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Original Research

Tree Leaf Morphology Shapes Particulate Matter Retention and Wash-off Dynamics under Simulated Rainfall

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Abstract

Urban vegetation mitigates air pollution by capturing particulate matter (PM) on leaf surfaces, yet rainfall can wash away accumulated particles, reducing retention efficiency. This study investigates how leaf morphological traits of ten tree species influence PM accumulation and retention under simulated rainfall. PM was categorized as rain-washable ($_{RW}$PM), surface-bound ($_{S}$PM), and wax-embedded ($_{W}$PM), with the sum of $_{S}$PM and $_{W}$PM defined as rain-indelible PM ($_{RI}$PM), reflecting long-term retention on leaves. Species varied significantly in PM accumulation. *Taxodium distichum, Paulownia tomentosa,* and *Araucaria araucana* showed the highest total PM, while *Platanus* × *acerifolia* and *Indesia polycarpa* showed the lowest. $_{RI}$PM was most abundant in *A. araucana*, *T. plicata*, and *P. tomentosa*. Total PM correlated positively with foliage type (r = 0.57) and negatively with petiole length (r = -0.59). Higher epicuticular wax content improved fine PM retention, emphasizing the role of chemical traits. In contrast, smooth-leaved species retained less PM, likely due to lower surface roughness. These findings highlight how both structural and biochemical leaf characteristics affect PM capture and retention. They offer valuable insight for selecting tree species in urban planning to enhance air pollution mitigation and contribute to healthier urban environments.

Keywords: air pollution mitigation, leaf traits, epicuticular waxes, pollutant retention, urban greenery

Introduction

The rapid expansion of urban populations and increasing vehicular emissions have significantly degraded air quality in cities. Particulate matter (PM) is a critical component of urban air pollution, posing a threat to human health and the environment. It is a

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Table 1. Morphological traits of leaves of the examined plant species.

	Foliage type	Size	Shape	Margin	Petiole	Surface
A. araucana	Needles	small	simple	entire	short	smooth
C. deodara	Needles	small	simple	entire	short	smooth
G. biloba	Leaf	small	compound	entire	long	smooth
I. polycarpa	Leaf	large	simple	entire	short	smooth
L. tulipifera	Leaf	large	simple	entire	long	smooth
P. tomentosa	Leaf	large	simple	entire	long	hairy
P. sachalinense	Leaf	large	compound	entire	long	hairy
P. acerifolia	Leaf	large	compound	serrated	long	hairy
T. distichum	Needles	small	simple	serrated	short	smooth
T. plicata	Needles	small	compound	entire	short	smooth

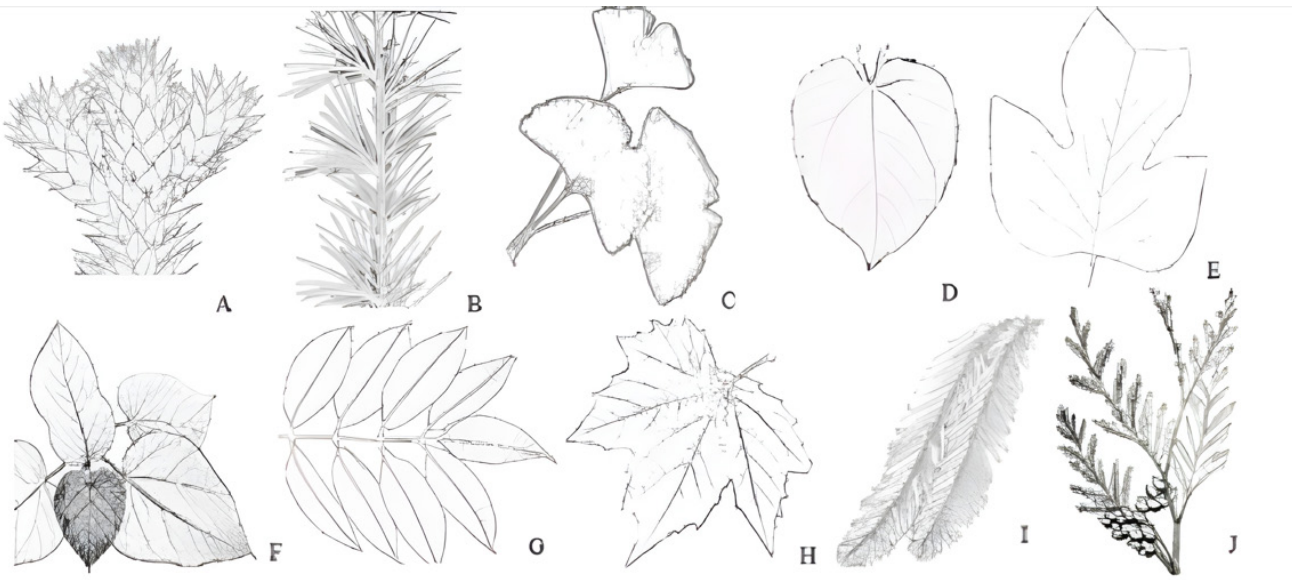

Fig. 1. Leaf shapes of the examined plant species: *A. araucaria*-A; *C. deodara*-B; *G. biloba*-C; *I. polycarpa*-D; *L. tulipifera*-E; *P. tomentosa*-F; *P. sachalinense*-G; *P. acerifolia*-H; *T. distichum*-I; *T. plicata*-J.

heterogeneous mixture of airborne particles, including hazardous substances, such as polycyclic aromatic hydrocarbons (PAHs), trace elements (TEs), furans, sulfur compounds, and asbestos [1]. Due to their small size, PM particles can remain airborne for extended periods and travel long distances [2]. Particulate matter is classified into three fractions based on particle diameter: PM_{10} (≤10 µm), $PM_{2.5}$ (≤2.5 µm), and PM_1 (≤1 µm), with the smallest being the most dangerous as they can enter the respiratory and circulatory systems [1-3].

Unlike soil or water pollution remediation, air purification is particularly challenging due to the dynamic and diffuse nature of atmospheric pollutants [4]. Thus, there is a need for effective, sustainable, and wide-scale air pollution control methods. Urban vegetation (trees, shrubs, and meadows) has emerged as a promising natural solution for mitigating air pollution [5]. Plants act as biological air filters, capturing PM on leaf surfaces through physical deposition [6]. However, the efficiency of PM capture varies widely among species, primarily due to differences in leaf morphology [7]. Leaf traits such as surface texture, wax content, and the presence of trichomes play a pivotal role in determining the effectiveness of PM accumulation [8]. For instance, species with needle-like leaves (*Pinus sylvestris* L., *Pinus mugo* Turra) and with wax-coated surfaces (*Taxus baccata* L., *Taxus* x *media* (Hayne) Chantr.) are particularly efficient at accumulating PM due to their increased surface area and hydrophobic properties [9]. Broad-leaved species with complex or serrated leaf shapes, such as *Stephanandra incisa* (Thunb.) Zabel and *Ligustrum obtusifolium* (Siebold & Zucc.) Franch., were observed to accumulate substantial amounts of PM due to their greater surface area [1, 6].

PM accumulation on foliage is a dynamic process influenced by atmospheric conditions, including wind speed and precipitation intensity. Rainfall, in particular, can remove previously deposited particles from leaf surfaces, affecting their short-term retention. On the other hand, the wash-off restores the leaf's capacity to accumulate new particles, thus sustaining the long-term potential of vegetation in air quality regulation [10]. Larger PM particles are more likely to be washed off during rainfall, while smaller particles tend to adhere more strongly, especially to leaves with high surface roughness or abundant in wax, as these traits are particularly relevant for PM accumulation and retention during rainfalls [11, 12]. Some studies have also shown that rainfall increases the "stickiness" of leaves, temporarily enhancing their ability to accumulate PM immediately after rain [13, 14]. To study these processes in detail, simulated rainfall in experimental settings is commonly used [15].

Despite increasing research on the role of vegetation in PM mitigation, there is still a need for more studies focusing on how various tree species, particularly newly introduced or non-native ones, perform under local environmental conditions [6]. While some studies address the effects of leaf morphological characteristics on PM accumulation and retention during precipitation, our knowledge of this topic is still incomplete, especially in the context of increasingly erratic precipitation associated with climate change [16]. Moreover, urban greenery is changing; cities are planting new species to better cope with climate stressors, yet the PM retention capacity of many of these species remains unexplored. In particular, intense rainfall events (cloudbursts), combined with longer dry periods, may lead to greater PM accumulation on leaf surfaces and increase the risk of re-suspension during wind episodes [17].

Considering the above-mentioned knowledge gaps, this study aims to evaluate the PM accumulation and post-rainfall retention capacities of ten deciduous and coniferous tree species. Rather than assuming a linear relationship between leaf complexity and retention, we explore the nuanced interactions that may arise. For example, while rough surfaces may initially trap more fine particles, they might also promote better PM wash-off due to slower droplet movement [18]. Using artificial rainfall, we examined how specific morphological traits (leaf surface structure, waxiness, trichome presence, etc.) influence PM wash-off dynamics. The findings may contribute to improved species selection for urban green infrastructure, prioritizing plants capable of long-term PM retention under changing climatic conditions.

Materials and Methods

The study was conducted on ten tree species (*Araucaria araucana* (Molina) K.Koch; *Cedrus deodara* (Roxb. ex D.Don) G.Don; *Ginkgo biloba* L.; *Indesia polycarpa* (Blume) Ridl.; *Liriodendron tulipifera* L.; *Paulownia tomentosa* (Thunb.) Steud.; *Phellodendron sachalinense* (F.Schmidt) Schisler; *Platanus × acerifolia* (Aiton) Willd.; *Taxodium distichum* (L.) Rich.; *Thuja plicata* Donn ex D.Don). The species were selected based on diverse leaf morphology (Table 1, Fig. 1), to allow for comparison of PM accumulation and retention by different surface types. Each specimen was purchased from a commercial nursery in the autumn and grown in individual containers in a greenhouse during the winter period. In total, the experiment was conducted in three replicates per species, with each replicate being a separate plant. All trees were cultivated in pots and irrigated by pouring water onto the trays beneath the containers in order to avoid wetting the foliage and accidentally removing the PM accumulated during the experiment. All specimens were grown in a uniform commercial potting substrate composed of a peat-based mixture commonly used in nurseries. This ensured standardized soil conditions across all replicates and allowed the study to focus exclusively on leaf-level processes of PM accumulation and wash-off, independent of soil-specific effects.

In spring, once the trees reached full foliage development, they were placed along a trafficked road for a two-week exposure period to enable traffic-PM deposition. To ensure comparability of results and avoid potential wash-off, the plants were protected from rainfall throughout the exposure period using transparent overhead covers.

Rainfall simulation was performed using distilled water. The pH of the water was modified to approximately 5.6 by adding a dilute sulfuric acid solution (H_2SO_4), replicating the acidity of typical atmospheric rainfall. Two precision bench sprayers (FHU KAMA, Skarżysko-Kamienna, Poland) were used for the spraying. Each sprayer was equipped with a boom fitted with a flat-fan hydraulic Teejet XR 11002 VP nozzle, delivering a uniform medium-droplet spray with droplet sizes ranging from 150 to 250 μm. The flow rate of each sprayer was calibrated before each simulation by collecting and measuring the outflow over 60 s at constant operating pressure (2 bar). The average discharge was 20±0.5 ml per 30 s sequence, ensuring reproducible application across replicates. To verify the uniformity of water distribution, three collecting trays were placed at equal distances under the spray boom during a test run. The coefficient of variation in collected volumes did not exceed 5%. All rainfall simulations were performed in the same closed chamber under stable temperature (22±2°C) and relative humidity (50±5%), ensuring consistent environmental conditions between replicates.

The stabilized plants were placed on stands within a closed chamber directly under the sprayers. Rainfall was applied in repeated 30-second sequences over a total duration of 10 min. The total water volume used per simulation was 200 ml per plant, corresponding to an equivalent rainfall intensity of approximately 20 mm/m^2, which reflected a typical short-duration urban rain event. Plastic containers were positioned 30-50 cm below the plants to collect the runoff water generated during each sequence. The collected runoff was subsequently transferred into sealed bottles for further laboratory analysis.

Additionally, plant material samples (each with an estimated leaf or needle surface area of approximately 300 cm^2) were collected from branches after the simulation to evaluate PM retention both on the leaf surface and within the epicuticular wax layer.

Quantification of PM in Simulated Rain Runoff ($_{RW}$PM)

Particulate matter washed off by simulated rainfall (rain washable PM, $_{RW}$PM) was quantified following a modified protocol based on a previously described method [16]. Runoff water was initially passed through a 100 µm mesh sieve to eliminate non-PM particles. The remaining solution was subsequently filtered through a sequential set of pre-weighed filters to isolate three particle size fractions: PM 0.2-2.5 µm, PM 2.5-10 µm, and PM 10-100 µm. After filtration, filters were dried at 60°C for 30 min, equilibrated for 30 min under controlled conditions, and weighed using an analytical balance (XS105DU, Mettler-Toledo Inc., Switzerland) equipped with a deionization unit (HAUG, Switzerland). All filtrations were conducted using a vacuum-assisted system with 47 mm glass funnels (PALL Corp., USA). The mass of retained PM was calculated as the difference in filter weight before and after filtration.

Quantification of Surface PM ($_S$PM) and In-Wax PM ($_W$PM) Remaining on Leaves after Rainfall

To assess concentrations of PM remaining on the foliage surface and that embedded within epicuticular waxes following rainfall (rain indelible PM - $_{RI}$PM), a two-step sequential extraction procedure was employed. Surface PM ($_S$PM), defined as particles that persisted on the leaf surface after rain exposure but were removable by water, was collected by immersing each subsample in 250 ml of distilled water and agitating for 60 s. The extract was filtered using the same sequence and types of filters described for $_{RW}$PM. Subsequently, the same plant material was rinsed with 150 ml of chloroform under gentle agitation for 45 s to extract wax-embedded PM ($_W$PM). The chloroform solution was then subjected to the identical filtration and weighing protocol as described above.

Wax quantification

For each sample, the amount of epicuticular wax dissolved in chloroform was determined by evaporating the solvent in pre-weighed beakers. This provided a measure of wax content, allowing for the normalization of PM quantities relative to wax concentrations.

Leaf area Measurement and PM Normalization

The leaf surface area of each sample was determined using a Plant Leaf Area Meter (Skye Instruments Ltd., Llandrindod Wells, UK). PM concentrations obtained from both rain-washed runoff and leaf washing, as well as the amount of wax, were normalized to the leaf area, resulting in PM content expressed as µg of PM per cm^2 of leaf surface area.

Statistical Analysis

The data were analyzed using one-factor analysis of variance (ANOVA) with Statgraphics Plus 4.1 (Statpoint Technologies Inc., Warrenton, VA, USA). The normality of data distribution was verified using the Shapiro-Wilk test, while the homogeneity of variances was checked with Bartlett's test. Statistical differences among the means of groups were determined using Tukey's honestly significant difference (HSD) post hoc test, with significance set at $p \leq 0.05$.

In addition, a correlation analysis was performed to assess the relationships between wax content and PM fractions. Pearson's correlation coefficients (r) were calculated, and their statistical significance was evaluated using a t-test ($n = 30$). The corresponding p-values were used to determine whether the observed correlations were statistically significant ($p \leq 0.05$).

Spearman's rank correlation coefficients were calculated to evaluate the relationships between different PM fractions, categories, and selected morphological features of leaves. This non-parametric method was chosen due to its ability to measure the strength and direction of monotonic relationships, making it suitable for analyzing associations that do not follow a normal distribution.

Results and Discussion

Interspecific Differences in PM Accumulation and Retention

This study revealed significant interspecific differences in the amount of PM retained on the leaf surfaces of ten tree species. The ability of different tree species to accumulate and retain total PM ($_{RW}$PM + $_{RI}$PM, where $_{RI}$PM = $_S$PM + $_W$PM) varied substantially. The highest total PM accumulation occurred in *T. distichum* (96.5 µg/cm^2), *P. tomentosa* (95.8 µg/cm^2), and *A. araucana* (94.9 µg/cm^2), while the lowest were observed in *I. polycarpa* (44.1 µg/cm^2) and *P. acerifolia* (42.5 µg/cm^2) (Fig. 2). The $_{RW}$PM fraction peaked in *T. distichum* (39.1 µg/cm^2) and *P. tomentosa* (34.5 µg/cm^2), whereas lowest amounts were found in *I. polycarpa* (15.0 µg/cm^2) and *P. acerifolia* (11.4 µg/cm^2) (Fig. 2). The $_{RI}$PM fraction, which indicates long-term retention, reached its maximum in *A. araucana* (65.1 µg/cm^2), *T. plicata* (62.8 µg/cm^2), and *P. tomentosa* (61.3 µg/cm^2),

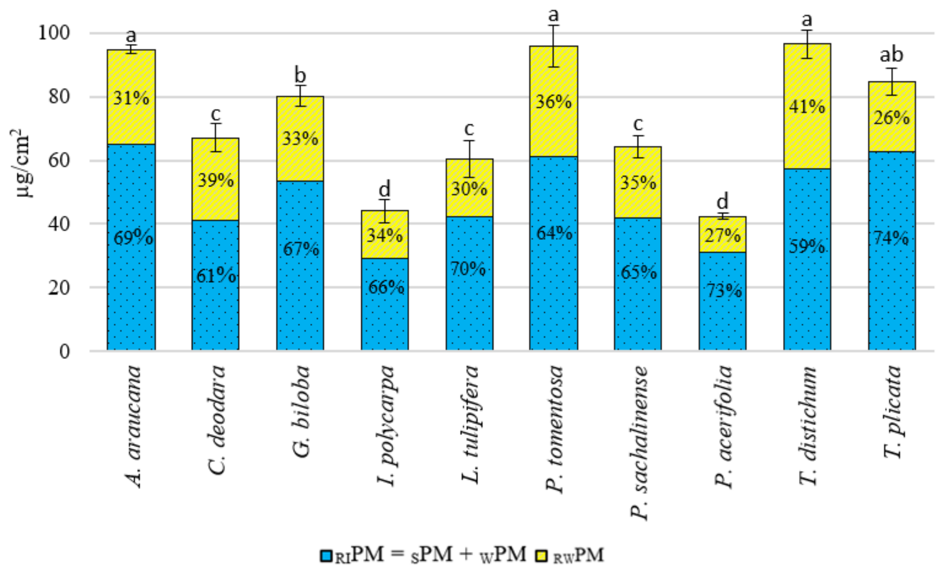

Fig. 2. Total PM accumulation on the leaves of ten tree species, divided into $_{RI}$PM and $_{RW}$PM fractions. Values inside the bars indicate the percentage contribution of each fraction to the total PM load. Different letters above the bars denote significant differences between species ($p<0.05$).

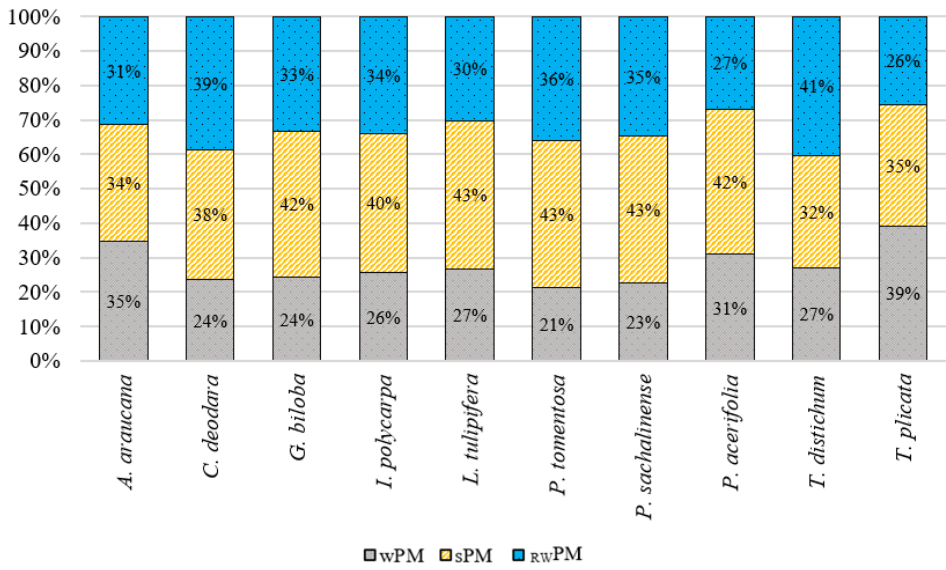

Fig. 3. Shares of PM fractions ($_{W}$PM - in-wax PM, $_{S}$PM - surface PM, $_{RW}$PM - rain washable PM) on the leaves of 10 plant species

while the lowest retention occurred in *P. acerifolia* (31.0 µg/cm^2) and *I. polycarpa* (29.1 µg/cm^2). The persistence of substantial $_{RI}$PM suggests that these species are highly efficient in pollutant retention. This effectiveness is likely attributed to a combination of macroscopic and microscopic leaf traits, including the presence of trichomes, complex venation, high stomatal density, and cuticular waxes [19-21], which collectively enhance the effective surface area and promote airborne particle entrapment. *A. araucana* demonstrated particularly strong $_{RI}$PM retention, likely due to a dense layer of waxes that act as an adhesive matrix – consistent with previous findings [22, 23]. Additionally, structural traits like vertical leaf orientation and rigidity, as seen in *T. distichum,* may reduce PM resuspension during rainfall.

Conversely, *P. acerifolia*, despite its relatively low total PM accumulation (42.5 µg/cm^2) and low share of the $_{RW}$PM fraction (27%), demonstrated a comparatively higher stability of retained PM fractions when considering the proportion of $_{RI}$PM to total PM. This suggests that while overall accumulation is low, a higher fraction of the retained PM may be resistant to wash-off. In the case of *I. polycarpa*, its smooth, hairless leaf surfaces likely promote particle flushing under rainfall [24-26], which could explain its low PM retention. These findings reinforce the idea that physical leaf architecture

Table 2. Proportion of $_{RW}$PM to total PM on leaves.

Species	Percentage of $_{RW}$PM to total PM [%]			
	10-100	2.5-10	0.2-2.5	Total
A. araucana	32.5	29.8	31.8	31.5
C. deodara	38.0	48.2	27.8	38.8
G. biloba	34.8	33.4	27.3	33.2
I. polycarpa	32.8	39.8	27.6	34.1
L. tulipifera	36.5	21.3	31.9	30.2
P. tomentosa	70.0	31.5	38.7	50.7
P. sachalinense	41.6	39.3	26.5	38.4
P. acerifolia	24.0	23.8	17.9	23.2
T. distichum	77.4	28.3	41.3	48.7
T. plicata	42.7	22.3	22.4	31.2
Mean	43.1	31.8	29.3	36.0

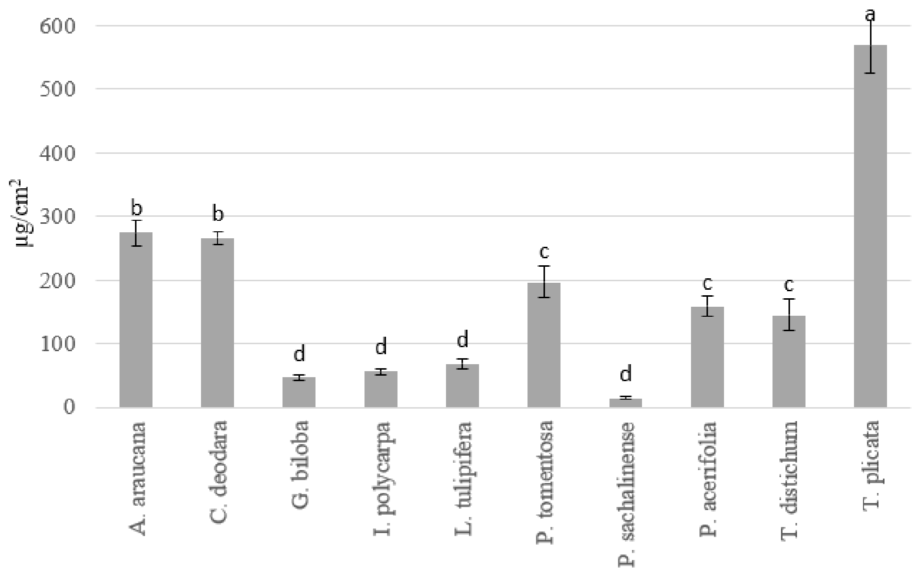

Fig. 4. Concentrations of epicuticular wax on the leaves of 10 plant species.

plays a key role in both the initial accumulation and subsequent retention of PM.

The Role of Epicuticular Waxes and Surface Structure in PM Retention

Interspecies variation was recorded in the distribution of $_{RW}$PM, $_{S}$PM and $_{W}$PM fractions (Fig. 3). Analyzing both $_{S}$PM and $_{W}$PM revealed distinct interspecific patterns of deposition and retention. Species such as *T. plicata* and *A. araucana* had the highest share of $_{W}$PM, which correlated with substantial epicuticular wax content. Quantitative analysis of wax concentrations confirmed these observations: the greatest wax content occurred in *T. plicata* (569.3 μg/cm^2), followed by *A. araucana* (274.1 μg/cm^2) and *C. deodara* (265.9 μg/cm^2) (Fig. 4). Moderate wax levels were recorded for *P. tomentosa* (197.2 μg/cm^2), *P. acerifolia* (158.7 μg/cm^2), and *T. distichum* (145.1 μg/cm^2). The lowest wax content was detected in *P. sachalinense* (14.5 μg/cm^2), which was only 2.5% of the total wax content recorded for *T. plicata*. Other species with relatively low wax production included *G. biloba* (46.6 μg/cm^2), *I. polycarpa* (56.1 μg/cm^2), and *L. tulipifera* (67.9 μg/cm^2).

These waxes form microscale structures (e.g., crystals, rods, and plates) that enhance surface tackiness and serve as adsorption sites for airborne particles [15, 27]. The chemical composition of the waxes – particularly those with higher molecular weight – tends to enhance cohesion and prolong the retention of fine PM particles [28]. These observations are reflected in the correlation data, where foliage type was positively

Table 3. Correlations between leaf traits and PM on leaves and after washing. Bold values indicate statistically significant correlations (p≤0.05).

PM types and fractions	Foliage type	Size	Shape	Margin	Petiole	Surface
$_{RI}$PM 10-100	0.28	-0.52	0.14	0.00	-0.38	0.04
$_{RI}$PM 2.5-10	0.50	0.17	0.00	-0.07	-0.52	-0.34
$_{RI}$PM 0.2-2.5	0.28	-0.35	0.21	0.21	-0.45	0.11
$_{S}$PM	0.14	-0.17	0.21	0.00	-0.38	0.04
$_{W}$PM	0.64	-0.09	0.00	-0.07	-0.66	-0.34
$_{RI}$PM	0.50	-0.17	0.07	-0.07	-0.52	-0.19
$_{RW}$PM 10-100	0.57	0.00	-0.36	-0.43	-0.59	-0.19
$_{RW}$PM 2.5-10	0.57	0.00	-0.50	-0.21	-0.73	-0.34
$_{RW}$PM 0.2-2.5	0.43	-0.09	-0.21	-0.36	-0.52	-0.11
Total $_{RW}$PM	0.43	0.00	-0.28	-0.36	-0.52	-0.11
Total PM	0.57	0.00	-0.21	-0.28	-0.59	-0.19

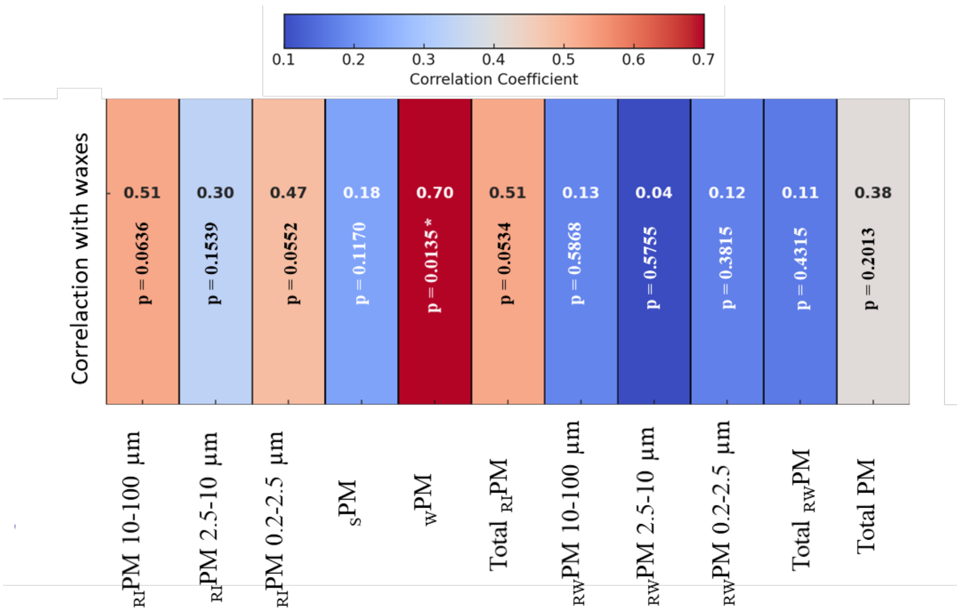

Fig. 5. Correlation between wax content and PM fractions. Statistically significant correlations (*p*≤0.05) are indicated with an asterisk.

associated with $_{W}$PM (r = 0.64) (Table 3), and the wax content itself showed the strongest relationship with the $_{W}$PM fraction (r = 0.70, p<0.001) (Fig. 5).

In contrast, the highest share of the $_{S}$PM fraction was recorded for *L. tulipifera, P. tomentosa,* and *P. sachalinense*. This indicates effective initial interception of particles but comparatively lower resistance to removal by environmental factors such as rainfall. Their relatively rough leaf surfaces promote the mechanical deposition of PM; however, in the absence of a strong chemical adhesion mechanism – such as thick or complex wax structures – these particles are more easily dislodged [24, 25]. This functional separation between accumulation and retention is key for evaluating the suitability of plant species for air pollution mitigation, especially in dynamic urban environments [25, 29, 30].

It is important to note that correlations between leaf surface traits such as smoothness or hairlessness and PM retention were generally weak and statistically non-significant in our dataset. Thus, while previous studies support the role of microstructures and leaf hairs in PM retention, our data suggest these effects may be less pronounced or variable among the studied species in urban environments.

PM Wash-off and the Influence of Particle Size and Leaf Morphology

Wash-off patterns varied notably between species and particle sizes. The mean share of $_{RW}$PM for the individual size fractions (PM 10-100; PM 2.5-10 and PM 0.2-2.5) was 43.1%, 31.8%, and 29.3%, respectively (Table 2). For the $_{RW}$PM 10-100, the highest share of $_{RW}$PM relative to total accumulation was observed in *T. distichum* and *P. tomentosa*, despite these species' strong interception capacities. This highlights a trade-off between high surface complexity and the weak adhesion of larger PM fractions, as observed in previous studies [31, 32]. In contrast, the lowest values for this fraction were recorded in *P. acerifolia*. Conversely, *A. araucana* and *T. plicata* showed low wash-off rates, particularly for $_{RW}$PM 2.5-10 and $_{RW}$PM 0.2-2.5. Their epicuticular wax layers and detailed microstructures offer both physical entrapment and chemical stability, minimizing particle loss during rainfall [29, 30]. Longer petioles were associated with lower amounts of $_{RW}$PM, as indicated by strong negative correlations ($r = -0.73$ for $_{RW}$PM 2.5-10; $r = -0.59$ for $_{RW}$PM 10-100). This suggests that increased petiole length, and thus increased leaf mobility, may facilitate the washing off of PM. Foliage type showed positive correlations with washed PM in fine particles, notably $r = 0.43$ for $_{RW}$PM 0.2-2.5, reinforcing the importance of both wax structure and needle morphology in fine PM stabilization (Table 3).

It should also be noted that wax production is a dynamic process. Environmental factors like temperature, light, and pollution influence both the quantity and structure of waxes throughout the growing season [33]. Such seasonal and environmental variability can impact PM retention efficiency over time, particularly in deciduous species with fluctuating surface traits [34]. The differences between natural and simulated rain in washing off PM mainly stem from the variability of natural rainfall. Simulated rain provides controlled conditions but does not capture the full complexity of natural conditions. In practice, both types of rain have their limitations, and different plants respond to them in various ways [35]. Thus, understanding plant response under simulated rain provides a conservative estimate of their potential in urban environments [36].

Conclusions

This study underscores the critical influence of both structural and biochemical leaf traits on the accumulation and retention of particulate matter (PM) across different size fractions. *T. distichum*, *P. tomentosa*, and *A. araucana* demonstrated high PM capture efficiency, attributable to features such as needle-like architecture (*A. araucana*, *T. distichum*), rigid leaf orientation, and abundant epicuticular waxes (*P. tomentosa*). These traits were strongly associated with elevated levels of both surface-bound and wax-associated PM, as confirmed by consistently positive correlations with total, washable, and ultrafine particle fractions.

Conversely, species with larger, smooth leaves, such as *P. × acerifolia* and *I. polycarpa,* generally exhibited lower PM accumulation. However, their relatively high retention stability under low-stress conditions may be linked to aerodynamic factors such as reduced surface shear and turbulence. This highlights that effective PM retention can result from both active structural adhesion and passive stabilization mechanisms.

The findings emphasize that a comprehensive strategy, integrating multiple morphological traits – such as foliage type, leaf size, and petiole length – alongside chemical attributes like wax content, is necessary when selecting plant species for urban environments. Such an approach is crucial for tailoring urban greening projects to local meteorological patterns. For instance, in regions characterized by frequent, intense rainfall, species demonstrating a high capacity for retaining rain-indelible PM ($_{RI}$PM), like *A. araucana* and *T. plicata,* would be optimal for ensuring long-term air quality benefits. In contrast, in drier climates with lower rainfall frequency and intensity, species with high initial capture efficiency, such as *T. distichum*, may be prioritized, as the risk of PM wash-off is less pronounced. Similarly, the negative correlation between petiole length and PM retention suggests that in windy urban canyons, species with more rigid foliage could offer more stable capture.

However, it is important to acknowledge the limitations of this study when translating these findings into practice. The extrapolation of results from simulated rainfall to natural conditions carries inherent risks, as our controlled methodology does not fully capture the complexity of real-world precipitation. Natural rain events vary in intensity, duration, and droplet size, and are often accompanied by dynamic wind, which can significantly alter PM wash-off and re-suspension dynamics. Therefore, our findings should be considered a robust baseline that provides a conservative estimate of plant performance under controlled conditions.

Future research should focus on validating these findings under diverse field conditions to bridge this gap. Long-term, in situ studies are needed to account for the interplay between fluctuating pollution loads, seasonal phenological variability, and complex meteorological factors, including natural rainfall and wind patterns. Building upon this work will allow for the development of a more comprehensive, trait-based framework, validated under real-world conditions. This will be essential for maximizing the pollution-mitigating potential of urban vegetation and designing resilient, efficient green infrastructure strategies truly adapted to their environment.

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Data Availability

The data presented in this study are openly available on Zenodo.org at 10.5281/zenodo.15527235, reference number 15527235.

Conflict of Interest

The authors declare no conflict of interest.

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