 f	6.26 ± 0.72 b
Magnolia grandiflora	29.52 ± 0.66 a	32.26 ± 1.88 b	266.40 ± 10.05 g	30.08 ± 1.93 b
Pseudolarix amabilis	18.98 ± 2.12 b	70.61 ± 4.25 a	707.47 ± 13.02 c	63.22 ± 8.88 a
Pinus massoniana	14.15 ± 0.46 b	18.09 ± 1.02 d	581.33 ± 4.41 d	8.17 ± 0.67 b
Taxodium distichum	4.09 ± 0.22 c	8.11 ± 0.24 e	456.37 ± 11.95 e	1.16 ± 0.08 b
Photinia serratifolia	16.71 ± 0.31 b	19.01 ± 0.64 d	863.63 ± 9.18 b	10.01 ± 0.20 b
Rosa saturata	15.26 ± 0.90 b	26.48 ± 1.42 c	1094.13 ± 12.58 a	13.69 ± 1.13 b
Rhododendron simsii	13.04 ± 1.18 b	19.88 ± 1.89 d	966.87 ± 32.24 b	8.55 ± 1.52 b

Note: Different letters represent significant differences in the same index among different tree species ($p < 0.05$).

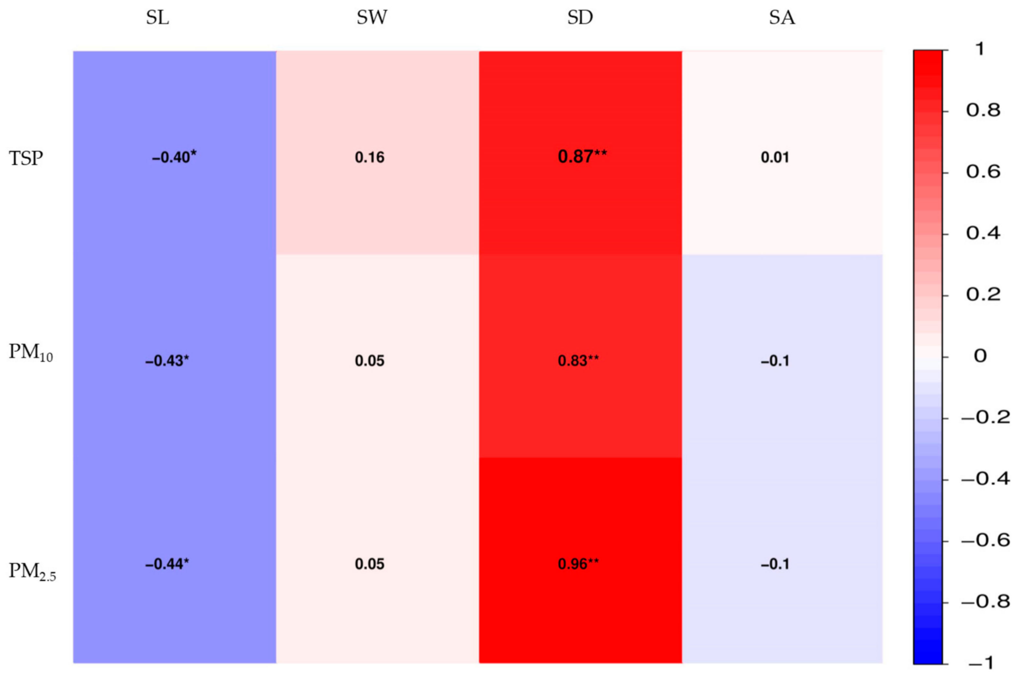

Figure 5. Heat map pertaining to the correlation relationship between the microstructural characteristics of the leaf surface and particle retention. Note: SD: stomatal density; SL: stomatal length; SW: stomatal width; SA: stomatal area. * represents a significant difference at the 0.05 level and ** represents a significant difference at the 0.01 level.

We further used SEM to explore the direct and indirect roles of different variables in the absorption of particulate matter by plant leaves (Figure 6). The SEM results were estimated by using both the maximum likelihood estimation method and the Bayesian estimation method. Specifically, stomatal density was directly related to the retention of $PM_{2.5}$, PM_{10}, and TSP in plant leaves, while the effects of stomatal length and stomatal area on particulate retention were mediated by stomatal density.

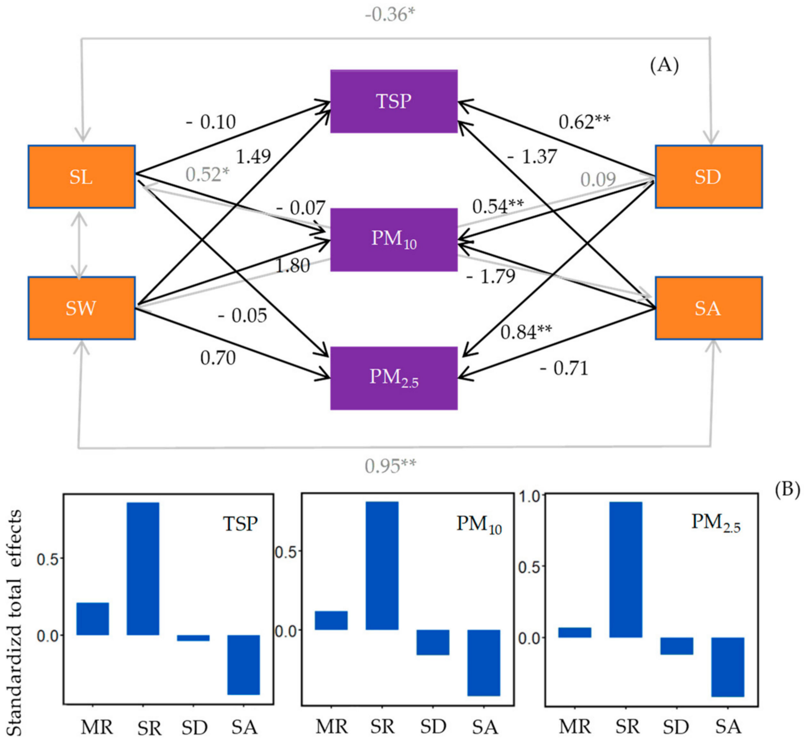

Figure 6. Structural equation modeling (SEM) for the effects of leaf surface microstructure on particle retention. (**A**) The parameters of the designed path in SEM were estimated using the maximum likelihood estimation method. Numbers adjacent to arrows are standardized path coefficients, analogous to relative regression weights and indicative of the effect size of the relationship. The gray arrow shows the correlation between the influencing factors. (**B**) Total standardized effects of each variable on particulate retention from SEM. * represents a significant difference at the 0.05 level and ** represents a significant difference at the 0.01 level.

4. Discussion

4.1. Leaf Surface Microstructure

The observation and analysis of the electron microscopic scanning of the leaves of the nine studied plants showed that the microstructures of the leaves were different. The roughness and microstructures differed between the leaves of different plants, even between the adaxial and abaxial surfaces of the same plant leaves. The ability of plants to retain particulate matter was directly related to the microstructure of the foliage and was the result of a synergistic effect of various factors, such as the folds, grooves, stomata, villus length, and waxy structure on the leaf surface [32]. Generally, the rougher the leaf surfaces, the greater the differences in the depths of folds and grooves, and the greater the number of villi and waxy structures, the more conducive these conditions were to the interception of particles and the improvement of dust retention ability. In contrast, leaves with relatively smooth surfaces, a lower density of stomata, and shallower grooves were less able to absorb dust [19]. Trichomes increase the leaf area by several folds and provide an additional surface for particulate retention [33]. The leaf morphological structures affected the amount of dust trapped on the leaf and the stability of the particles adsorbed on the leaf surface. For example, a leaf surface that has dense ridge grooves can firmly trap a large number of particles [34], while a smooth leaf surface has a lower capacity to accommodate particles and presents weak adhesion. As a result, these particles were also more easily removed by rain or strong winds. For most of the leaves of these nine species, no stomata were observed on the adaxial side. However, they did possess stomata on the abaxial side.

4.2. Particulate Retention Capacity of the Leaf Surface

The accumulation of particulate matter by greening plants is a complex and poorly characterized process, and it is affected by a number of factors such as leaf surface microstructure and macroscopic structure (e.g., stomatal density, leaf wettability, leaf area, and the shape and number of trichomes) [35]. Leaf microstructure, leaf exudates, and environmental pollution are the main factors that affect plant leaf particulate retention capacity. From a plant classification perspective, shrubs were found to retain more PM per unit area, a trend that may be related to shrubs being located lower and closer to the ground than the other types of plants and therefore more likely to adsorb PM from the soil and ground dust. Studies have shown that leaves of small size with high stomatal conductance and large leaf hairs can capture more PM [36,37]. In our study, we found that the increase in stomatal density increased the retention of particles. However, the length of pores was significantly negatively correlated with the retention of particles ($p < 0.05$). The larger the stomatal density, the stronger the transpiration of the leaves, which makes it easier for particles to be distributed, resulting in an increased deposition rate of particles [38].

The results showed that coniferous species such as shrubs and trees accumulated more PM. In research conducted by Nobel, their results showed that compared with large and flat leaves, particles in the air are more likely to collide with small leaves, which have a thicker boundary layer [39]. This also explains, scientifically, the better retention effect for PM shown by shrubs and coniferous trees. In the nine green plants, *Rhododendron simsii* and *Rosa saturata* among shrubs and *Osmanthus fragrans* and *Pseudolarix amabilis* among trees were found to have greater particulate interception capacity. *Rhododendron simsii* and *Rosa saturata* have high horticultural value due to their attractive flower colors. *Osmanthus fragrans* is a high-frequency greening tree species widely planted in the south of the Yellow River. *Pseudolarix amabilis* is a famous ancient remnant plant, which grows fast and has strong resistance to fire hazards. These four species were found to possess a strong ability to adsorb PM, suggesting that they should be planted and utilized in areas affected by severe air pollution.

5. Conclusions

In this study, nine greening tree species were selected to examine their particulate matter retention capacity and its relationship with the leaf surface of the plant structure. The study results showed that there was a significant difference in the ability of different greening tree species to absorb PM; *Rosa saturata* was found to have the best retention effect on TSP and $PM_{2.5}$ and *Rhododendron simsii* was found to have the best retention effect on PM_{10}. The microscopic morphology of the studied plant leaves was closely related to their atmospheric particulate matter retention capacity. The amount of PM retained in the plants' leaves was negatively correlated with stomatal length and significantly positively correlated with stomatal density, indicating that both of these characteristics may be regulatory factors affecting the ability to capture PM at the leaf level. A deep microscopic understanding of the leaves of each greening tree species aids in the selection of dust-suppressing tree species and is of great significance for the selection of appropriate landscaping tree species to control air pollution in cities.

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