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# Composition and size of retained aerosol particles on urban plants: Insights into related factors and potential impacts

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## HIGHLIGHTS

- Fine particles were the predominant components of retained particles with diverse types and sources.
- *E. japonicus* and *P. fraseri* were more efficient in particle accumulation than the other studied species.
- The leaf traits (e.g., large stomatal area, low stomatal density, small specific leaf area and high epicuticular wax content) contributed to particle deposition.
- This study gives insights into the relationship between leaf traits and particle accumulation, and provides a reference for the optimal selection of dust-retaining plants to alleviate aerosol pollutions.

## GRAPHICAL ABSTRACT


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## ABSTRACT

The role of plants in alleviating aerosol pollution has drawn extensive attention. Most studies focus on compositions of aerosol particles on urban plants, while the leaf traits related to particle retention have not yet been intensively studied. This study selected five typical urban plants (*Loropetalum chinense*, *Rhododendron simsii*, *Euonymus japonicus*, *Photinia × fraseri*, *Osmanthus fragrans*), and employed scanning electron microscope (SEM) and ion chromatography, aiming to investigate the accumulation features of aerosol particles and the relationships between leaf traits and particle retention. Results show that aerosol particles were mainly retained on the adaxial leaf surface, the fine particles ($\Phi \leq 2.5$ μm) were the predominant components (77.8 % by number) on the leaves, and the dominant water-soluble ions of particles were $Ca^{2+}$, $SO_4^{2-}$, and $NO_3^-$. By comparison, *E. japonicus* and *P. fraseri* were efficient in the retention of fine and coarse particles ($2.5 < \Phi \leq 10$ μm), but *L. chinense* was capable to retain more large particles ($\Phi > 10$ μm). The correlation analysis indicates that leaf traits are closely related to the accumulation of aerosol particles. The result shows that plant leaves with larger stomatal area, lower stomatal density, smaller specific leaf area and higher in epicuticular wax content can retain more aerosol particles. This result indicates that the leaves are capable of retaining aerosol particles via the synergy of multiple leaf traits, such as higher wax content and the fewer but larger stomata on their leaf surfaces. This study is helpful to understand the interactions between leaf traits and particle retention, and it further contributes to the selection of potential dust-retaining plants, which is of great significance for the alleviation of urban air pollution.

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## 1. Introduction

Haze pollutions with high concentration of fine particulate matter (PM) has a significant impact on human health, the climate, and ecosystem (Colonna et al., 2022; Jaafar and Loh, 2014; Wang et al., 2018). PM pollution has been becoming one of the most serious environmental problems, and therefore it has drawn extensive attention around the world (Kang et al., 2018; Yue et al., 2019). PM is suspended from a few seconds to several days in the ambient air, which contains heavy metals, polycyclic aromatic hydrocarbons, viruses, and bacteria (Li and Shao, 2009; Sun et al., 2018; Zhang et al., 2021a). Since plants are constantly exposed to air, their vast leaf areas serve as a principal sink for PM pollutants (Rai, 2016), and PM has adverse effects to vegetation.

Recent studies have shown that PM accumulates on the foliar surface through dry or wet deposition, which affects the stomatal conductance and decreases the rate of photosynthesis (Li et al., 2019; Yu et al., 2018). Additionally, PM depositing on leaves causes degradation of epicuticular wax, induces changes in leaf wettability, and inhibits plant transpiration (Neves et al., 2009; Rai, 2016), once particles can be retained on the leaf surface and are absorbed via the leaf stomata (Han et al., 2020). In another aspect, plants could be used to alleviate PM pollution through retaining aerosol particles (Zhang et al., 2020a). Fares et al. (2020) estimated that urban tree species could remove 8 and 8.4 kg $ha^{-1}$ $yr^{-1}$ of $PM_{10}$ in two urban parks in Italy; Nowak et al. (2014) reported that the total amount of $PM_{2.5}$ removal by urban trees in the conterminous United States was 27,000 tons in 2010; Tallis et al. (2011) concluded that the urban tree canopy of the Greater London Authority was estimated to remove between 852 and 2121 tons of $PM_{10}$ annually. Lots of studies show that green plants are effective in alleviating the PM pollution in urban air.

Plant leaves are the main organs that retain PM (Xu et al., 2019b). However, the PM retention on the leaf surface is a dynamic result between PM capture and resuspension (Xie et al., 2018; Zhang and Ma, 2021), and the leaf traits directly affect the relative PM retention area and the PM adsorption efficiency (Li et al., 2021). Some studies found that the trichome density (Zhang et al., 2021b), grooves and folds of leaf surface (Weerakkody et al., 2018b), stomatal density (Marien et al., 2019) and aperture (Xu et al., 2019a) can increase the relative PM deposition area of plant leaves. Moreover, the leaf with a complex shape also exhibits a great potential to retain PM. Zhang et al. (2021b) found that the higher form coefficient and lower width-to-length ratio enhanced $PM_{2.5}$ deposition capacity. Moreover, when particles deposit on the leaves, the waxiness on the foliar surface can affect the amount of retained PM by wrapping particles and reducing particle resuspension (Zhang et al., 2020a). Xu et al. (2019a) revealed that the higher wax content was aligned with the higher PM adsorption by leaf.

Therefore, the PM retaining efficiency on the leaf surface is associated with the plant traits (Shao et al., 2019). Moreover, plant species is an important factor influencing the particle retention capacity. For example, PM deposition flux (Xu et al., 2018) and dry deposition velocity on conifer species are greater than those on broadleaved trees (Beckett et al., 2000; Zhang et al., 2020b). There are significant differences in the particle retention capacity of arbors, shrubs, and herbs (Shao et al., 2019). Therefore, the differences between the mass and amount of particles retained by different plant species have received considerable attention in the previous studies (He et al., 2020; Li et al., 2021; Weerakkody et al., 2018b). However, rare studies focus on chemical composition and distribution of PM on the leaf surfaces in microscopic scale, which is important and direct evidence to show how leaf surfaces retain various particles of different sizes.

To more accurately evaluate the amounts and types of PM retained on the leaf surface, the scanning electron microscopy (SEM) technique is an effective method to characterize aerosol particles on in-situ leaf surface (Konczak et al., 2021; Pace et al., 2021). Compared with traditional particle filtration, SEM is not only used to count particles number, but also used to determine the particle size and PM distribution on the leaf surfaces. Moreover, energy dispersive X-ray spectroscopy (EDS) coupled with SEM can analyze elemental composition of PM and is capable to analyze the PM sources (Konczak et al., 2021; Sgrigna et al., 2020).

To provide a better understanding of the relationship among leaf traits, the compositions and particle-size distributions of PM on the leaf surfaces, In this study, four shrubs (*Loropetalum chinense*, *Rhododendron simsii*, *Euonymus japonicus*, *Photinia* × *fraseri*) and one arbor (*Osmanthus fragrans*) were selected as the studied species, which are typical garden plants in urban cities of eastern China. SEM was used to observe the microstructures of leaf surfaces of plant species, as well as amounts and distributions of PM on the leaf surfaces. This study is helpful to understand the interactions between leaf traits and particle retention, to provide a comparison on the PM retention capacities of the five species, and to give insight into the selection of potential dust-retaining plants. These results are of great significance to understand the abatement of urban air pollution through the urban plants.

## 2. Materials and methods

### 2.1. Sampling site and plant selection

The sampling site is located in Zijingang Campus of Zhejiang University, Hangzhou city, China (30°18′16″N, 120°5′48″E). As typical urban area surrounded by the main roads (Fig. 1), there is not any industry but a few construction sites around the campus. Based on plant life form and leaf texture, five typical garden plants were selected in this study (Table 1), including three evergreen shrubs, one deciduous shrub, and one evergreen broadleaved tree (Table 1). Table 1 displays the details of each plant and their leaf characteristics.

### 2.2. Sample collection

The leaf samples were collected on April 5, 2021, after it was successive sunny for four days. As the sampling control, four healthy leaves without pests or diseases were selected from each tree, with five replications. In total, 20 leaves of each species were collected. The leaves were randomly sampled from a height of 0.5–1 m for the shrubs and 1.5–2 m for the trees in four directions. The leaf samples were placed in labelled petri dishes and transported into the laboratory, and then they were dried at room temperature for three days. The 10 leaves of each species were prepared for the scanning electron microscope (SEM) analyses, and the rest 10 leaves were used for the analyses of leaf traits.

### 2.3. Measurements on composition characteristics of retained particles

The leaf samples were placed in an oven at 60 °C for 24 h until they were completely dried. Six fragments (5 mm × 5 mm) were cut from the dried leaves each, three of them were randomly selected for observations on the adaxial and abaxial surfaces, respectively. Moreover, these fragments were stuck on the sample chamber of SEM with conductive adhesive, and the surfaces of leaf samples were gold-sprayed by an ion sputter coater KYKY SCB-12 for 40 s.

Particle morphology on the surfaces of leaves was observed through the SEM (Phenom XL, Phenom-World, The Netherlands), and elemental compositions of the major particle types were obtained by an energy-dispersion X-ray spectrometer (EDS). Here, thirty-six images for each species were acquired with a magnification of ×500, ×2000, respectively. Moreover, SEM images were manually processed by the RADIUS 2.0 software (EMSIS GmbH, Germany) to determine size distributions and number densities of particles on leaf surfaces, and element compositions were obtained from EDS, as reported by Baldacchini et al. (2017), the particle mass per unit leaf area (μg/$cm^2$) was estimated.

### 2.4. Measurements of water-soluble ions

Previous studies mostly adopted the filtrate-weigh method to quantify particle deposition on leaves (Konczak et al., 2021; Shao et al., 2019), which tended to ignore the mass of water-soluble ions, resulting in the underestimation of PM retention ability of plant species (Xu et al., 2018). In this study, the mass of water-soluble ions was conducted based on the

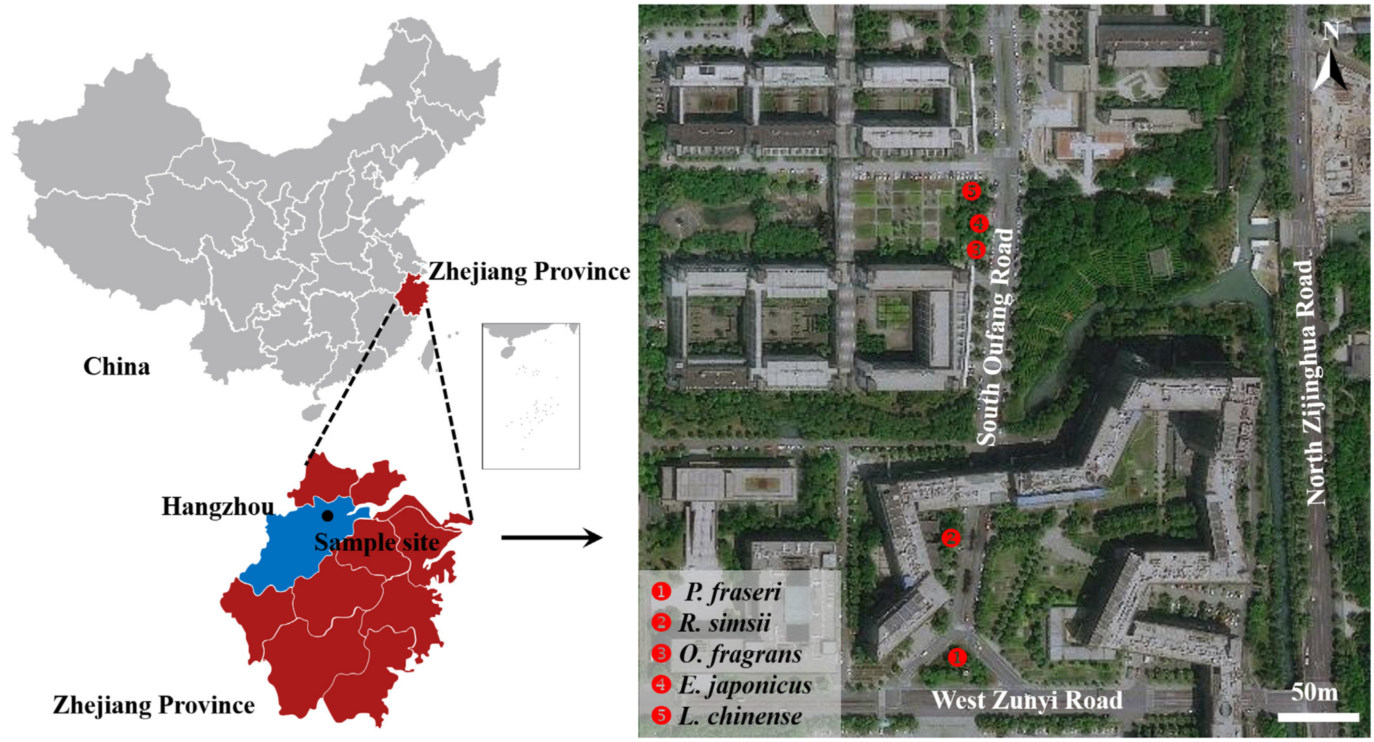



**Fig. 1.** The sampling site of this study, and the red dots indicate sampling plots.

method proposed by Baldacchini et al. (2017). The particles were classified into fine particles ($\Phi \leq 2.5$ μm), coarse particles ($2.5 < \Phi \leq 10$ μm) and large particles ($\Phi > 10$ μm) based on particle sizes, as well as the total suspended particulate (TSP) which is the sum of fine, coarse, and large particles on leaf surfaces.

The collected leaves were soaked in a beaker containing 70 mL of deionized water for 2 h before stirring the solution using a glass rod for 1 min. The solution was transferred to a 100-mL volumetric flask, which was diluted with the deionized water. Then the sample solution was injected into a clean and small plastic bottle with a label via a 10 mL syringe with a 2.2 μm filter. Finally, the sample solution was injected into the ion chromatography system (Dionex ICS-90) which shows five major cations (i.e., $Na^+$, $NH_4^+$, $K^+$, $Mg^{2+}$, and $Ca^{2+}$) and five major anions (i.e., $Cl^-$, $NO_2^-$, $SO_4^{2-}$, $F^-$ and $NO_3^-$).

## 2.5. Measurements of leaf traits

The leaf images of each species were obtained through the EPSON V700 scanner (Seiko Epson, Nagano, Japan), and then analyzed by the WinFOLIA (Regent Instruments Inc., Quebec, Canada) to obtain the leaf area (LA, $cm^2$) and width-to-length ratio (W/L) data. After the image scanning, all leaf samples were dried at 60 °C for 24 h to consistent weight, and were weighed using a high-precision electronic balance (0.01 mg). This data was recorded as $m_1$ (mg), and specific leaf area (SLA, $cm^2$/ mg) was calculated by the below equation:

$$SLA = LA/m_1 \quad (1)$$

Dried leaf samples were placed into petri dishes, which contain about 200 mL of trichloromethane. After these leaves were completely soaked in the trichloromethane for 3 min, they were placed in a fume cupboard until the trichloromethane had completely evaporated. Finally, they were reweighted as $m_2$ (mg). The difference between $m_1$ and $m_2$ was the value of epicuticular wax content (EWC, mg/g).

The stomatal density (SD, N/$cm^2$) of the leaf surface and the stomatal area (SA, $\mu m^2$) were also determined from SEM images by RADIUS 2.0 software.

## 2.6. Data analyses

In this study, the data was analyzed using SPSS 26.0 statistical software (SPSS Inc., Chicago, IL, USA). Most of the charts were created with Origin 2021 software (OriginLab Corp., Northampton, MA, USA). One-way analysis of variance (ANOVA) and Duncan's multiple comparison were

**Table 1**
Characteristics of the studied species.

| Species | Family | Life form | Leaf texture | Leaf shape | Leaf characteristics |
|---|---|---|---|---|---|
| *Loropetalum chinense* | Hamamelidaceae | Evergreen shrub | Leathery | Ovate | Adaxially sparsely covered trichomes, abaxially densely covered stellate trichomes. |
| *Rhododendron simsii* | Ericaceae | Deciduous shrub | Leathery | Ovate | Adaxially densely covered brown trichomes, abaxially sparsely covered stellate trichomes. |
| *Euonymus japonicus* | Celastraceae | Evergreen shrub | Leathery | Elliptic or obovate | Glabrous, rough. |
| *Photinia × fraseri* | Rosaceae | Evergreen shrub | Leathery | Oblong-elliptic or obovate-elliptic | Glabrous, smooth. |
| *Osmanthus fragrans* | Osmanthus | Evergreen broadleaved trees | Leathery | Elliptic or elliptic lanceolate | Glabrous, rough. |

conducted to compare the differences among the sizes, masses and number densities of PM, as well as the leaf traits of plant species. Pearson's correlation was used to analyze the relationship between PM mass and leaf traits.

## 3. Results

### 3.1. Microstructures of leaf surfaces and characteristics of retained particles

Based on the SEM images, the adaxial and abaxial surfaces of plant leaves both retained aerosol particles with different shapes and sizes (Fig. 2). Interestingly, there were more particles on the adaxial surface than those on the abaxial surface of plant leaves. Moreover, the microstructures of the leaf surfaces varied between adaxial and abaxial surfaces (Fig. 2). The adaxial leaf surface contained trichomes, wrinkles, grooves, and dot-like projections, whereas the abaxial leaf surface contained stomata, trichomes, and warts. The retained aerosol particles were mainly distributed around the trichomes, grooves, and veins of the leaves.

The adaxial surface of *L. chinense* leaf was densely covered by large particles and some fine particles randomly scattered, while their abaxial surface had a large number of stomata, obvious veins, and deep grooves retaining abundant aerosol particles (Fig. 2a, b). The adaxial and abaxial surfaces of *R. simsii* both scatted warts and trichomes (Fig. 2c, d). The leaf microstructures of *E. japonicus* and *P. fraseri* were similar and covered with thick wax on their surfaces (Fig. 2e-h). Moreover, the adaxial surface of *O. fragrans* exhibited clear grooves formed by veins, which retained some particles, while the abaxial surface contained dense stomata in wide open spaces (Fig. 2i, j). On the whole, the stellate trichomes of the adaxial leaf surface and the deep grooves surrounding stomata of the abaxial surface could effectively gather particles.

Based on the high-resolution SEM images coupled with EDS, different types of particles with different compositions were retained on the foliar leaves (Fig. 3), including mineral particles containing Si and Al (Fig. 3a, c, g, h), heavy metal particles containing Fe (Fig. 3d), biogenic particles containing C, O, and minor N (e.g., fungal spores) (Fig. 3e), and abundant secondary particles containing S and Ca (Fig. 3b, f). These particles were commonly distributed on the adaxial and abaxial surfaces of plant leaves, especially accumulating around the stellate trichomes or uneven grooves, and even forming dense clusters (Fig. 3f-h). It is interesting that some fine particles were observed to enter the stomata with a big diameter or wide opening (Fig. 3b, c).

Based on the analyses of water-soluble ions in the retained particles, the results showed that mass fractions of water-soluble ions in PM significantly changed in different plant leaves (Fig. 4). On the whole, $K^+$(19 %–49 %), $Ca^{2+}$ (15 %–47 %), $SO_4^{2-}$ (12 %–26 %), and $NO_3^-$ (6 %–19 %) accounted for 73 % to 88 % of the total water-soluble ions, with an average of 78 %, indicating that they are dominant in the water-soluble ions. By comparison, there existed considerably fewer $NH_4^+$, $F^-$, and $Na^+$ in the PM on the leaves, but these were also the important compositions of the deposited particles on different plant leaves. Later, we will further discuss the reason for variations of the water-soluble ions in Section 4.

### 3.2. Compositions of retained particles and efficiency of plant retention

The number densities of particles deposited on five plants were significantly different (Fig. 5, $p < 0.05$). Specifically, *E. japonicus* and *P. fraseri* were both higher in the number densities of fine and coarse particles on the adaxial and abaxial leaf surfaces, followed by *O. fragrans*, *R. simsii*, and *L. chinense* (Fig. 5a, b, d, e), displaying high retention ability for fine and coarse particles. It should be noticed that, although *L. chinense* was the lowest in number densities of fine and coarse particles, it was the highest in number densities of large particles among these five species (Fig. 5c, f), exhibiting its efficiency in retaining large particles.

Besides, number fractions of fine, coarse, and large particles varied among different plant species ($p < 0.05$, Fig. 6a). Specifically, the fine particles were the predominant component of particulates retained on the adaxial and abaxial leaf surfaces of the plant leaves, and the number fractions ranged from 55 % to 89 % with an average of 77.8 % of the total PM, following by coarse particles at 18.4 % (ranging from 10 % to 31 %). The number fractions of large particles were lowest in the total PM, ranging from 1 % to 14 %, with an average of 3.7 %. Surprisingly, *L. chinense* retained fine particles in the lowest number fraction of 55 %, but attached large particles in the highest number fraction of 14 % among the studied plants.

The abilities for particle retention on the adaxial and abaxial surfaces of plant leaves exhibited a significant difference. Fig. 6b shows that the particle number fraction of the adaxial surface was much higher than that of the abaxial surface. Specifically, the particles mainly aggregated on the adaxial surface ranging from 63 % to 90 % of the total PM, with an average of 76.5 %, and the rest small number fraction of particles on the abaxial surfaces (Fig. 6b). For example, the number fraction of fine particles on the adaxial surface of *R. simsii* leaves (91 %) went beyond ten times that of its abaxial surface (9 %). The result indicates that the adaxial surface of plant leaves is more competent to retain particles than the abaxial surface.

The distribution patterns of fine, coarse, and large particles significantly changed on the adaxial and abaxial leaves of different plants. The abaxial surface of plant leaves should not be ignored because their retaining particles ranged from 10 % to 37 % of the total PM, with an average of 23.5 % (Fig. 6b). Besides, the number fraction of large particles exhibited a different pattern from that of fine and coarse particles. It should be noted that the abaxial surface of *R. simsii* leaves retained the lowest fraction of fine particles (9 %), but it retained the highest portion of large particles (54 %).

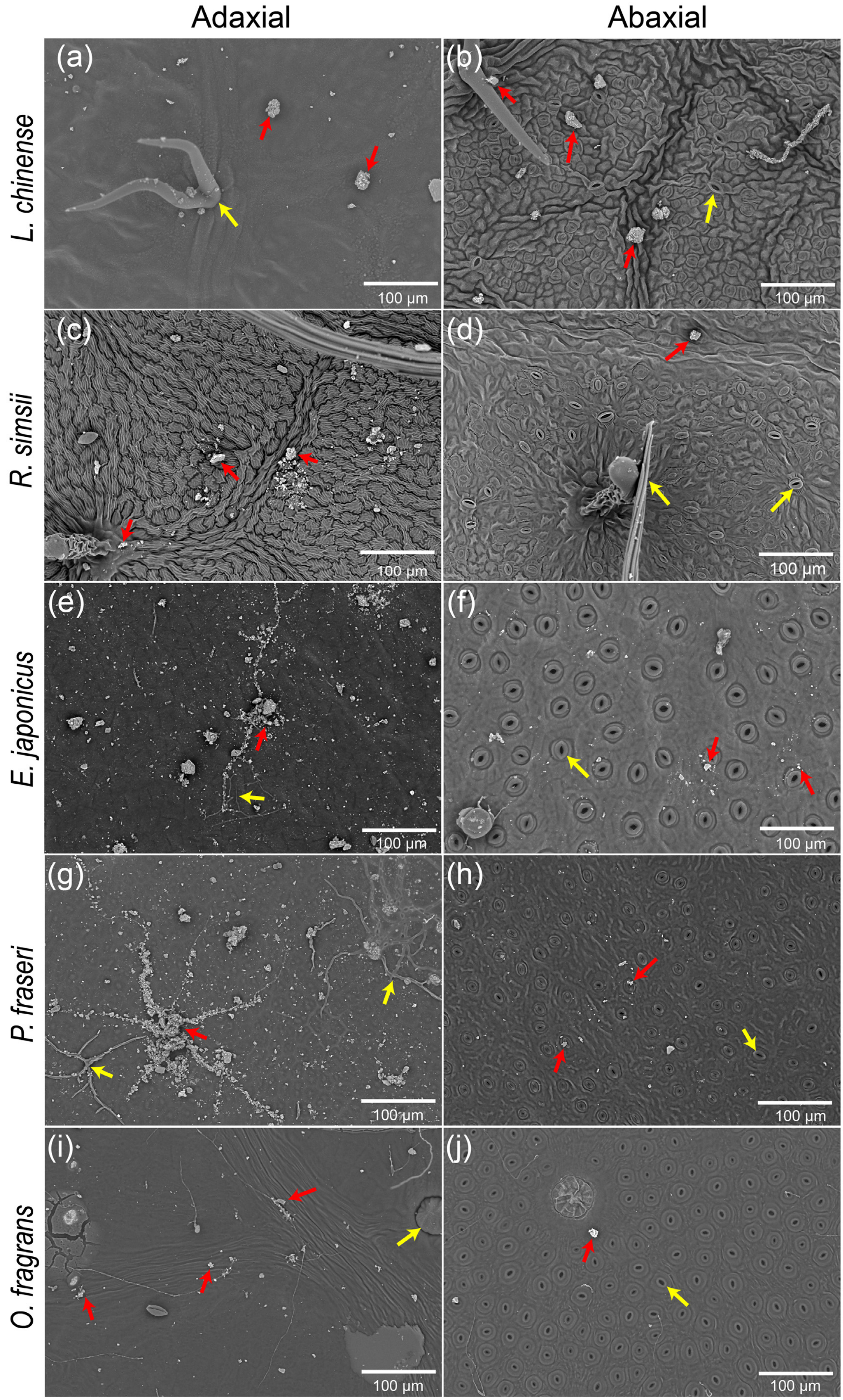
### 3.3. Leaf traits and their correlations with particle retention

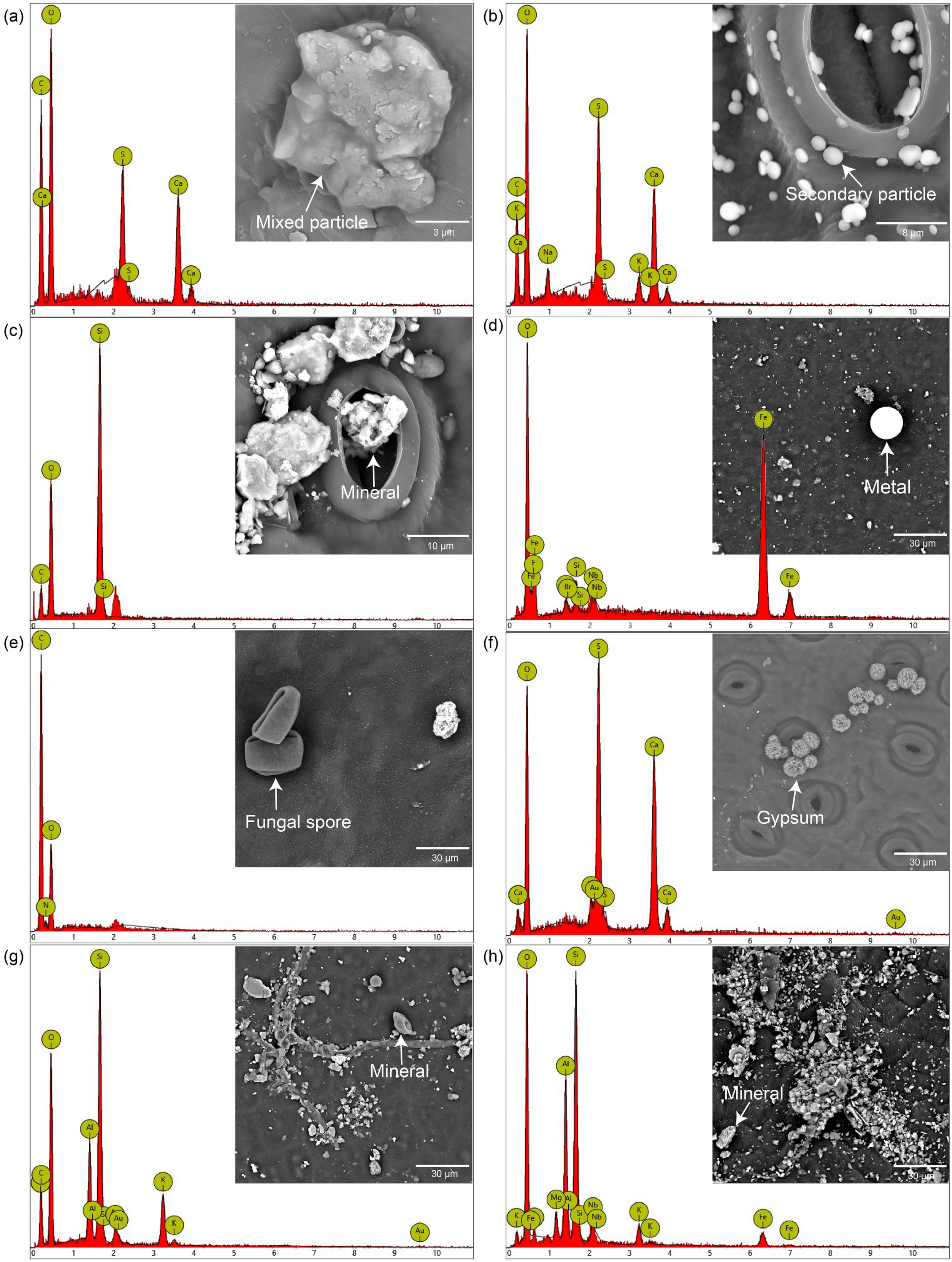
The leaf traits of five plants exhibited different characteristics (Fig. 7). The width-to-length ratio of *L. chinense* leaves (0.66) was higher than those of other plants, with the ratios ranging from 0.36 to 0.50, suggesting that the leaf shape of *L. chinense* is close to a circle (Fig. 7a). Besides, *L. chinense* has the lowest LA, but the highest in SLA, indicating it is low in leaf biomass. On the opposite, *P. fraseri* and *O. fragrans* have higher LA, but lower in SLA, with an indication of their high in leaf biomass (Fig. 7b, c). We found that *P. fraseri*, *L. chinense,* and *E. japonicus* contained higher EWC than other plants (Fig. 7d). In the abaxial leaves of the plants, they contained abundant stomata. For *E. japonicus*, *P. fraseri*, and *O. fragrans*, their SD tended to be opposite to their stomatal area (Fig. 7e, f). For example, *E. japonicus* had the largest SA but the lowest SD, while *O. fragrans* held a rather small SA but the highest SD. However, *L. chinense* and *R. simsii* exhibited small SA and medium SD.

We found significant differences in the masses of fine particles, coarse particles, and TSP retained on the leaf surfaces of the five plants ($p < 0.05$) (Fig. 7g-i). Specifically, the *E. japonicus* leaves kept the highest masses of fine particles, coarse particles, and TSP among the plants, suggesting their high ability to retain aerosol particles. Interestingly, *L. chinense* leaves kept low masses of fine particles and coarse particles, but they retained a high mass of TSP, indicating its advantages in retaining large particles.

To better understand what factors were closely related to the retaining ability of plant leaves for aerosol particles, the correlations between the leaf traits and particle mass were conducted (Table 2 and Fig. 8). The results show that EWC exerted a strong positive correlation with the TSP mass ($p < 0.05$), while SD was negatively related to the mass accumulation of TSP on the foliar surfaces ($p < 0.05$). Interestingly, SA was positively correlated with the fine particle mass ($p < 0.05$), but SLA was negatively correlated ($p < 0.05$).

**Fig. 2.** SEM images of the adaxial and abaxial leave surfaces of five species (×500 magnification). *L. chinense* (a, b), *R. simsii* (c, d), *E. japonicus* (e, f), *P. fraseri* (g, h) and *O. fragrans* (i, j). The red arrows indicate the typical particles retained on the foliar surfaces, the yellow arrows indicate the leaf traits (e.g., stomata, trichomes, wrinkles, grooves, vein of leaves and dot-like projections).


Adaxial
Abaxial
L. chinense
R. simsii
E. japonicus
P. fraseri
O. fragrans
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
100 μm


(a)
Mixed particle
3 μm
(b)
Secondary particle
8 μm
(c)
Mineral
10 μm
(d)
Metal
30 μm
(e)
Fungal spore
30 μm
(f)
Gypsum
30 μm
(g)
Mineral
30 μm
(h)
Mineral
30 μm

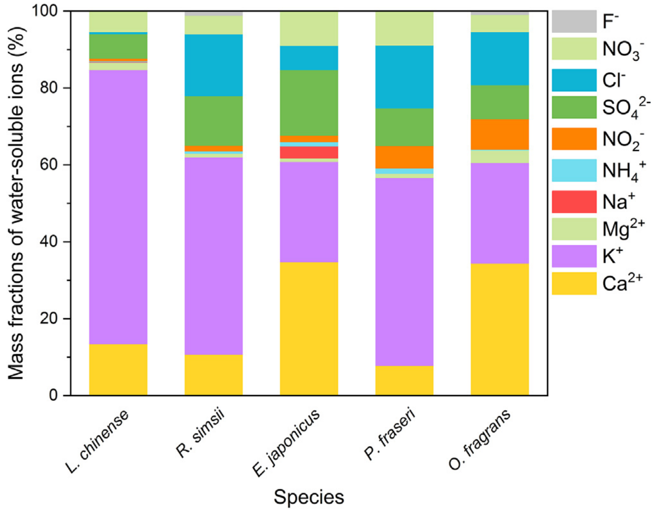



**Fig. 4.** The mass fractions of water-soluble ions in the total suspended particles on the leaves of five plant species. The presence of $K^+$ in a high concentration could be mainly caused by the leaking out of cell fluids in leaf tissue.

## 4. Discussion

This study shows that fine particles were the predominant components of particulates retained on the surfaces of plant leaves, more than the total of coarse and large particles (Fig. 6), which significantly contributed to mitigating $PM_{2.5}$ that negatively influenced air quality and human health (Colonna et al., 2022). Besides, there were large amounts of different particles, such as mineral particles, heavy metal particles, biogenic particles (e.g., fungal spores) and secondary aerosol particles retaining on the leaf surfaces of different plants (Fig. 3), and the results confirmed the statement that the deposited particles delivered microorganisms and heavy metals to plant leaves (Li and Shao, 2009; Sun et al., 2018; Zhang et al., 2021a), exhibiting adverse effects on vegetations.

Based on mass measurements of water-soluble ions, this study showed that $K^+$, $Ca^{2+}$, $SO_4^{2-}$ and $NO_3^-$ were dominant in the water-soluble ions of deposited particles (Fig. 4). Similarly, Cao et al. (2022) found that $Ca^{2+}$, $K^+$, and $NO_3^-$ were dominant water-soluble ions of PM on the coniferous leaves, and Xu et al. (2018) quantified $Ca^{2+}$, $SO_4^{2-}$ and $NO_3^-$ as the major components of PM retained on the tree leaves of urban Beijing. Generally, $NO_3^-$ and $SO_4^{2-}$ sourced from secondary inorganic aerosol, and $Ca^{2+}$ were from road and construction dust (Zhang et al., 2021a). However, as a macro-element of plants, $K^+$ in high concentration could be caused by leaking out of cell fluids in leaf tissue during sample treatment (Ma et al., 2021; Xu et al., 2019b), instead of being from the deposited aerosol particles. Moreover, there existed considerably less $NH_4^+$, $F^-$, and $Na^+$ in the PM on foliar leaves, and the reason may be that some ions (e.g., $NH_4^+$, $NO_3^-$, $Na^+$, $SO_4^{2-}$ etc.) on foliar surfaces can be absorbed by plant leaves as foliar fertilizers (Chater and Garner, 2018; Li et al., 2020; Romo-Perez et al., 2021).

The retention efficiencies for aerosol particles changed among different plant species and foliar surfaces (i.e., adaxial or abaxial surfaces). This study illustrated that *E. japonicus* and *P. fraseri* were more efficient in the retention of fine and coarse particles, while *L. chinense* was capable to retain large particles, indicating their advantages in the retentions for different aerosol particles (Fig. 5). Besides, there were more particles on the adaxial surface than those on the abaxial surface of plant leaves. Our microscopic analysis shows that the adaxial surface decreased the resuspension of aerosol particles, and there formed complex structures by trichomes and reticulate veins, increasing the roughness and retention mass of PM. The conclusion is in agreement with the previous studies (He et al., 2020; Weerakkody et al., 2018a). The results suggest that the urban plants played important and different roles in the removal of ambient particles.

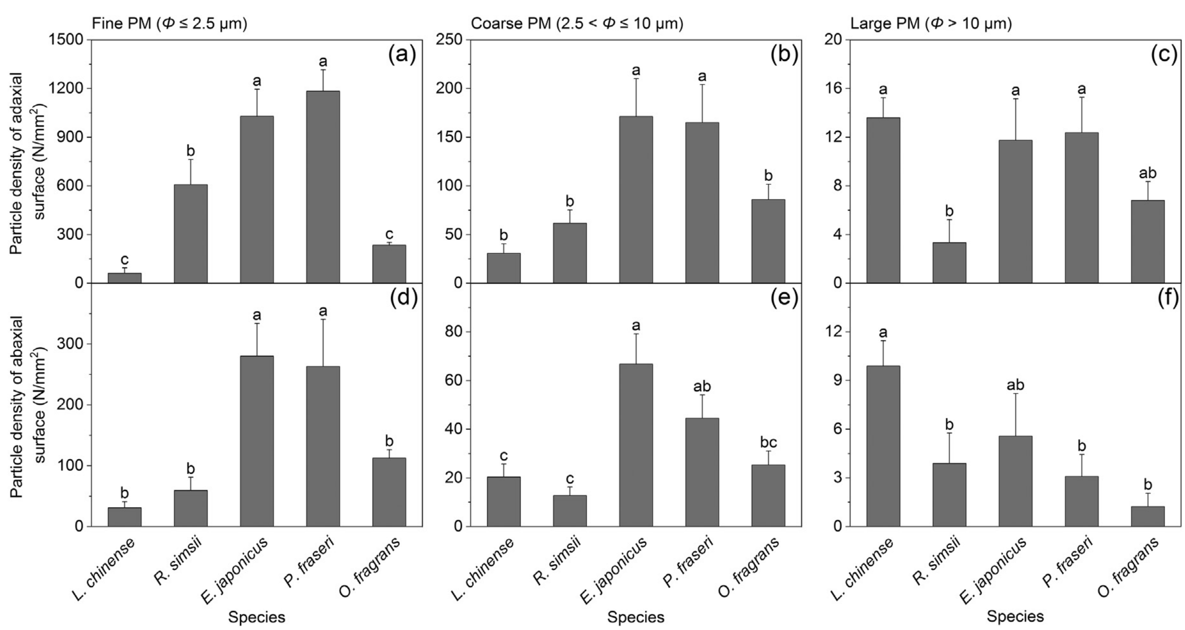



**Fig. 5.** The densities of fine particles ($\Phi \leq 2.5$ μm) (a, d), coarse particles ($2.5 < \Phi \leq 10$ μm) (b, e), and large particles ($\Phi > 10$ μm) (c, f) on the adaxial and abaxial surfaces of five plant species. The data are presented as the mean ± SE ($n = 9$). Bars with different letters indicate significant differences.

**Fig. 3.** The particle types were detected by a high-resolution SEM image coupled with EDS. (a) particle containing mineral and sulfate (×20000), (b) secondary aerosol particles existing inside and outside of the stoma (×10000), (c) mineral particles entered into the stoma (×7000), (d) spherical metal (Fe) particle (×2000), (e) biogenic particles (fungal spores, ×2000), (f) gypsum particles ($CaSO_4$, ×2000), (g) particles accumulated around the trichomes (×2000), and (h) particle cluster (×2000) on the leaf surface.

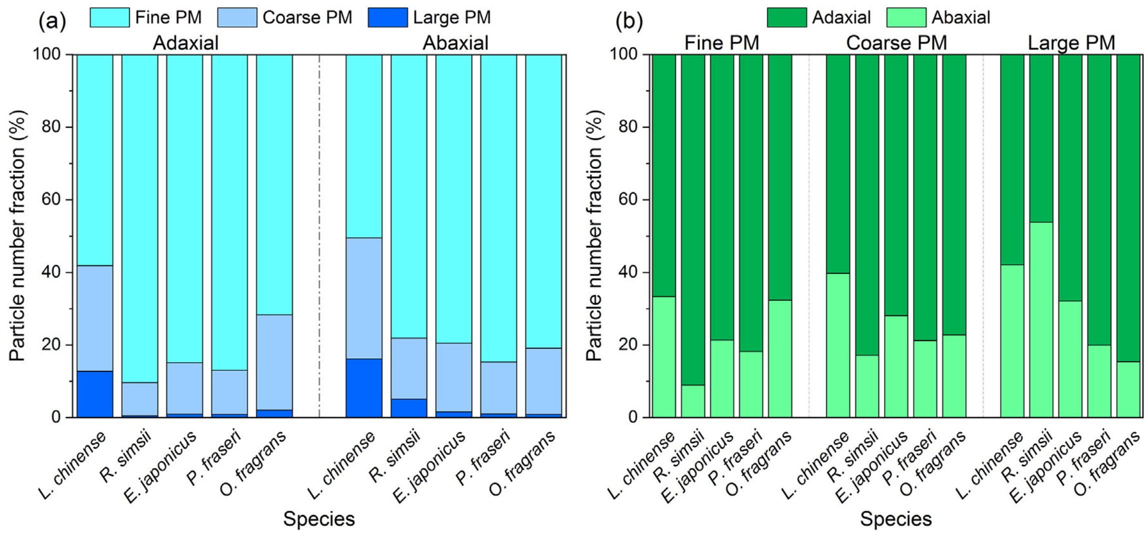



**Fig. 6.** Summary on the number fractions of fine particles ($\Phi \leq 2.5$ μm), coarse particles ($2.5 < \Phi \leq 10$ μm), and large particles ($\Phi > 10$ μm) on the adaxial and abaxial surfaces of five plants (a), and the number fractions of the adaxial surface and abaxial surface for fine particles, coarse particles and large particles (b).

Leaf traits were closely related to the accumulation of aerosol particles (Table 2, Fig. 7). Especially, the EWC exerted a significant positive correlation with the mass of particle accumulation, and leaf surfaces with high EWC increased the retainment duration and mass accumulation of aerosol particles. Similarly, previous studies have reported a positive correlation between the wax content and particle retention of plant leaves (Popek et al., 2018; Xu et al., 2019a) and foliar surfaces with high EWC that can alleviate the retained particles from being re-suspended by wind or being washed out by rain (Cai et al., 2019; Yan et al., 2019). Therefore, the leaf wax contributes to increase the retainment duration and mass accumulation of aerosol particles.

We noticed that the SD was negatively related to particle accumulation (Table 2), and it was affected by the stomatal size and stomatal conductance related to the deposition of aerosol particles. However, the result is contrary

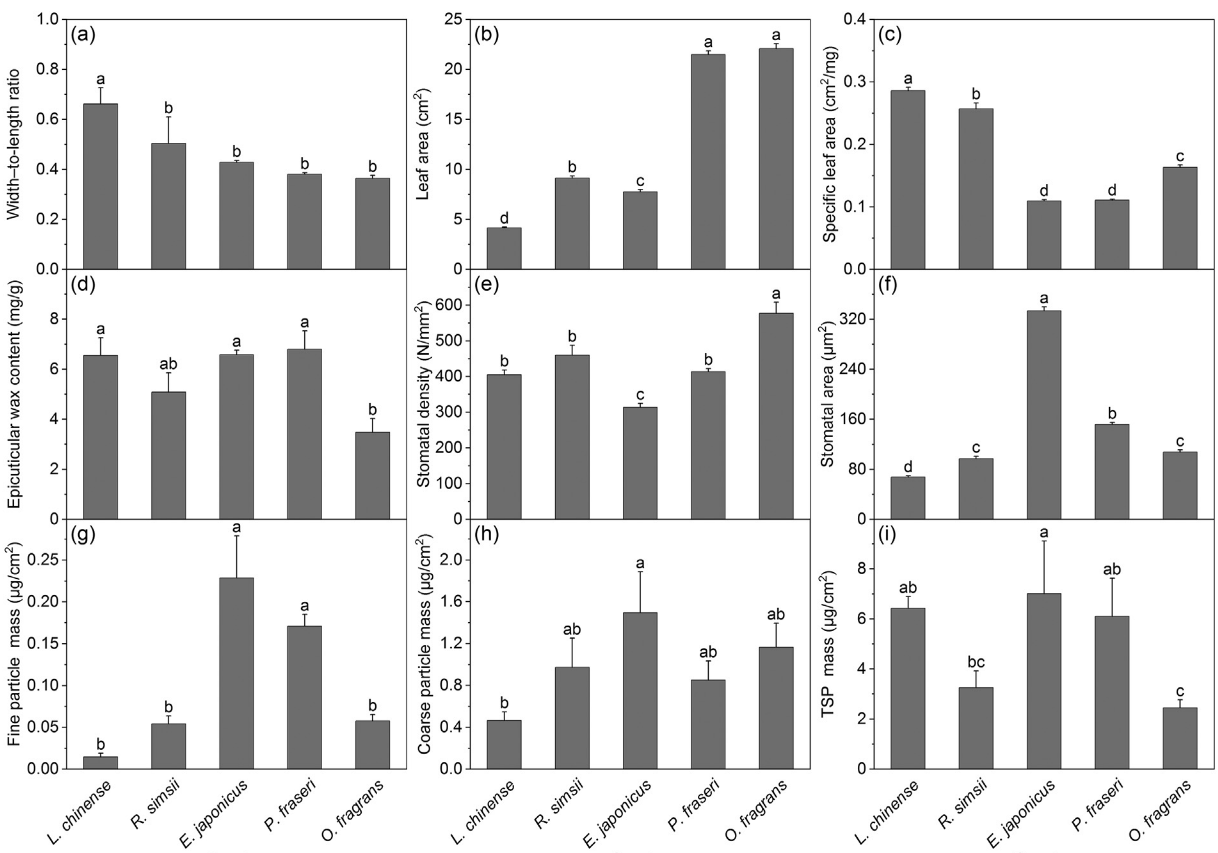



**Fig. 7.** Leaf traits and PM mass on leaves of five plant species: (a) width-to-length ratio (W/L), (b) leaf area, (c) specific leaf area (SLA), (d) epicuticular wax content (EWC), (e) stomatal density (SD), (f) stomatal area (SA), (g) fine particles mass, (h) coarse particles mass, and (i) total suspended particulate (TSP) mass. Bars with different letters indicate significant differences.

**Table 2**
Correlations between the particle mass and leaf traits.

| Leaf traits | Fine particles | Coarse particles | Total suspended particles |
|---|---|---|---|
| Width-to-length ratio (W/L) | −0.584 | −0.614 | 0.301 |
| Leaf area (LA) | 0.168 | 0.129 | 0.442 |
| Specific leaf area (SLA) | −0.881* | −0.462 | −0.240 |
| Epicuticular wax content (EWC) | 0.456 | −0.382 | 0.940* |
| Stomatal density (SD) | −0.613 | 0.001 | −0.907* |
| Stomatal area (SA) | 0.914* | 0.615 | 0.523 |

* $p < 0.05$.

to the statement by Rasanen et al. (2013), but it is in agreement with the conclusion by Marien et al. (2019). On the other hand, SA is positively correlated with the capture of fine particles. The result is consistent with Gao et al. (2021) who concluded that leaves with large SA can accumulate more fine particles. This study revealed that the SLA was negatively correlated with the mass accumulation of fine particles (Table 2). The result is consistent with one previous study by Zhang et al. (2020b) that SLA is negatively correlated with leaf thickness, and the leaves with low SLA are implied to be thick and small (Poorter et al., 2009), as well as being stiffer and covered with wax so that they would be competent in the retainment of fine particles from their resuspension to the air (Chiam et al., 2019). The result indicates that leaves with low SLA and high EWC are favorable for increasing deposition and reducing resuspension of aerosol particles, contributing to their accumulation on plant leaves.

This study indicates that plants with different leaf traits play different roles in retaining aerosol particles. Especially for the leaves with larger SA, lower SD, smaller SLA and higher EWC, they can retain more fine particles. However, the potential impacts on plant leaves by aerosol particles cannot be ignored. For example, stomata play an important role in the respiration, transpiration, and photosynthesis of plants, and tend to be more vulnerable and sensitive to particle deposition. Once deposited on leaf and absorbed by the stoma, aerosol particles can exert adverse impacts on plant physiology (Rai, 2016), resulting in low stomatal conductance and consequently reducing the transpiration and photosynthesis rates of plant leaves. Therefore, further studies concerning the interactions between plants and aerosol particles are urgent for the optimal selection of dust-retaining plants, and it is also significant for the understanding of the alleviation on aerosol pollution by urban vegetation.

## 5. Conclusions

Aerosol particles were mainly retained on the adaxial surface of plant leaves, and fine particles were the predominant components of retained particles, including mineral particles, heavy metal particles, biogenic particles (e.g., fungal spores) and secondary aerosol particles. Besides, $Ca^{2+}$, $SO_4^{2-}$ and $NO_3^-$ were dominant in water-soluble ions of deposited particles, while considerably less $NH_4^+$, $F^-$ and $Na^+$ of particles deposited on foliar leaves could be foliar fertilizers of plants. The presence of $K^+$ in a high concentration could be mainly caused by the leaking out of cell fluids in leaf tissue. The sources of water-soluble ions of deposited particles and their potential impacts on plants deserve further investigation.

Leaf traits were closely related to the accumulation of aerosol particles, and plants with different leaf traits exhibited different retention efficiencies. *E. japonicus* and *P. fraseri* were efficient in the retention for fine and coarse particles, while *L. chinense* was capable to retain large particles. For the plant leaves with larger stomatal area, lower stomatal density, smaller specific leaf area, and higher epicuticular wax content can retain more aerosol particles. Further study concerning the interactions between plants and aerosol particles is needed for the optimal selection of dust-retaining plants, and for the understanding of the alleviation on aerosol pollution by urban plants.


**Fig. 8.** The diagram for the microstructures and impacting factors of aerosol particles retaining on the adaxial or abaxial surface of plant leaves.

## CRediT authorship contribution statement

**Siqi Chen:** Investigation, Methodology, Data curation, Writing – original draft. **Hua Yu:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing. **Xiaomi Teng:** Investigation, Methodology. **Ming Dong:** Supervision. **Weijun Li:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

## Data availability

Data will be made available on request.

## Declaration of competing interest

The authors declare that there is no conflict of interest.

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