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How Does Leaf Surface Micromorphology of Different Trees Impact Their Ability to Capture Particulate Matter?

Weikang Zhang *, Zhi Zhang, Huan Meng and Tong Zhang

College of Forestry, Shenyang Agriculture University, Shenhe District, Shenyang 110866, China; zhangzhi@syau.edu.cn (Z.Z.); 2016500016@syau.edu.cn (H.M.); tongzhang@syau.edu.cn (T.Z.)

* Correspondence: zhwk1986@syau.edu.cn; Tel.: +86-026-88487150

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Abstract: Particulate matter (PM), including PM_{10} and $PM_{2.5}$, has a major impact on air quality and public health. It has been shown that trees can capture PM and improve air quality. In this study, we used two-way ANOVA to investigate the significance of micro-morphological leaf surface characteristics of green trees in capturing PM at different parks in Beijing. The results show that leaf structure significantly impacts the ability of plants to capture PM. *Pinus tabuliformis* Carr. and *Pinus bungeana* Zucc. were mainly impacted by the density of stomata, waxy cuticle, and epidermis, while the major contributor to PM retention in other test trees, including *Acer truncatum* Bunge, *Salix matsudana* Koid., *Populus tomentosa* Carr. and *Ginkgo biloba* Linn. was leaf roughness. There were significant variations in leaf-droplet contact angle (representative of leaf wettability) and the ability of trees to capture PM ($p < 0.05$): the bigger the contact angle, the less able the plant was to capture particulate matter.

Keywords: leaves; particulate matter; contact angle; leaf structure; roughness

1. Introduction

Rapid industrialization and urbanization have led to serious air pollution challenges in many parts of China. As one of China's largest cities, Beijing has suffered from severe air pollution due to this rapid urbanization and increase in motorized transportation [1,2]. According to statistics from the Beijing Municipal Environmental Monitoring center (BJMEMC), 42 days in 2015 reached severe levels of $PM_{2.5}$ pollutions, accounting for 12% of the whole year. The average concentration during these heavily polluted days was over 280 $\mu g/m^3$ (BJMEMC, 2015). In recent years, particulate matter (PM) has been a major component of air pollution in Beijing [3]. Particulate matter can regulate global, regional [4], and local climates [5,6]. This phenomenon is also linked to a range of health problems, including damage to the respiratory and cardiovascular systems and even premature death [7,8]. Studies have showed that when concentration of PM_{10} (aerodynamic diameter of particles $\leq$ 10 μm) and $PM_{2.5}$ (aerodynamic diameter of particles $\leq$ 2.5) in the air increases to 10 $\mu g/m^3$, the incidence of respiratory damage increases by 1.06% and 1.12% respectively [9].

Urban trees can remove suspended particulate matter from the atmosphere. Urban forests can therefore be considered as a kind of "biotechnology" for improving urban air quality [10–12]. According to data from 2012 and 2013, it is estimated that urban trees could remove 696,000 tons of $PM_{2.5}$, 1,439,000 tons of NO_2 and 907,000 tons of O_3 in the United States, providing a feasible way to improve air quality [13]. The ability of urban trees to reduce the concentration of airborne particulates is achieved through a number of mechanisms. Trees can intercept and accumulate atmospheric particulate matter through their leaves, and this ability depends on different traits such as crown size, tree height, leaf area density, leaf pubescence, and leaf stomata which provide a large surface area on which deposition and absorption can occur [11,14,15]. Trees can also influence particulate matter concentration by changing air humidity, releasing volatile organic compounds, altering wind speed and temperature, and acting as physical barriers to prevent the penetration of pollutants into certain areas [16–19].

Trees are most efficient in capturing atmospheric particulate matter through their foliage [20], which has a special role in reducing the content of fine particles [20–22]. Different tree species have different leaf properties, which results in individual variation in their ability to capture particulate matter. Previous studies have demonstrated that leaf surface characteristics, including leaf shape, shape of waxy cuticles, extent of leaf pubescence, adhesiveness, roughness and leaf surface wettability (water retention) all have a powerful effect on the level of particulate matter absorbed [23–26]. However, these studies did not quantify the correlation between particulate matter accumulation and leaf characteristics. The aim of this study is to (1) investigate the quantitative interrelationship between the amount of PM captured by leaves, roughness, stomata and leaf wettability of six tree species; (2) determine which leaf trait influenced the ability of plants to capture PM.

2. Material and Methods

2.1. Sampling Sites

We collected samples from four sites in Beijing (Table 1): Nanhaizi Park, Beijing Xishan National Forest Park, Beijing Botanical Garden and Songshan Nature Reserve. The four sites are inhabited by many tree species and surrounded by settlements and vehicular traffic on all sides. The main source of pollutants at these sites are anthropogenic and vehicular activities.

Table 1. Description of sample sites.

Sites	Coordinates	Main Source of Pollutants
Nanhaizi Park	116°28′37″ E, 39°46′10″ N	Anthropogenic and vehicular activities, detailed data in [27]
Beijing Xishan National Forest Park	116°12′26″ E, 39°59′01″ N	
Beijing Botanical Garden	116°12′54″ E, 40°00′01″ N	
Songshan Natural Reserve	115°48′48″ E, 40°30′07″ N	

2.2. Sampling

We measured the density of accumulated particulate matter on the leaves of twenty plant species. These species were selected from the study sites because they are common throughout Beijing and have distinct leaf characteristics. Of these twenty, we chose to make detailed measurements of the leaf characteristics of the most common species: *Pinus tabuliformis* Carr., *Pinus bungeana* Zucc., *Acer truncatum* Bunge, *Salix matsudana* Koid., *Populus tomentosa* Carr., and *Ginkgo biloba* Linn. We measured leaf wettability, leaf roughness and surface microstructure. Three replicate samples of each plant species were collected at each site according to the method in [15]. The replicate plants were defined as those individuals with similar physical and environmental characteristics such as height, trunk diameter and water, soil and wind conditions. All trees sampled had been at these sites for at least 3 years and samples were collected after 10 days without rainfall. We collected 100 g of leaves from each tree.

2.3. Density of PM Accumulated by Leaves

The efficiency of particulate matter removal was measured using a wind tunnel experiment. The tunnel was 0.5 m wide, 0.5 m high, and 1.00 m in length (Figure 1). The total length of the wind tunnel occupied by branches was 1 m. The experiment was carried out at a wind speed of 20 m/s. By using 20 m/s wind speed, the potential for each leaf can be determined by dividing the total amount of particulate captured by the number of leaves. The kind of PM utilized for the test is TSP (the total suspended particulate matter), PM_{10} and $PM_{2.5}$.

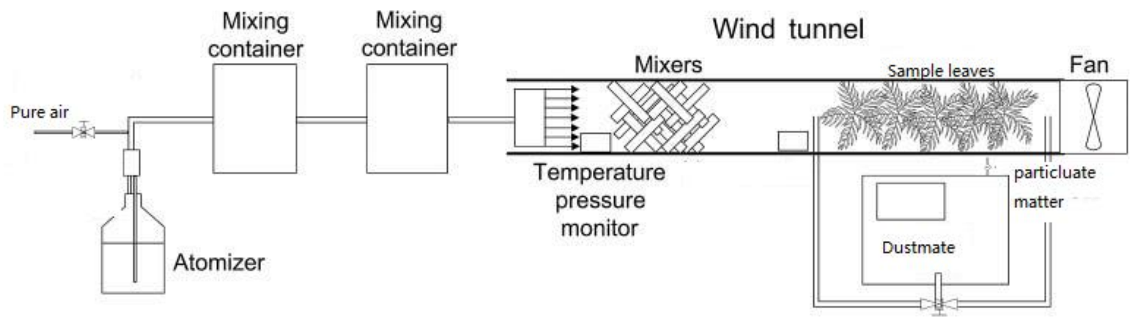

Figure 1. A sketch of the wind tunnel experimental setup.

The tunnel was sampling filtered room air. The room air aerosol number concentration was fairly constant (<1 μg/m^3) and was around 10 m^3. Firstly, sample leaves were placed in the wind tunnel, then the pure air that did not contain the particulate matter was introduced into the wind tunnel through a plenum with several openings. Secondly, a fan carried out at a wind speed of 20 m/s to blow the sample leaves in tunnel. This process continued for about 6–10 min, in order to ensure that all of the particulate matter on the surface of the leaves was suspended in the tunnel air. It has been confirmed that a wind speed of 20 m/s and a duration of 6–10 min can remove >80% particulate matter from leaves [18]. Lastly, the Dustmate (Turnkey, Newcastle, UK) instrument was used to measure the particulate concentration of the tunnel air.

The formula used to calculate the adsorptive amount of the particulate matter per unit of leaf area of different tree species is as follows:

$$Mi = \sum_{1}^{n} \frac{m_{ij}}{S_i} \quad (1)$$

where M represents the mass of the captured particulate matter by leaf area of different tree species (unit: μg/cm^2), i represents different tree species, j represents the types of particulate species, $n = 3$ different replicates, S represents the leaf areas (unit: cm^2), and m_{ij} represents the mass of TSP, PM_{10}, and $PM_{2.5}$ (unit: μg).

2.4. AFM Scanning Features and Microstructure of Leaf Surface

The surface structures of the sample leaves were examined by atomic force microscopy (AFM) and a S-3400 Scanning electron microscope (Hitachi, Tokyo, Japan).

2.5. Leaf Wettability

The standardized contact angle between water droplets and the leaf surface (θ) can be used to represent the wettability of leaves (Table 2). Firstly, 7.5 μL distilled water was dropped on to the adaxial surface of the fresh leaf samples. Next, images of the droplet were taken with a digital camera (Canon Eos 5D DS, Canon, Tokyo, Japan) fitted with a macro lens (Sony micro 105 mm F2.8EX DG, Sony Corporation, Tokyo, Japan). The left and right contact angles of the droplet were measured manually using a goniometer (JC2000C1, Zhongchen Science & Technoloy Co. Ltd., Shanghai, China) at room temperature. The above process was completed within one hour of sample collection.

Table 2. The relationship between droplet contact angle and leaf wettability.

Contact Angle	Leaf Wettability
$\theta \leq 40°$	super-hydrophilic
$40° < \theta \leq 90°$	Wettable
$110° < \theta \leq 150°$	non-wettable
$150° < \theta$	highly non-wettable

2.6. Statistical Analysis

SPSS 18.0 software was used for statistical analysis (SPSS software Co., New York, NY, USA). We conducted a two-way analysis of variance (ANOVA) to determine whether there were significant differences in leaf PM accumulation and surface roughness between different species and at different sampling times. We assumed significance at $p < 0.05$. The relationship of leaf PM retention amount and leaf roughness was tested using Pearson's correlation analysis.

3. Results

3.1. Densities of Particles Deposited on Leaf Surfaces of Twenty Plant Species

Table 3 shows that the average particulate matter density value settling upon leaf surfaces varies with the plant species at the sampling sites. All twenty species captured some particulate matter on their leaves, but the amount of PM varied significantly between species. *C. deodara*, *J. procumbens*, *P. orientalis*, *P. tabuliformis*, captured larger densities of particulate matter on the leaf surface compared with other species (8.71 ± 0.49 μg/cm^2, 7.38 ± 0.19 μg/cm^2, 5.68 ± 0.22 μg/cm^2, and 4.31 ± 0.44 μg/cm^2 respectively). *G. biloba*, *K. paniculata*, *Q. mongolica*, *R. pseudoacacia*, and *P. tomentosa* captured the smallest densities of particulate matter (1.47 ± 0.09 μg/cm^2, 1.38 ± 0.42 μg/cm^2, 1.21 ± 0.04 μg/cm^2, 1.16 ± 0.13 μg/cm^2 and 0.97 ± 0.21 μg/cm^2 respectively).

Table 3. Particle density per unit area on leaves of twenty tree species/(μg/cm^2) (Standard ± error). * [28].

Plant Species	TSP	PM_{10}	PM_{10}/TSP	$PM_{2.5}$	$PM_{2.5}/PM_{10}$
Cedrus deodara G.Don	8.71 ± 0.49	7.10 ± 0.24	81.52%	1.49 ± 0.07	20.99%
Juniperus procumbens Sieb.	7.38 ± 0.19	5.05 ± 0.23	68.43%	1.06 ± 0.03	20.99%
Platycladus orientalis Fran.	5.68 ± 0.22	4.65 ± 0.11	81.87%	1.23 ± 0.02	26.45%
Pinus tabuliformis Carr.	4.31 ± 0.44	2.85 ± 0.14	66.13%	1.48 ± 0.09	51.93%
Juniperus chinensis Linn	4.29 ± 0.12	2.52 ± 0.16	58.74%	1.52 ± 0.02	60.32%
Syringa reticulata Subsp.	3.94 ± 0.34	3.52 ± 0.21	89.34%	1.32 ± 0.11	37.50%
Lonicera maackii Maxi	3.88 ± 0.18	2.73 ± 0.08	70.36%	1.24 ± 0.01	45.42%
Amygdalus davidiana Carr	3.43 ± 0.30	3.18 ± 0.25	92.71%	1.05 ± 0.09	33.02%
Pinus bungeana Zucc.	3.43 ± 0.14	2..07 ± 0.17	60.35%	1.05 ± 0.01	50.72%
Armeniaca sibirica Lama.	3.16 ± 0.28	2.82 ± 0.07	89.24%	0.96 ± 0.06	34.04%
Carya cathayensis Sarg.	2.5 ± 0.11	1.63 ± 0.08	65.20%	0.76 ± 0.12	46.63%
Salix matsudana Koid.	2.36 ± 0.26	1.9 ± 0.19	80.51%	1.02 ± 0.06	53.68%
Buxus megistophylla Levl.	1.95 ± 0.12	1.81 ± 0.11	92.82%	0.45 ± 0.05	24.86%
Magnlia denudata Desr.	1.76 ± 0.22	1.25 ± 0.30	71.02%	0.41 ± 0.07	32.80%
Acer pictum Subsp.	1.61 ± 0.17	1.41 ± 0.12	87.58%	0.89 ± 0.01	63.12%
Ginkgo biloba Linn.	1.47 ± 0.09	1.30 ± 0.10	88.44%	0.32 ± 0.04	24.62%
Koelreuteria paniculata Laxm.	1.38 ± 0.42	1.00 ± 0.15	72.46%	0.30 ± 0.04	30.00%
Quercus mongolica Fisc.	1.21 ± 0.04	0.80 ± 0.02	66.12%	0.51 ± 0.03	63.75%
Robinia pseudoacacia Linn.	1.16 ± 0.13	0.79 ± 0.09	68.10%	0.32 ± 0.02	40.51%
Populus tomentosa Carr.	0.97 ± 0.21	0.71 ± 0.13	73.20%	0.12 ± 0.05	16.90%

* TSP: the total suspended particulate matter. PM_{10}: aerodynamic diameter of particles ≤ 10 μm. $PM_{2.5}$: aerodynamic diameter of particles ≤ 2.5 μm.

3.2. Leaf Surface Micromorphology

Some surface structures of the six most common species (*P. tabuliformis*, *P. bungeana*. *G. biloba*, *P. tomentosa*, *A. truncatum*, *S. matsudana*) are shown in Table 4. The micromorphology of *P. tabuliformis*, is roughly characterized by its epidermal cells lining, with crumpled epidermal cells and crystalline cell boundaries. The wax is in the form of granules, the stomata are circular and smaller in size, and their periodicity was high. The stomata are protected with waxy rings and cuticular arches. The species exhibited wavy cuticle surface structures. The micromorphology of *P. bungeana* is similar to that of *P. tabuliformis*. These properties play a key role in making the plants resistant to particulate matter pollution. The leaf veins can be clearly seen from the micrographs of the adaxial leaf epidermis of *G. biloba*, *P. tomentosa*, *A. truncatum*, and *S. matsudana*. The epidermal cells of *G. biloba* on the proximal leaf surface are distinctly extended with the convex periclinal wall. The whole leaf is homogeneously covered with a dense wax tubule. The epicuticular waxes generally show only minor changes until late summer or autumn. The leaves of *P. tomentosa* show little epicuticular wax. Stomata character is mostly irregular and protected with a cell wall. Cuticle surface is rugose or wrinkled. The epidermal cells on the adaxial leaf surface of *A. truncatum* are isodiametrically distributed with a slightly convex periclinal cell wall. Hairs are only found on the leaf surface of *S. matsudana*.

Table 4. Leaves microcosmic structure of different tree species.

Plant Species	Leaf Characters			
	Epicuticular Wax	**Cuticle**	**Epidermis**	**Stomata**
Pinus tabuliformis	Visible	closely packed and Wavy	Dust laden	Circular, High frequency and dust filled
Pinus bungeana	Visible	Wavy and irregularity	Dust laden	Oval, frequency and dust filled
Salix matsudana	shallow	Smooth and sparse	Obvious fluctuation and hairs	Big and Less stomata
Acer truncatum	Inconspicuous	Disorganized	Wall and groove	Radially and parallel
Ginkgo biloba	Sparse	Smooth, some papillae	No hairs	Small and Globosely
Populus tomentosa	inconspicuous	Rugose and clear	No hairs and groove	Small and radially

3.3. Effects of Leaf Surface Roughness and Wettability on PM Retention

Change in Tables 5 and 6 shows the droplet contact angle and roughness of the six common plant species. There was clear differencesbetween the droplet contact angle and roughness between different species. During the growing season, the leaves of *P. tabuliformis* and *P. bungeana* had lower contact angles and roughness than the other four plant species, and their leaves were classified as highly wettable. The average roughness of the front and back sides of the leaves, in descending order, are as follows: *S. matsudana* (276.52 ± 30.82 nm) > *A. truncatum* (133.05 ± 23.05 nm) > *G. biloba* (129.17 ± 35.90 nm) > *P. tomentosa* (72.65 ± 7.98 nm). Two-way ANOVA found that differences between roughness and the amount of particulate captured in *Pinus tabuliformis* and *Pinus bungeana* were not significant. However, differences between roughness and *Salix matsudana*, *Ginkgo biloba*, *Acer truncatum*, and *Populus tomentosa* were significant ($p < 0.05$).

This sequence is similar to that of the contact angle in the six plant species (Table 5). However, the trend in particulate matter density on leaf surfaces is different from that of both contact angle and roughness. The amount of particulate matter captured by the six species was correlated with both leaf contact angles and leaf roughness (Tables 5 and 6). The droplet contact angle was negatively correlated with total particulate matter density in the six investigated species.

Table 5. Roughness and particulate matter captured by leaves in different trees.

Species	Contact Angle	Standard Error	Roughness	Standard Error	Total Particles	Standard Error
Pinus tabuliformis	62.33	6.21	54.81	3.19	8.64	0.22
Pinus bungeana	53.15	7.93	51.87	1.81	6.55	0.25
Salix matsudana	86.93	8.76	276.52	30.82	5.28	0.31
Acer pictum	76.12	8.70	133.05	23.05	3.91	0.18
Ginkgo biloba	99.64	11.01	129.17	35.90	3.09	0.13
Populus tomentosa	79.10	9.93	72.65	7.98	1.80	0.15

Table 6. Statistics related to correlation between roughness and particulate matter captured by leaves in different trees. *r* refers to correlation coefficient. Statistical significance (* $p < 0.05$) is based on the *t*-test *. [15].

Species	Roughness	Std. Error	Total Particles	Std. Error	*r*	Significance
Pinus tabuliformis	54.81	3.19	8.64	0.22	0.42	*
Pinus bungeana	51.87	1.81	6.55	0.25	0.41	*
Salix matsudana	276.52	30.82	5.28	0.31	0.93	*
Acer truncatum	133.05	23.05	3.91	0.18	0.85	*
Ginkgo biloba	129.17	35.90	3.09	0.33	0.87	*
Populus tomentosa	72.65	7.98	1.80	0.15	0.82	*

* Roughness—nm, Total particles = TSP—μg/cm^2.

4. Discussion

To statistical analysis, particle size, the proportions of PM_{10}/TSP (the total suspended particulate matter, TSP) and $PM_{2.5}$/PM_{10} is 58.74%–92.82% and 16.90%–63.75%. The maximum diameter of particulate matter can be up to 25 μm. The percentage of total particulate matter on the leaf surface consisting of PM_{10} was 55%–65%, more effectively captured by plants than $PM_{2.5}$ (Table 3). This is mainly because the small diameter of $PM_{2.5}$ makes itself difficult to settle on the leaf surface, so that $PM_{2.5}$ captured by leaf surfaces is easily suspended.

Leaf characteristics had a strong effect on the density of PM on the leaf surface. The amount of particulate matter captured by the six species was significantly correlated with both leaf contact angles and leaf roughness (Figures 2 and 3). The droplet contact angle was negatively correlated with total particulate matter density in the six investigated species, which means the wettability of leaves has an important effect on the ability of leaves to capture PM. The wettability of leaves mainly depends on the chemical nature of theirs surface, for example, the leaf surface of hydrophobic plants contains lipids [23,29,30]. On a smooth leaf surface, contact angles may reach > 90°, such as in *G. biloba* and *P. tomentosa*. On such surfaces, the hydrophobic properties of epicuticular wax greatly reduces the contact area between the particles and the leaf surface. Therefore, the physical adhesion forces between particulate matter and the leaf surface are lower [12]. These characteristics could lead to the lowest amount of particles settling upon *G. biloba* and *P. tomentosa* leaf surfaces. In contrast to smooth surfaces, rough hydrophobic surfaces have considerably lower contact angles because air is enclosed between the surface structures. Plants with an uneven surface microstructure, a large stomata density and fluffy groove structure, such as *P. tabuliformis*, *P. bungeana and S. matsudana*, therefore have a greater ability to capture PM.

P. tabuliformis, *P. bungeana* are coniferous trees, and their PM capture capacity was less influenced by leaf roughness ($r = 0.42, 0.41$) than in broadleaf trees. The capture ability of broadleaf leaves was strongly affected by the leaves' roughness in different seasons. However, the change in $PM_{2.5}$ capturing capacity of leaves in both conifer and broadleaf species was significantly affected by structural characteristics, such as the leaf stomata, epicuticular wax, cuticle, epidermis, and other leaf surface features. The density of the ridges, grooves and micro-configurations of epidermal cells, such as cell peaks, valleys, and recesses, determine the roughness of the leaf surface [31]. According to the research, the micro-roughness of the leaf surfaces closely correlates with the density of particulate matter depositing on blade surfaces in all experimental species other than *P. tabuliformis* and *P. bungeana*.

As shown in Table 6, the surface roughness of broadleaf species is greater than that of conifer species. However, the dust-retention ability of conifer leaf is higher than that of broadleaf [32]. Therefore, the particle capture ability of conifers is mainly affected by epidermal wax, stoma and cuticle. The surface roughness of broadleaf species is directly proportional to the trapping ability of the leaves; this surface roughness and other morphological features significantly contribute to the capture ability of the leaves.

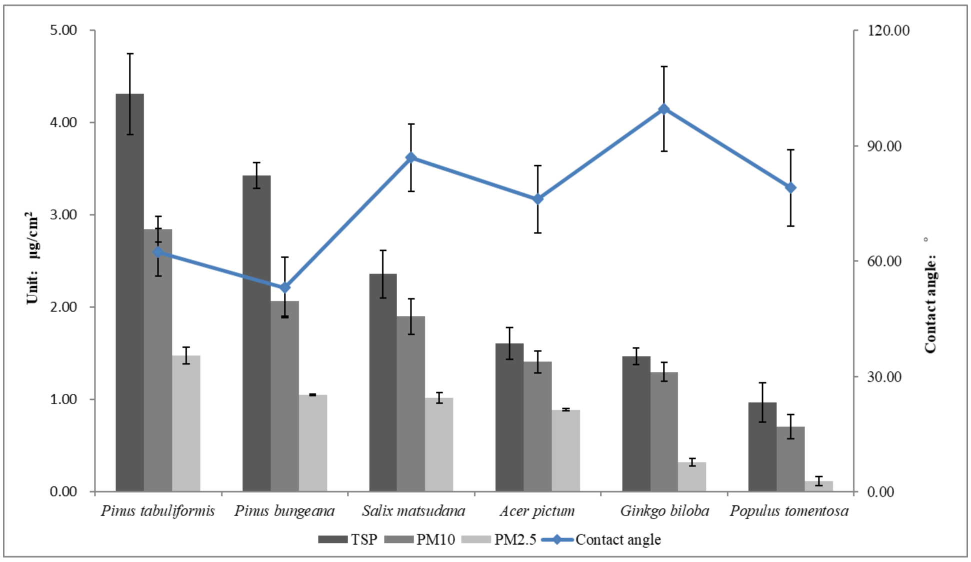

Figure 2. Relationship between the capture ability and contact angle of leaves of different species. Mean values was reported ± standard error; n = 3.

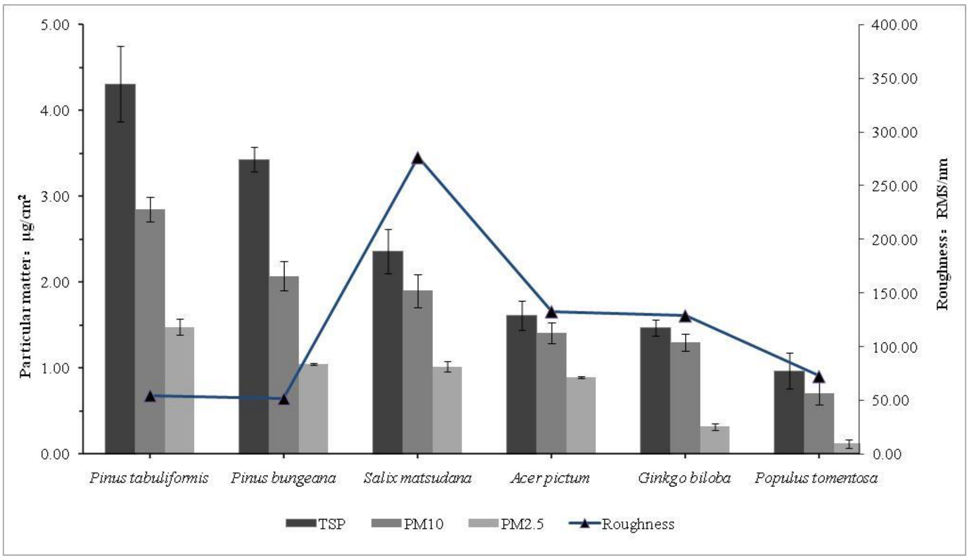

Figure 3. Relationship between the capture capability and roughness of different kinds of leaves. Mean values was reported ± standard error; n = 3.

Particulate matter retention in leaves is not only influenced by leaf characteristics, but also by external conditions. These factors include the density of leaf area index (LAI), rainfall, wind temperature and speed. Some studies have demonstrated that the number of particulate matter deposited on leaf surfaces is influenced by local rainfall, whereby the particulate can be washed away from the leaf surface. The amount of rainfall that has a significant impact on this process remains uncertain [33,34]. The density of leaf area index and tree cover is another important factor, the grain trapping ability was positively correlated with the total leaf area of each tree [35]. In order to measure amount of particulate matter removal by urban forests, the modeling of PM retention should be considered., for example Nowak et al. (2013) have applied i-tree model to estimate and study the amount of $PM_{2.5}$ removed by trees in ten 64 cities of the United States. The model concluded that the total amount of air particulate matter removed by trees varied 65 from 4.7 to 64.5 tons each year.

It is also important to consider the potential impacts of particulate matter retention on plant health. When the density of particulate matter on the leaf surface reaches a certain level, it can affect transpiration, respiration, photosynthesis, and plant growth [36,37]. At the same time, in the future, more research is needed to explore and discuss these factors.

5. Conclusions

In this study, there were significant differences between the ability of different plant species to accumulate PM. We examined the relationship between particulate matter and leaf surface characteristics, and found that the leaf surface effected the plant's ability to capture particles. The degree of particulate matter retention and resuspension varied according to the plant species, underlining the importance of (1) leaf characteristics and surface microstructure, and (2) chemical composition and structure of cuticle layer (i.e., variability in the quantities of individual wax constituents responsible for cuticle hydrophobicity, cuticle thickness, morphology and alternation of the structure with age). The amount of PM retained by leaves was negatively correlated with droplet contact angles on the leaf surface, suggesting that leaf surface properties, especially the leaf wettability, may be one of the regulatory factors affecting PM capture ability at the leaf level.

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