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ENVIRONMENTAL
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Research Article

Comparing the compositions and influence of aerosol particles retained on trees, shrubs, and herbs

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ARTICLE INFO

Article history:

Received 19 August 2024

Revised 22 November 2024

Accepted 28 November 2024

Available online 4 December 2024

Keywords:

Aerosol particles

Leaf texture

Leaf functional traits

Particle capture

Plant growth form

ABSTRACT

Aerosol particle pollution has become an increasing serious environmental problem, and urban vegetation plays a long-lasting and positive role in mitigating it. This study compared the particle capture abilities of trees, shrubs, and herbs, and examined the compositions and influence of aerosol particles accumulated on leaf functional traits. Retained particles primarily contained Ca^{2+} , K^+ , SO_4^{2-} , NO_3^- and NH_4^+ , indicating their anthropogenic origins. The leathery-leaved tree *Osmanthus fragrans* and the papery-leaved herb *Alternanthera sessilis* demonstrated the higher competence in particle accumulation than other plants, and leaf morphologic structures (e.g., leaf grooves, trichomes, waxy layers, and stomata characteristics) were closely associated with particle capture by plant species. Particle retention negatively impacted stomata, impeding photosynthesis, and reducing transpiration. In response to particle accumulation, plants tended to decrease specific leaf area and adjust stomatal conductance. Both growth form and leaf texture significantly influenced the particle capture abilities of different plant species. The substantial contribution of plants, particularly herbs in the lower vegetation strata, to particle removal should not be overlooked. Vegetation with a tree-shrub-herb configuration excels at particle capture, offering potential advantages in mitigating particle pollution and enhancing ecological benefits.

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Introduction

Air pollution has become a critical environmental issue (Lelieveld et al., 2015), and particulate matter (hereinafter referred to as particle) is one of the major air pollutants

(Gunthe et al., 2021). Aerosol particles are always characterized as the smaller size, higher pollution level, wider range of occurrences, and more complex spatial distributions, posing considerable threats to human health and adverse effects on environmental health. Fine particulate matter ($\text{PM}_{2.5}$) can penetrate deeply into the respiratory tract, and even enter the bloodstream, posing a significant risk of worsening pulmonary function, reducing cardiovascular health, and aggravating chronic respiratory diseases (Cen, 2015). Moreover, the hazardous toxicity of particles to human health is closely

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correlated with their size, chemical composition, mixed structure, and spatial distribution (Harrison and Yin, 2000; Manisalidis et al., 2020; Nel, 2005). In addition, particles have adverse effects on the environment, such as contributing to smog problems, especially in winter (Schichtel et al., 2017), sharply reducing agricultural yields (Gallagher et al., 2002), and decreasing biodiversity in ecosystems (Finer et al., 2008). Therefore, it is urgently necessary to find effective and economical ways to reduce particle pollution.

When considering eco-sustainable control measures to combat aerosol particles, urban vegetation can serve as a biological filter for mitigating particle pollution (Escobedo et al., 2008; Han et al., 2020; Nguyen et al., 2015). Capturing particle is a crucial ecosystem service provided by urban vegetation (Salmond et al., 2016), and plants offer other ecological benefits, such as enhancing bioclimate comfort by offering shade against ultraviolet rays, altering wind speeds, reducing storm intensity, and lowering traffic noise levels (Seamans, 2013). Therefore, urban vegetation acts as a natural receptor for particles (Terzaghi et al., 2013), and has been proposed as an economically and ecologically compatible strategy to reduce particle pollution (Ozdemir, 2019). For example, Yin et al. (2011) concluded that urban vegetation has the capacity to remove 9 % of total suspended PM_{2.5}, while Maher et al. (2013) showed that roadside tree leaves can adsorb over 50 % of indoor particles, thereby improving air quality. Urban plants can purify aerosol particles through mechanisms including interception, sedimentation, diffusion, transmission, and a combination of these processes (Beckett et al., 2000; Janhäll, 2015). Although some intercepted particles can be absorbed by plants, the majority retain temporarily on the leaf surfaces. These particles are eventually resuspended in the atmosphere, are moved to the ground by changes in airflow (Zheng and Li, 2019), are washed off by rainfall (Weerakkody et al., 2018), or are deposited on the ground with fallen leaves and twigs (Subhash et al., 2004). In brief, urban vegetation has a long-lasting and positive effect on reducing particle pollution.

The capacity for particle retention is largely influenced by prevailing meteorological conditions and the morphological characteristics of different plant species (Wang et al., 2006). For example, wind speed and direction can significantly affect the mechanisms of interception and resuspension (Jacob and Winner, 2009). Turbulent airflow and associated impaction contribute to high particle deposition (Tong et al., 2015), while precipitation can wash away or dissolve the particles retained on plant leaves (Xu et al., 2017). Urban vegetation varies in species composition and associated canopy structure (Xu et al., 2019). The complexity of the structure and the leaf cover area are important factors in determining the effectiveness of particle retention by vegetation (Hofman et al., 2016). Additionally, particle retention efficiency varies significantly among plant species, influenced by factors such as leaf size, leaf texture, and morphologic microstructures (Perini et al., 2017; Sæbo et al., 2012). For example, leaf characteristics like phyllotaxis, shape complexity, surface dimension, and epicuticular texture can affect the capture of aerosol particles (Prusty et al., 2005). Furthermore, the microstructural features of foliage, such as epicuticular waxiness (Dzierzanowski et al., 2011), stomata, folds, ridges (Chen et al., 2017), trichomes

(Zhang et al., 2019), and emitted sticky substances, significantly affect particle deposition per unit area (Kwak et al., 2019; Petroff et al., 2008). These features increase leaf surface roughness compared to smooth surfaces, enhancing particle capture (Li et al., 2020).

Urban greening includes a wide variety of vegetative structures, such as trees, shrubs, and herbs, which vary in their effectiveness at alleviating aerosol particle pollution (Dzierzanowski et al., 2011; Weber et al., 2014). Previous studies have primarily focused on the role of trees in particle retention (Li et al., 2019b). The contribution of shrubs and herbs to particle mitigation has often been neglected, despite their widespread cultivation in urban areas (Sillars-Powell et al., 2020). Furthermore, there is a lack of rigorous evaluation of the particle capture capacities of plants with different growth forms (i.e., plant species that share similar life-history). In this study, we selected two trees (*Osmanthus fragrans* and *Broussonetia papyrifera*), two shrubs (*Euonymus japonicus* and *Kerria japonica*), and two herbs (*Hydrocotyle vulgaris* and *Alternanthera sessilis*) with varying leaf characteristics as the target experimental plants. The aims of this study were as follows: (1) to evaluate the particle capture capacities of plants with different growth forms, (2) to assess the impacts of retained particles on leaf functional traits, and (3) to explore the correlations between leaf functional traits and particle capture capacity. This study will provide scientific insights for developing sustainable urban vegetation strategies to combat aerosol particle pollution.

1. Materials and methods

1.1. Sampling sites

The samples were collected from Hangzhou Normal University (30°17'24"N, 120°0'29"E), located in Hangzhou, a high urbanized city in Zhejiang Province, Eastern China. It is located in a subtropical monsoon region with a subtropical climate, characterized by warm and moist conditions and four distinct seasons: a rainy spring, a hot and humid summer, a dry autumn, a dry and cold winter. In 2021, the mean temperatures range from a maximum of 29.3 °C in summer to a minimum of 6.5 °C in winter, with an average annual temperature of 18.8 °C (<http://www.stats.gov.cn/sj/ndsj/2022/indexch.htm>), which is favorable for the growth of broad-leaved plants. The main sources of aerosol particles were heavy traffic and vehicle exhausts. In 2021, the annual average mass concentrations of PM₁₀ and PM_{2.5} were 55 µg/m³ and 28 µg/m³, respectively (<http://www.stats.gov.cn/sj/ndsj/2022/indexch.htm>). The studied sites are located on the university campus, which covers an area of 216.7 hectares, and is characterized by extensive vegetation and a relatively low mass concentration of aerosol particles.

1.2. Studied species

Based on leaf texture, particle capture capacity, growth adaptability, and distribution area in urban vegetation, six plant species with different growth forms were selected as the representative species of urban greening to explore

Table 1 – Biological characteristics of the studied plants.

Plant species	Family	Growth form	Leaf texture	Leaf shape	Leaf characteristics
<i>Osmanthus fragrans</i>	Oleaceae	Evergreen tree	Leathery	Elliptic or elliptic lanceolate	Glabrous, rough.
<i>Broussonetia papyrifera</i>	Moraceae	Deciduous tree	Papery	Ovate or elliptical-ovate	Adaxially sparsely covered trichomes, abaxially densely covered hooked trichomes.
<i>Euonymus japonicus</i>	Celastraceae	Evergreen shrub	Leathery	Elliptic or obovate	Glabrous, rough.
<i>Kerria japonica</i>	Rosaceae	Deciduous shrub	Papery	Ovate or triangular-ovate	Adaxially sparsely covered trichomes, abaxially densely covered stellate trichomes along the veins.
<i>Hydrocotyle vulgaris</i>	Araliaceae	Perennial herb	Leathery	Elliptic or elliptic-lanceolate	Glabrous, smooth.
<i>Alternanthera sessilis</i>	Amaranthaceae	Perennial herb	Papery	Obovate or obovate-lanceolate	Glabrous, rough.

their capacities for accumulating aerosol particles, including two trees (*Osmanthus fragrans* and *Broussonetia papyrifera*), two shrubs (*Euonymus japonicus* and *Kerria japonica*), and two herbs (*Hydrocotyle vulgaris* and *Alternanthera sessilis*). *O. fragrans* is an evergreen tree, widely planted in subtropical regions with significant economic and cultural importance (Mu et al., 2014). *B. papyrifera* is a deciduous tree, extensively distributed across Asia due to its rapid germination and high resistance to adverse habitats (Jiao et al., 2022). *E. japonicus* is an evergreen shrub, commonly used for street ornamentation due to its attractive variegate leaves and high tolerance to air pollution (Yucedag et al., 2019). *K. japonica* is a deciduous shrub, commonly cultivated along streets and characterized with its flowers (Luo et al., 2021). *H. vulgaris* and *A. sessilis* are perennial herbs that grow in the lower strata of urban vegetation and are widely distributed across Southern China (Jiang et al., 2021; Tang et al., 2020). Additionally, these plant species differ in leaf texture, for instance, *O. fragrans*, *E. japonicus*, and *H. vulgaris* have leathery leaves, while *B. papyrifera*, *K. japonica*, and *A. sessilis* have papery leaves (Table 1).

1.3. Sample collections

Leaf samples were collected on January 4, 2022, ten days after the rainfall, following a ten-day period of particle accumulation. Each composite sample consisted of leaves randomly selected from the four quadrants of an individual plant, with five replicates. Twenty leaf samples of each studied species were collected per treatment, half for Scanning Electron Microscopy (SEM) observation and the other half for other measurements. Samples were randomly collected at heights of 1.5–2 m for trees, 0.5–1 m for shrubs, and 0.1–0.2 m for herbs above ground. Plant leaves of similar age, in good condition, and of average size were selected as sample objects, while unhealthy leaves, such as those damaged by insects or affected by disease, were excluded. The leaves from studied plant species distributed across the campus were sampled and immediately placed into labeled plastic petri dishes to prevent secondary contamination. Half of the sampled leaves were placed with the top side up, and the other half were placed with the underside up, with minimal agitation to prevent the deposited particles from falling off. The leaf samples were immediately transported to the laboratory after collection, placed in sealed petri

dishes in a 60 °C oven for 24 h, and then stored in a constant temperature and humidity environment to achieve a constant weight before further observation and testing.

1.4. Quantitative analysis of retained particles

1.4.1. Composition characteristics of particles

For leaf samples of each tested plant species, five were placed with the top side up and five with the underside up, to observe the particle compositions and morphological structures on the adaxial and abaxial surfaces, respectively, using Scanning Electron Microscopy (Phenom XL, the Netherlands) coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS). For each tested leaf, two 5 mm × 5 mm square segments were excised near the midrib, avoiding the veins, before being mounted onto the sample stage using double-sided adhesive tape. Then, the sample segments were coated with a thin layer of gold (Au) to increase conductivity using a sputter machine (KYKY SCB-12), before SEM observation at a low accelerating vacuum voltage (15 kV). Samples were scanned using random photography at a magnification of 2000× with a 30 μm scale to observe the integrated configurations (e.g., size, number and composition) of particles retained on both the adaxial and abaxial surfaces, as well as leaf morphological structures, including trichomes, stomata, wax, grooves, and so on. Five SEM images of each leaf segment were captured at magnification of 2000×, resulting in a total of twenty SEM images of the adaxial leaf surface and twenty of the abaxial leaf surface for each plant species. Additionally, typical particles accumulated on the leaf surfaces were recorded at a higher magnification (8000×) with a 10 μm scale, and their sources were identified based on elemental compositions.

Based on particle size, the retained particles were categorized into fine particles ($\Phi \leq 2.5 \mu\text{m}$), coarse particles ($2.5 < \Phi \leq 10 \mu\text{m}$), large particles ($\Phi > 10 \mu\text{m}$), and total suspended particles (TSP). The particle diameters were automatically measured using the Weka Segmentation tool based on SEM micrographs to minimize man-made counting errors. The size distribution and number density of retained particles were measured through Image-J software (National Institutes of Health, USA). Mass concentration and number density were used for the quantitative analysis of the retained particles. For each plant species, we randomly selected five SEM micrographs

of the adaxial leaf surface and five of the abaxial leaf surface to measure the mass concentration and number density of retained particles. Specifically, the mass concentration of retained particles per unit leaf area ($\mu\text{g}/\text{cm}^2$) was evaluated using Eqs. (1) and (2), while the number density of retained particles per unit leaf area ($10^4 \text{ N}/\text{mm}^2$) was calculated using Eq. (3) (Abhijith and Kumar 2020).

$$V_i = \frac{4}{3}\pi \left(\frac{D_i}{2}\right)^3 \quad (1)$$

$$m = \frac{\sum_i V_i \rho}{S} \quad (2)$$

$$N_d = \frac{\text{Num}_i}{S} \quad (3)$$

where, V_i (μm^3) is the particle volume; D_i (μm) is the particle diameter; m ($\mu\text{g}/\text{cm}^2$) is the mass concentration of particles per unit leaf area; ρ ($2 \text{ g}/\text{cm}^3$) is the average density of particles (Abhijith and Kumar 2020); N_d ($10^4 \text{ N}/\text{mm}^2$) is the mean number density of matched particles; Num_i is the number of matched particles; S (μm^2) is the area of the sampled SEM photograph.

1.4.2. Measurements of water-soluble inorganic ion

Five leaf samples from each plant species were randomly selected for the measurements of water-soluble inorganic ions. To extract retained particles from the leaf surfaces, each leaf sample was immersed in 50 mL of distilled water in a 50 mL centrifuge tube and placed in an oscillator, shaking at a rotation speed of 30 r/min for 2 h to ensure that all water-soluble inorganic ions were washed off the leaf surfaces and dissolved in the water. Water-soluble inorganic ions, such as Ca^{2+} , K^+ , SO_4^{2-} , NO_3^- , NH_4^+ , and so on, were measured using ion chromatography (Dionex ICS-600), and their mass concentrations were calculated using Eq. (4):

$$W_i = \frac{C_i V_s}{LA} \quad (4)$$

where, W_i ($\mu\text{g}/\text{cm}^2$) is the mass concentration of a specific water-soluble inorganic ion per unit leaf area; C_i (mg/L) is the mass concentration of a specific water-soluble inorganic ion; V_s (cm^3) is the volume of distilled water in the centrifuge tube (50 cm^3); LA (cm^2) is the corresponding leaf area.

1.5. Measurement of foliar functional traits

1.5.1. Photosynthesis-related parameters

The photosynthesis-related parameters, including photosynthesis rate (P_n , $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$), stomatal conductance (G_s , $\text{mol}/(\text{m}^2 \cdot \text{s})$) which is a key measure that quantifies the gas exchange ability of stomata, transpiration rate (T_r , $\text{mmol}/(\text{m}^2 \cdot \text{s})$), and leaf temperature (T_{leaf} , $^\circ\text{C}$), were measured on the sunny day between 9:00 am and 18:00 pm, using a portable LOCOR 6400 Photosynthesis System (Li-6400). This system was equipped with a standard leaf chamber, as well as high-accuracy temperature and light sensors. The measurements of the sampled leaves were conducted under the following conditions: light intensity was approximately 800–1000 $\text{mmol}/(\text{m}^2 \cdot \text{s})$, relative humidity ranged from 30%–35 %,

and CO_2 concentration was maintained at $400 \mu\text{mol}/\text{mol}$. Additionally, the chlorophyll a/b content was measured using the SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan) under the same leaf sampling conditions as those used for photosynthetic efficiency measurements.

1.5.2. Morphological characteristics of plant leaves

Leaf samples were scanned to acquire individual leaf images using the EPSON V700 scanner (Seiko Epson, Nagano, Japan). The images were then analyzed to measure leaf area (LA , cm^2) using the leaf surface analysis software WinFOLIA (Regent Instruments Inc., Quebec Canada). Specific leaf area is one of the fundamental leaf functional traits related to plant adaptation to external stress (Xu et al., 2020). The specific leaf area of plant samples was calculated using Eq. (5):

$$SLA = \frac{LA}{m_1} \quad (5)$$

where, SLA (cm^2/mg) is the specific leaf area of a leaf sample; LA (cm^2) is the leaf area of a leaf sample; m_1 (mg) is the dried leaf mass of a leaf sample.

Leaf samples were immersed in 200 mL of chloroform for 90 s to completely remove the wax layer from the leaf surface. After rinsing, the leaves were oven-dried at 60°C to a constant weight. The quantity of epicuticular waxes (WC , mg/cm^2) was determined using Eq. (6):

$$WC = \frac{m_1 - m_2}{LA} \quad (6)$$

where, WC (mg/cm^2) is the epicuticular wax mass per unit leaf area; m_1 (mg) is the mass of the dry leaf with wax layer; m_2 (mg) is the mass of the dry leaf without wax layer; LA (cm^2) is the leaf area of a leaf sample.

1.6. Data analysis

Statistical analyses were performed using SPSS 20.0 (SPSS Inc., Chicago, USA). Graphics were created with Origin 2021 (Origin Lab Crop., Northampton, USA) and Adobe Illustrator CC 2021 (Adobe Systems Inc., USA). Two-way analysis of variance (Two-way ANOVA) was performed to analyze the accumulated particles and leaf functional traits of plants with different growth forms and leaf textures. Principal component analysis (PCA) was conducted to assess the effects of retained particles and water-soluble inorganic ions on the tested plant leaves. Additionally, Spearman's correlation analysis was used to study the relationships between the mass concentration of retained particles and the leaf functional traits of plants with different growth forms.

2. Results

2.1. The composition characteristics of particles retained on plants with different growth forms

Plant growth forms and leaf textures significantly affected the mass concentrations of retained particles, including fine particles ($\Phi \leq 2.5 \mu\text{m}$), coarse particles ($2.5 < \Phi \leq 10 \mu\text{m}$), large particles ($\Phi > 10 \mu\text{m}$), and total suspended particles (TSP) (Table 2,

Table 2 – Two-way ANOVA on the characteristics of particles retained on plant leaves with different growth forms and leaf textures.

Particle characteristics	F_f	F_t	$F_f \times F_t$
<u>Mass concentration</u>			
Fine particles	0.973	33.440***	100.345***
Coarse particles	5.243**	3.255	59.402***
Large particles	41.650***	67.137***	22.671***
TSP	21.733***	12.891***	41.319***
<u>Number density</u>			
Fine particles	13.555***	0.500	85.002***
Coarse particles	11.552***	5.271*	101.102***
Large particles	19.505***	27.807***	8.189***
<u>Ion concentration</u>			
Ca ²⁺	11.005***	0.648	14.020***
K ⁺	14.917***	15.917***	5.076*
SO ₄ ²⁻	6.824**	3.104	2.808
Cl ⁻	4.478*	5.562*	7.143**
NO ₃ ⁻	6.271**	4.850*	1.022
Na ⁺	2.121	6.965*	5.486**
F ⁻	2.274	8.840**	4.952*
NH ₄ ⁺	7.004**	1.659	1.780
Mg ²⁺	4.417*	1.510	0.002

F_f : treatment of growth forms; F_t : treatment of leaf textures.
 “*”: $p < 0.05$; “**”: $p < 0.01$; “***”: $p < 0.001$.

Fig. 1; $p < 0.001$). Leathery leaves exhibited a decreasing trend in the mass of retained fine particles, coarse particles, and TSP from trees to shrubs to herbs, while an increasing trend was observed in the mass of large particles. For papery leaves, the mass of all particles retained on herbs was significantly higher than that on trees and shrubs. Additionally, for trees and shrubs, leathery leaves retained the higher mass of fine particles, coarse particles, and TSP compared to papery leaves. However, papery leaves of herbs retained a significantly higher mass of particles of all sizes compared to their leathery leaves. For example, the herb *A. sessilis* with papery leaves retained the highest mass of coarse particles, large particles, and TSP.

The number density of retained particles varied with plant growth forms, leaf textures, and their interactions (Table 2, Fig. 2). For particles deposited on leathery leaves, the number density of fine and coarse particles increased from trees to shrubs, followed by a sharp decrease in herbs. In contrast, the number density of large particles showed a continuous increase from trees to shrubs to herbs. For papery leaves, the number density of fine, coarse, and large particles deposited on herbs was nearly three times higher than on trees and shrubs. Compared to papery leaves, the leathery leaves of trees and shrubs retained a higher density of fine and coarse particles but a lower density of large particles. However, herbs with papery leaves were more efficient at retaining particles than those with leathery leaves. For example, *A. sessilis*, an herb with papery leaves, exhibited the highest density of deposited fine, coarse, and large particles.

Scanning electron micrographs revealed the distribution of particles and the morphologic structures of leaf surfaces (Fig. 3). On both the adaxial and abaxial sides of plant leaves, particles were unevenly aggregated. Stomata were distributed on the abaxial side of trees and shrubs, while they were

present on both the adaxial and abaxial sides of herbs. Particles tended to accumulate in the grooves around the stomata. The leathery-leaved tree *O. fragrans*, shrub *E. japonicus*, and herb *H. vulgaris* were covered with a thick wax layer. The particles deposited on the tree *O. fragrans* and the shrub *E. japonicus* aggregated on hyphae (a network structure formed by fungi), while the particles deposited on herb *H. vulgaris* were trapped in the shallow grooves (Fig. 3i and j). The papery-leaved tree *B. papyrifera* and shrub *K. japonica* exhibited deep grooves on the adaxial side (Fig. 3c and g). In particular, the abaxial side of the tree *B. papyrifera* was densely covered with trichomes, facilitating particle deposition (Fig. 3d). In contrast, the adaxial side of the herb *A. sessilis* extensively accumulated particles of all sizes (Fig. 3k). The abaxial side of the leaf surfaces exhibited hypostomatic morphology, with irregularly shaped particles distributed around the stomata, and in some cases, even entering them (Fig. 3d, h and l).

The high-resolution SEM-EDS images revealed the predominant types of particles deposited on trees, shrubs, and herbs of varying vegetation heights (Fig. 4). Specifically, for tree species, there were deposits of reticular-shaped fungal spores rich in C, O, and S, irregularly shaped mineral particles with high contents of Al and Si, and aggregated secondary particles containing high amounts of Ca, O, and S (Fig. 4a–d). For shrub species, there were circularly shaped fly ash particles rich in Si, Ca and O, as well as mineral particles with angular edges, primarily comprised of Si, O, and Ca (Fig. 4e and f). Additionally, various secondary particles with spherical and regular shapes were rich in Si, S, and Ca (Fig. 4g and h). For herb species, there were irregularly shaped mineral particles with high contents of Si and O, as well as an abundance of secondary particles rich in S, Ca, and C (Fig. 4i–k). Additionally, for both shrub and herb species, some mineral particles were covered with secondary particles containing a broad range of elements, including Si, S, and Ca (Fig. 4h and l).

The concentrations of water-soluble inorganic ions in deposited particles varied depending on plant growth form, leaf texture, and their interaction (Table 2, Fig. 5). Among the nine types of tested water-soluble inorganic ions in deposited particles, Ca²⁺, K⁺, SO₄²⁻, Cl⁻, and NO₃⁻ were predominant (Fig. 5a–e). SO₄²⁻, NH₄⁺, and Mg²⁺ were primarily influenced by plant growth form, while Ca²⁺ was affected by both plant growth form and its association with leaf texture. Additionally, NO₃⁻ varied with plant growth form and leaf texture, while K⁺ and Cl⁻ varied with plant growth form, leaf texture, and their interactions. Plants with different growth forms and leaf textures exhibited varying ion contents in deposited particles. For tree species, the leathery-leaved *O. fragrans* had higher contents of Ca²⁺, SO₄²⁻, Cl⁻, and Na⁺, but lower contents of K⁺, NO₃⁻, and Mg²⁺, compared to the papery-leaved *B. papyrifera*. The papery-leaved shrub *K. japonica* exhibited the highest contents of Ca²⁺, SO₄²⁻, Cl⁻, and NO₃⁻, but the lowest content of NH₄⁺. The leathery-leaved herb *H. vulgaris* showed higher contents of SO₄²⁻ and Na⁺, but lower contents of K⁺, Cl⁻, and Mg²⁺ compared to the papery-leaved *A. sessilis*.

The principal component analysis (PCA) revealed the influence of mass accumulation and water-soluble inorganic ions in particles deposited on trees, shrubs, and herbs, with total contributions of 65.0 %, 67.9 %, and 57.3 %, respectively (Fig. 6). For tree species, the first principal component (PC1, 47.8 %)

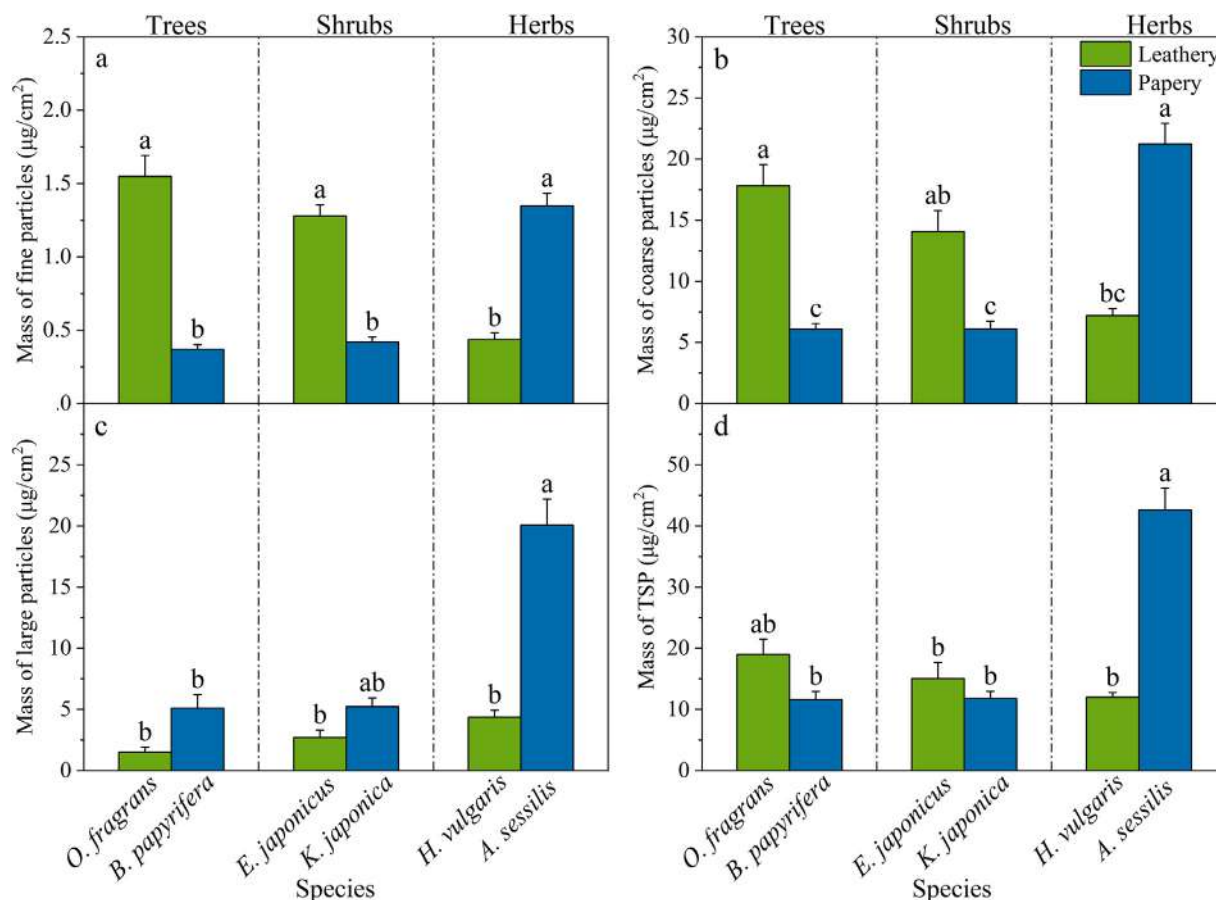


Fig. 1 – The mass concentrations of fine particles (a), coarse particles (b), large particles (c), and total suspended particles (TSP) (d) retained on the leaf surfaces of trees (*O. fragrans* and *B. papyrifera*), shrubs (*E. japonicus* and *K. japonica*), and herbs (*H. vulgaris* and *A. sessilis*), with leathery (green bar) and papery (blue bar) leaf textures, respectively. The data are presented as the Mean $\pm$ SE. Bars with different letters indicate significant differences, $p < 0.05$.

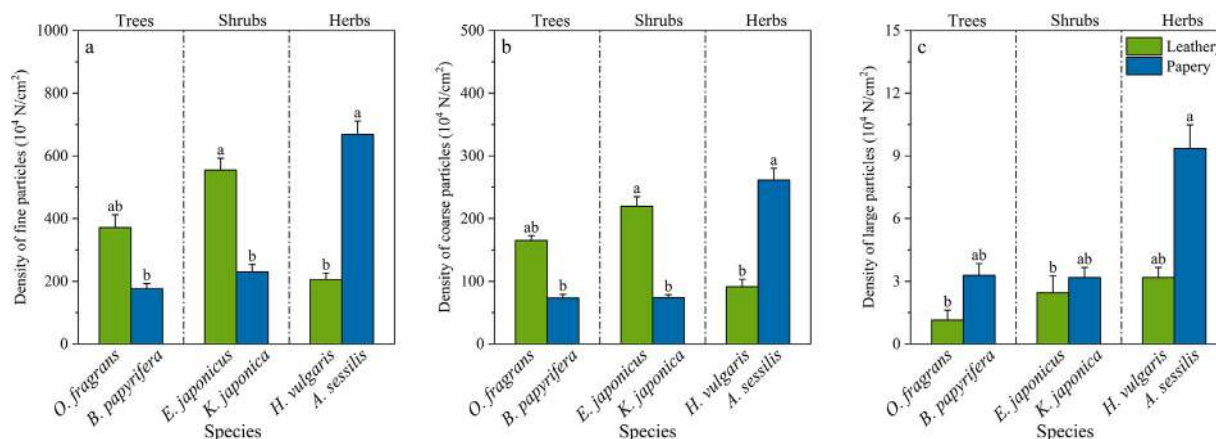


Fig. 2 – The number densities of fine particles (a), coarse particles (b), and large particles (c) retained on the leaf surface of trees (*O. fragrans* and *B. papyrifera*), shrubs (*E. japonicus* and *K. japonica*), and herbs (*H. vulgaris* and *A. sessilis*) with leathery (green bar) and papery (blue bar) leaf textures, respectively. The data are presented as the Mean $\pm$ SE. Bars with different letters indicate significant differences, $p < 0.05$.

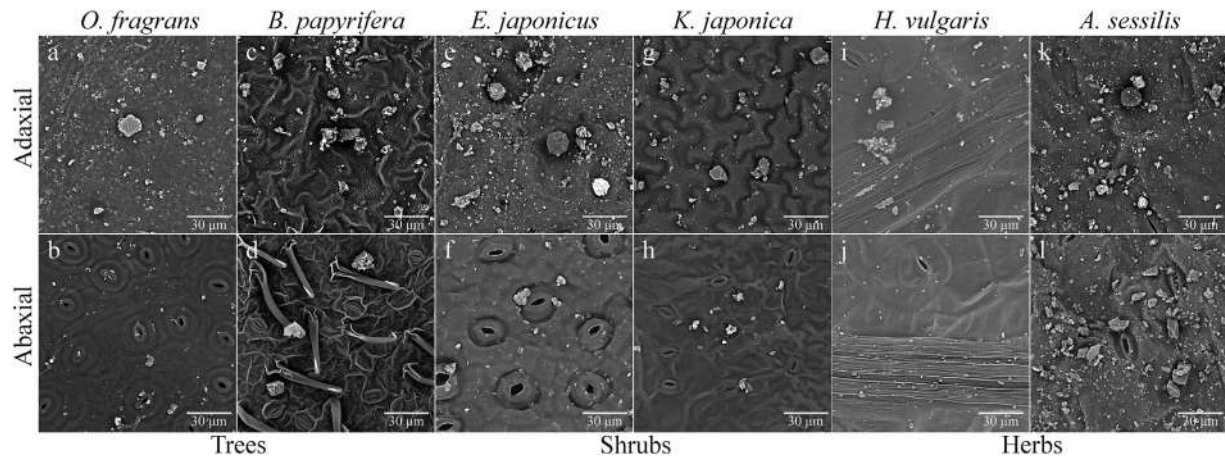


Fig. 3 – The scanning electron microscopy (SEM) images of the retained particles, as well as the micro-morphological characteristics of the adaxial (a, c, e, g, i, k) and abaxial (b, d, f, h, j, l) sides of the plant species, including *O. fragrans* (a, b), *B. papyrifera* (c, d), *E. japonicus* (e, f), *K. japonica* (g, h), *H. vulgaris* (i, j), and *A. sessilis* (k, l) at 2000× magnification, respectively.

Table 3 – Two-way ANOVA on the leaf functional traits of plants with different growth forms and leaf textures.

Leaf functional traits	F_f	F_t	$F_f \times F_t$
Leaf area	32.748***	20.345***	6.807**
Specific leaf area	10.658***	140.849***	64.937***
Leaf mass	33.700***	79.895***	26.067***
Leaf temperature	112.646***	12.525***	17.820***
Wax content	406.323***	529.349***	161.968***
Chlorophyll content	274.967***	549.666***	425.179***
Stomatal conductance	111.881***	158.398***	51.963***
Transpiration rate	332.884***	206.969***	63.105***
Photosynthesis rate	275.877***	205.315***	180.662***

F_f : treatment of growth forms; F_t : treatment of leaf textures.
 “*” $p < 0.05$; “**” $p < 0.01$; “***” $p < 0.001$.

was influenced by Ca^{2+} , fine particles, and coarse particles, while PC2 (17.2 %) was explained by NH_4^+ , NO_3^- , and large particles (Fig. 6a). For shrub species, PC1 (40.9 %) was positively related to Na^+ , Cl^- , and K^+ , but negatively related to TSP and fine particles. PC2 (27.0 %) was positively correlated with NO_3^- , SO_4^{2-} , and Ca^{2+} , but negatively related to K^+ , Cl^- , and Mg^{2+} (Fig. 6b). For herb species, PC1 (33.5 %) was explained by TSP, large particles, and coarse particles, while PC2 (23.8 %) was positively related to NH_4^+ , K^+ , and Na^+ , and negatively related to SO_4^{2-} and Ca^{2+} (Fig. 6c). Therefore, the characteristics of deposited particles had varying effects on different plant species.

2.2. Leaf functional traits of plants with different growth forms

The effects of particle deposition on morphological characteristics and leaf functional traits varied significantly with plant growth form and leaf texture (Table 3, Fig. 7, Appendix A Fig. S1 and S2). For tree species, the leathery-leaved *O. fragrans* had

higher leaf area, leaf mass, leaf temperature, wax content, and chlorophyll content, but a lower specific leaf area compared to the papery-leaved *B. papyrifera*. Notably, there was only a slight difference between these two species in stomatal conductance, transpiration rate, and photosynthesis rate under particle deposition. For shrub species, except for leaf area, specific leaf area, and leaf temperature, the leathery-leaved *E. japonicus* exhibited significant advantages in all other morphological characteristics and leaf functional traits compared to the papery-leaved *K. japonica*. Similarly, the leathery-leaved herb *H. vulgaris* surpassed the papery-leaved *A. sessilis* in most morphological characteristics and leaf functional traits, excluding leaf temperature and chlorophyll content. Overall, leathery-leaved shrubs and herbs outperformed papery-leaved ones in leaf functional traits under particle deposition.

2.3. Relationships between particle retention and leaf functional traits

Particle deposition correlated with the morphological characteristics and leaf functional traits of trees, shrubs, and herbs (Fig. 8). For trees, the masses of fine particles, coarse particles, and TSP were closely connected, positively correlating with leaf mass, leaf temperature, wax content, and chlorophyll content, but negatively correlating with specific leaf area. This relationship was reversed for large particles on trees (Fig. 8a). For shrubs, except for large particles, fine particles, coarse particles, and TSP were positively correlated with leaf mass, wax content, chlorophyll content, stomatal conductance, transpiration rate, and photosynthesis rate, but negatively correlated with specific leaf area and leaf temperature (Fig. 8b). For herbs, fine particles, coarse particles, large particles, and TSP were closely associated, showing a consistent pattern. They were positively correlated with leaf temperature and chlorophyll content, but negatively correlated with leaf area, specific leaf area, leaf mass, wax content, stomatal conductance, transpiration rate, and photosynthesis rate (Fig. 8c).

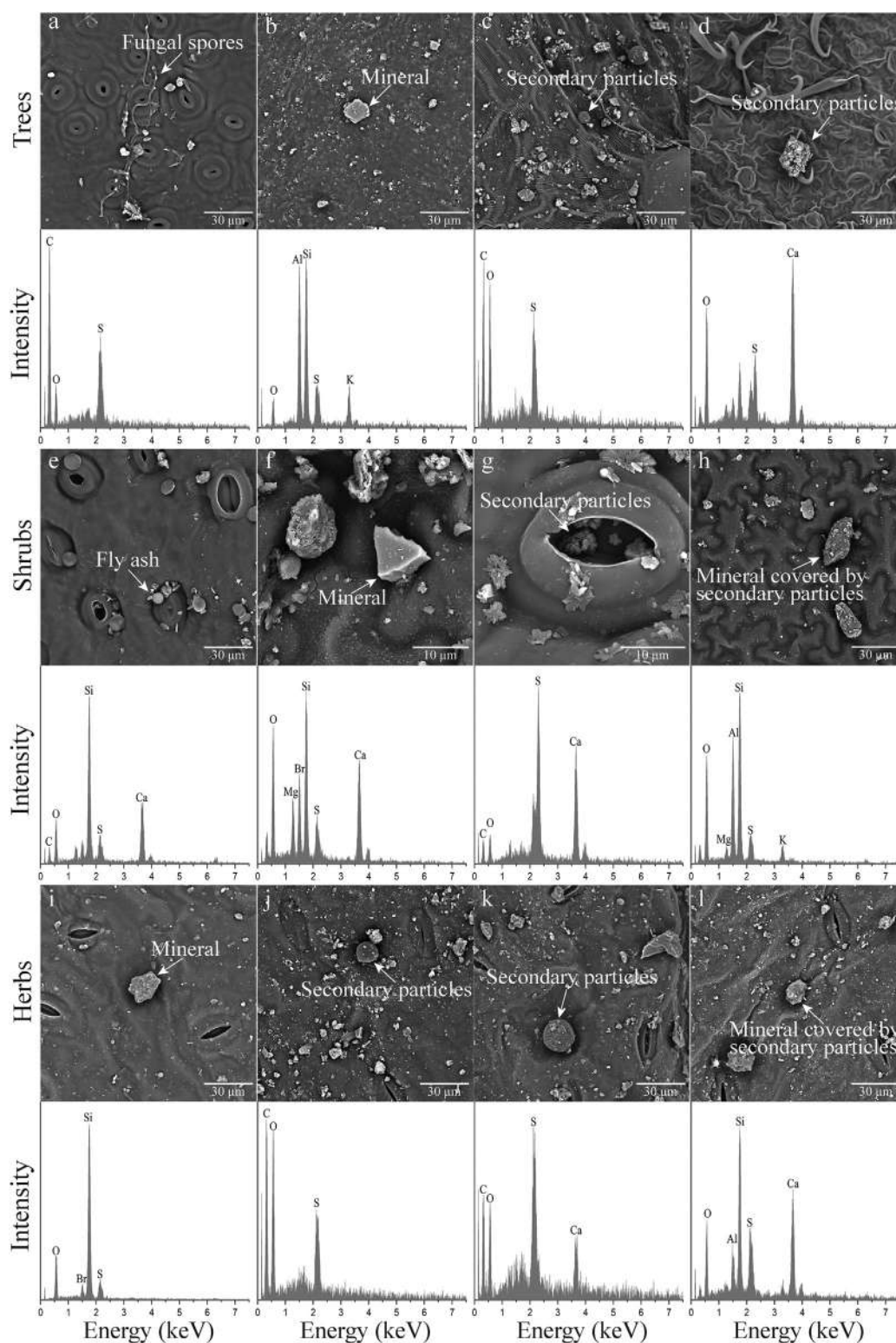


Fig. 4 – The high-resolution images obtained by scanning electron microscopy coupled with energy dispersion X-ray spectrometer (SEM-EDS) showed the main types of retained particles on the plant leaves. These included the fungal spores (a), mineral particles (b, f, i), secondary particles (c, d, g, j, k), fly ash particles (e), as well as the mineral particles covered with secondary particles (h, l), distributed on the leaf surface and even inside and outside the stomata of trees, shrubs, and herbs.

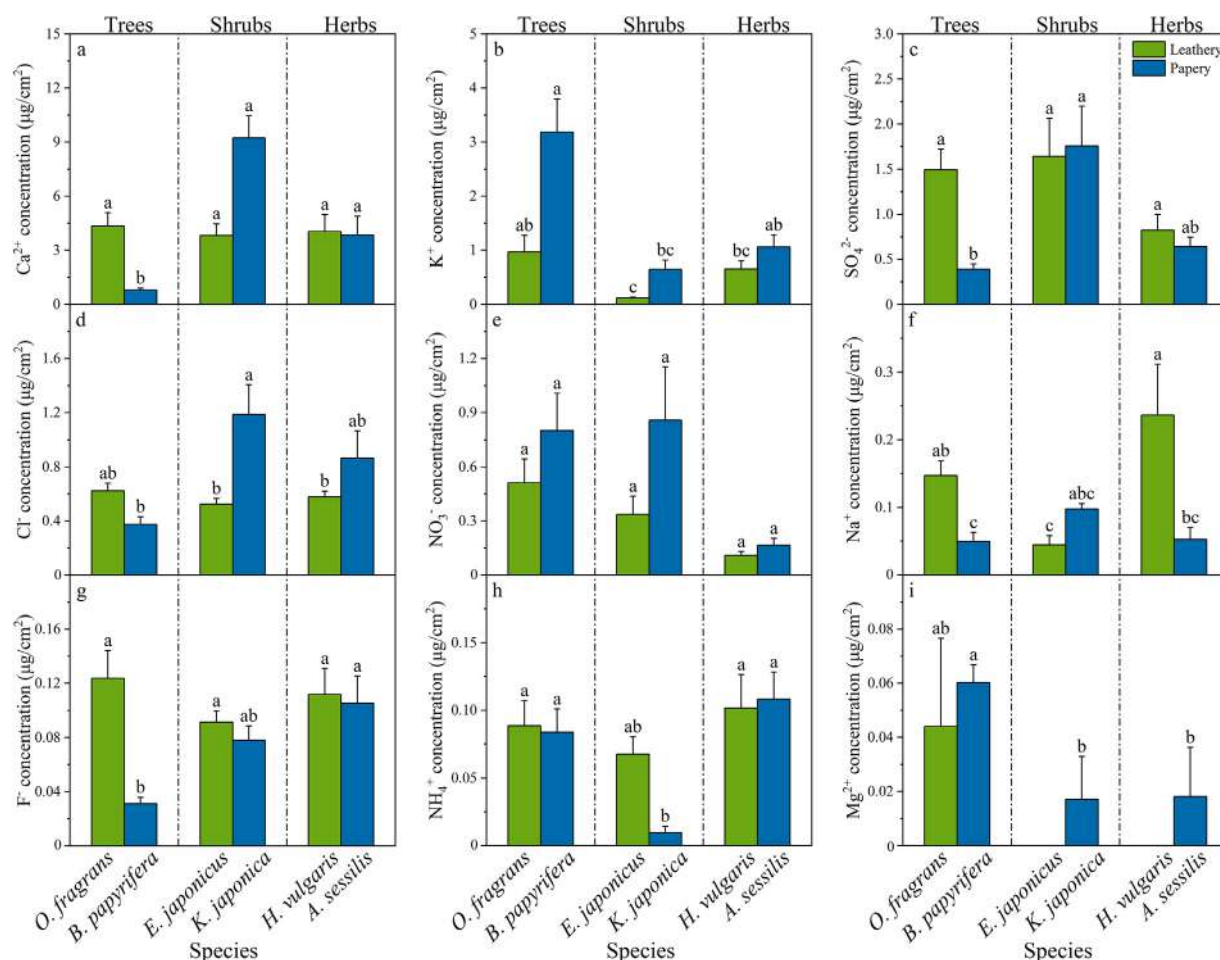


Fig. 5 – Mass concentrations of water-soluble inorganic ions, including Ca^{2+} (a), K^{+} (b), SO_4^{2-} (c), Cl^{-} (d), NO_3^{-} (e), Na^{+} (f), F^{-} (g), NH_4^{+} (h), and Mg^{2+} (i), in the particles retained on the leaf surface of trees (*O. fragrans* and *B. papyrifera*), shrubs (*E. japonicus* and *K. japonica*), and herbs (*H. vulgaris* and *A. sessilis*), with leathery (green bar) and papery (blue bar) leaf textures, respectively. The data are presented as the Mean $\pm$ SE. Bars with different letters indicate significant differences, $p < 0.05$.

3. Discussion

This study revealed that particle accumulation on plant leaves varies significantly with plant growth form and leaf texture. The substantial accumulation of fine particles by the leathery-leaved tree *O. fragrans* suggests that trees with leathery leaves are particularly effective at capturing particles compared to shrubs and herbs. This finding is consistent with previous studies. For instance, Zhao et al. (2024) analyzed 65 plant species in Beijing and found that trees retained 20 times more particles than shrubs. Similarly, He et al. (2020) reported that the evergreen trees *Taxus baccata* and *Pinus nigra* captured more particles than the evergreen shrubs *Prunus laurocerasus* and *Hedera helix*. This may be because trees have lush canopies, dense branches, and ample leaf area, which enable them to capture aerosol particles more effectively than shrubs and herbs with sparser structures (Chen et al., 2017; Yan et al., 2016). Additionally, the complex structure of plant groups reduces wind speed and air circulation, giving particles more time to settle on leaf surfaces (Salmond et al., 2013; Ysebaert et al., 2021).

Moreover, the papery-leaved herb *A. sessilis* demonstrated a high capacity for particle retention. Konczak et al. (2021) suggested that shrubs and vines play a significant role in retaining fine particles, while Abhijith and Kumar (2020) found that hedge leaves tend to accumulate a relatively higher mass of coarse particles than fine particles. The high mass of deposited particles on the leaves of herb *A. sessilis* may be attributed to the fact that herbs, as lower strata of vegetation, are more easily exposed to splashed soil compared to shrubs and trees (Chen et al., 2022). Additionally, this may be related to the fact that particles of different sizes have distinct deposition processes (Miao et al., 2022), with larger particles being more prone to colliding with leaf surfaces during sedimentation. For instance, fine particles tend to disperse, coarse particles deposit through collision, and large particles are more likely to return to the air as secondary suspension (Xu et al., 2022). This contributes to the greater mass of coarse particles being deposited on plant leaves.

Compared to papery-leaved plants, leathery-leaved plants accumulated a higher mass of fine and coarse particles, with the exception of the herbs *H. vulgaris* and *A. sessilis*. The high rigidity of leathery leaves makes them more effective at with-

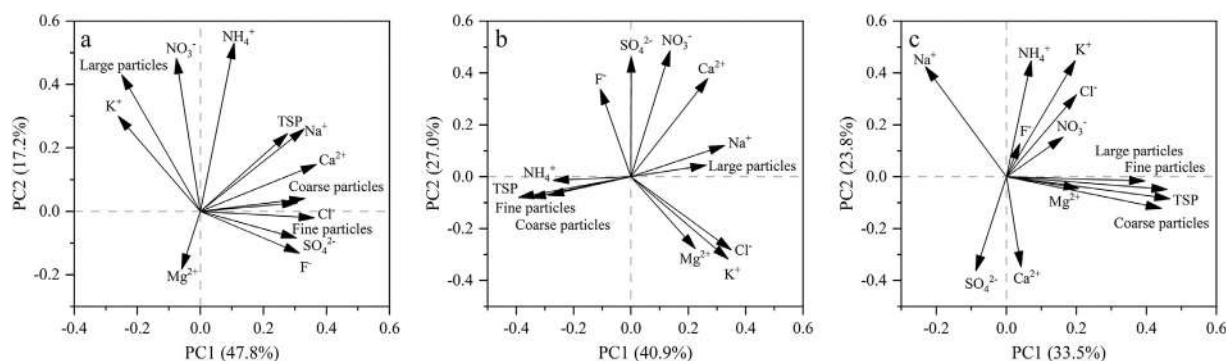


Fig. 6 – Principal component analysis (PCA) on the mass concentrations of particles of different sizes (i.e., fine particles, coarse particles, large particles, and total suspended particulates (TSP)), and the mass concentrations of water-soluble inorganic ions (such as, Ca²⁺, K⁺, SO₄²⁻, Cl⁻, NO₃⁻, Na⁺, F⁻, NH₄⁺, and Mg²⁺), from the leaf surfaces of trees (a), shrubs (b), and herbs (c), in response to different plant growth forms. PC indicates a principal component.

standing wind flow, resulting in increased particle deposition (Weerakkody et al., 2017). Additionally, smaller-sized particles tend to deposit in higher quantities. Shi et al. (2017) proposed the following order of particle number density for 14 urban plants: fine particles > coarse particles > large particles. However, in this study, the leathery-leaved tree *O. fragrans* exhibited a higher mass of fine and coarse particles, but had an intermediate particle density, indicating an uneven distribution of deposited particles. The disparity between the mass concentration and number density of deposited particles can be attributed to the relatively high mass of coarse particles. Additionally, the papery-leaved herb *A. sessilis* exhibited the highest density of deposited particles, indicating its superiority in particle retention.

The water-soluble inorganic ions of retained particles on plant leaves varied significantly among different plant species. Among all the water-soluble ions, Ca²⁺ was the most abundant. Similarly, Cao et al. (2022) found that Ca²⁺ (36.4 %) was the dominant ion component in particles retained on plant samples collected from 78 parks and campuses in China, and Ca²⁺ might be associated with sand and construction dusts (Velali et al., 2016). Moreover, SO₄²⁻ was the main ion component of retained particles, while NO₃⁻ was present at a medium concentration. Xu et al. (2018) observed high concentrations of SO₄²⁻ and NO₃⁻ in soluble particles on foliage. This may be because NO₃⁻ and SO₄²⁻ are dominant ions in secondary particles, formed by the gas-to-particle conversion of NO₂ and SO₂ from coal combustion or vehicle emissions (Khan et al., 2010). K⁺ was one of the major ions in particles captured on plant leaves, potentially emitted from biomass burning or leached from leaf surfaces (Li et al., 2019a; Xu et al., 2019). The low concentration of NH₄⁺ on leaf surface might be attributed to its absorption by plant leaves through the stomata or cuticle as a leaf fertilizer (Chen et al., 2020; Vátca et al., 2020). The low concentrations of Cl⁻ and Na⁺ suggest that waste incineration was minimal in the studied area (Wang et al., 2005). However, the concentration of Mg²⁺ was the lowest and even fell below the detection limit. In brief, measuring water-soluble inorganic ions provides insights into particle sources, indicating that the retained particles primarily originate from anthropogenic sources.

On the other hand, there are direct effects of dry-deposited inorganic compounds, which originate from deposited particles on leaf surfaces. The deposited atmospheric inorganic ions (NO₃⁻ and NH₄⁺) on leaf surfaces can generate the microscopic wetness and may cause epicuticular degradation of epicuticular wax (Katata and Held, 2021). In this study, the higher concentration of K⁺ in the papery-leaved *B. papyrifera* may be attributed to the leaching of inorganic ions from the leaf tissues, primarily due to leaf drying treatment. Additionally, the concentration of NO₃⁻ and NH₄⁺ may be potentially decreased by the treatment of leaf drying. Therefore, the measurement of inorganic ion with fresh leaf samples could be more effective to avoid the loss of water-soluble ions. Moreover, particles retained on plant leaves are likely to contain various organic compositions, such as, acetate and oxalate ions, some of which are essential for plant metabolism and catabolism (Frankowski, 2016; Gulick et al., 2023). The potential effects of organic compositions in retained particles on the plant leaves and their growth warrant further consideration.

This study provides insights into the role of leaf morphologic structures in particle retention across plant species, highlighting how the morphological characteristics of plant leaves are dominant factors in particle accumulation (Konczak et al., 2021; Li et al., 2021). This study found an abundance of large particles trapped in the leaf grooves of papery-leaved plants, allowing them to retain more large particles than leathery-leaved plants. This is consistent with the idea that grooves are key features of leaves for capturing particles (Liu et al., 2012). Different sizes of leaf grooves facilitate the trapping of different types of particles (Li et al., 2022). Furthermore, leaf trichomes often coexist with leaf grooves, enhancing the particle capture capability of plant leaves (Kardel et al., 2011; Kim et al., 2023; Mitchell et al., 2010). For instance, the papery-leaved tree *B. papyrifera* exhibits abundant trichomes that can capture large particles with their hooks. Therefore, the high accumulation of large particles by plants with papery leaves could be due to their dense grooves and trichomes, which effectively retain large particles and prevent them from being dislodged by airflow or re-suspended into the atmosphere.

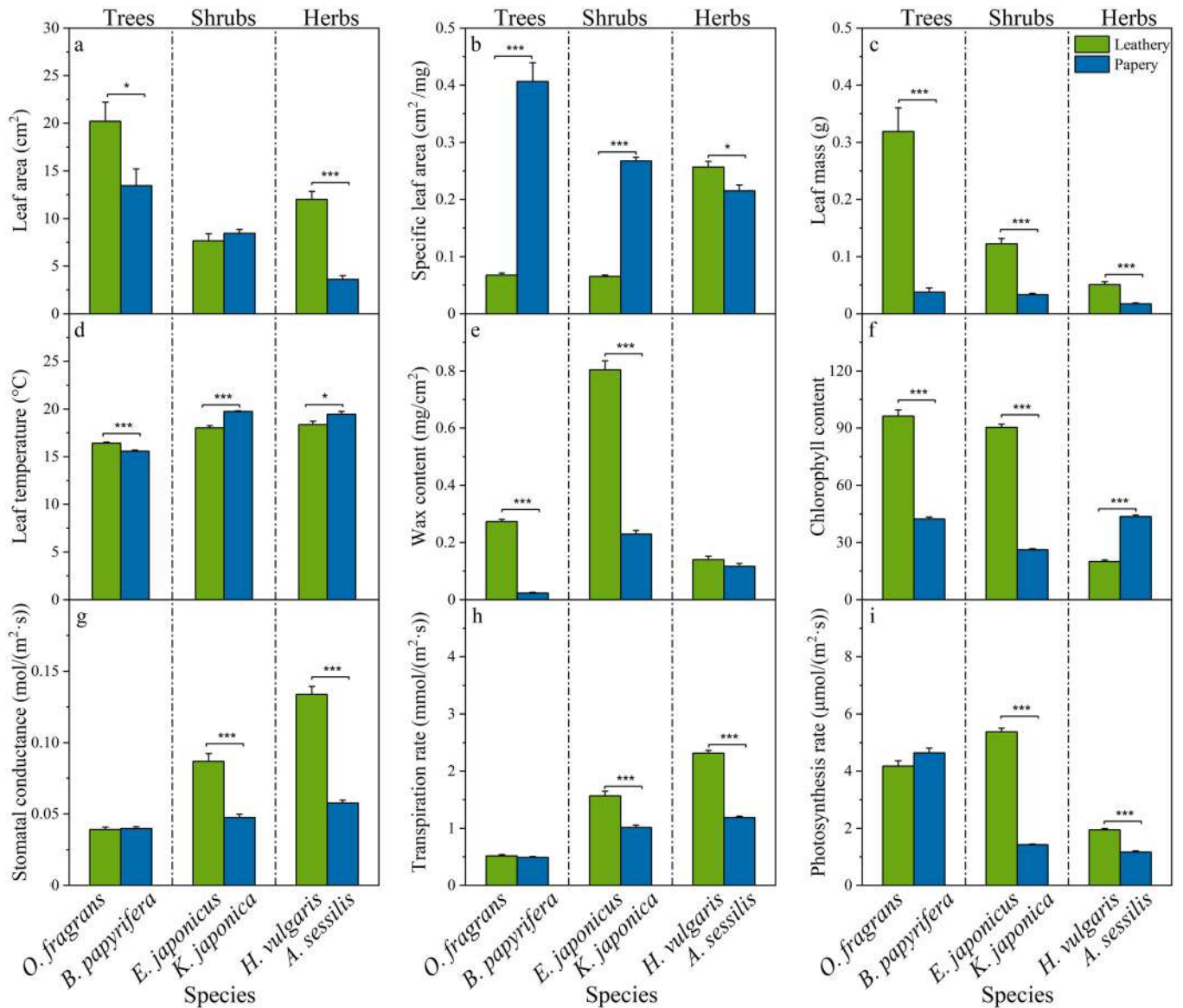


Fig. 7 – Leaf functional traits, including leaf area (a), specific leaf area (b), leaf biomass (c), leaf temperature (d), wax content (e), chlorophyll content (f), stomatal conductance (g), transpiration rate (h), and photosynthesis rate (i) of trees (*O. fragrans* and *B. papyrifera*), shrubs (*E. japonicus* and *K. japonica*), and herbs (*H. vulgaris* and *A. sessilis*) with leathery (green bar) and papery (blue bar) leaf textures, respectively. The data are presented as the Mean $\pm$ SE. “*”: $p < 0.05$; “***”: $p < 0.01$; “****”: $p < 0.001$.

Additionally, many morphological traits influence the particle capture efficacy of plant leaves (Gajbhiye et al., 2019; Räsänen et al., 2013). For instance, the waxy layer on plant leaves is thought to hinder contact between the leaf surface and deposited particles, leading to reduced particle capture. In this study, the leathery-leaved tree *O. fragrans* and the shrub *E. japonica*, both with prominent and visible wax layer, retained a high mass of particles. This finding aligns with the idea that a thick waxy layer on leaf surfaces facilitates particle accumulation (Mo et al., 2015; Shao et al., 2019). This can be explained by the sticky secretions in the waxy coating of plant leaves, which adhere to substantial aerosol particles (Niu et al., 2020). Therefore, high particle stabilization was evident both around stomata and on top of the ridges (Poppek et al., 2013). The waxy coating is directly proportional to the capacity

of plant leaves to trap atmospheric particles (Dang et al., 2022).

This study indicates that stomata play a crucial role in the interaction between plant leaves and particle retention. Leaf stomata are essential for plants to exchange gases (e.g., CO₂, etc.) during photosynthesis and respiration (Masterson, 1994). The leathery-leaved tree *O. fragrans*, with its higher particle density exhibited greater particle accumulation. Unlike trees and shrubs, which have stomata only on the abaxial side of their leaves, the herbs *H. vulgaris* and *A. sessilis* have stomata on both sides. Notably, *A. sessilis* has larger stomata pores, suggesting that its high particle capture ability can be attributed to its large stomata. The result is consistent with the idea that open stomata facilitate the retention of particles on leaf surfaces, and that plant leaves with large and dense stomata have

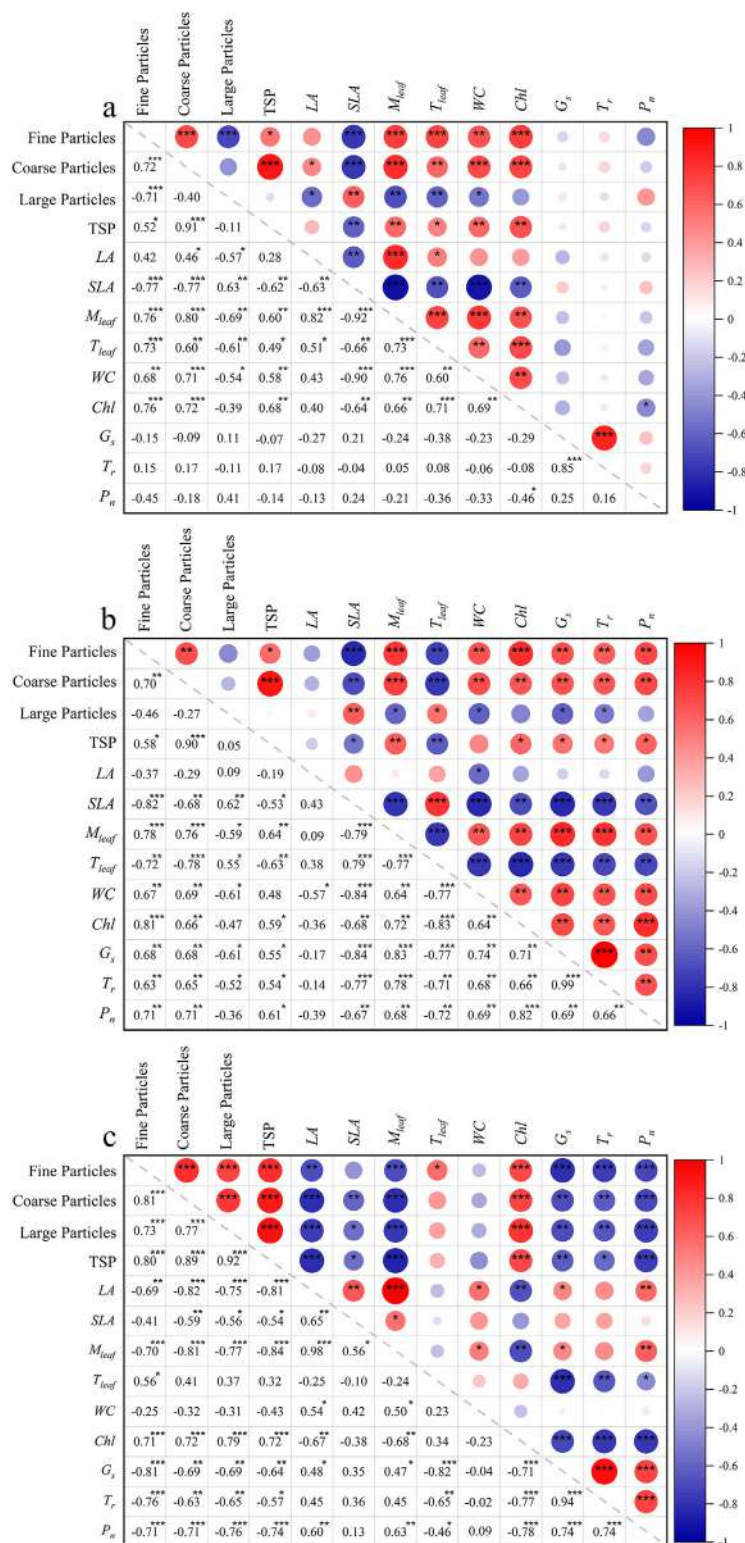


Fig. 8 – Spearman's analysis on the correlations between the mass concentrations of particles of different sizes (i.e., fine particles, coarse particles, large particles, and total suspended particulates (TSP)) and leaf functional traits, including leaf area (LA), specific leaf area (SLA), leaf mass (M_{leaf}), leaf temperature (T_{leaf}), wax content (WC), chlorophyll content (Chl), stomatal conductance (G_s), transpiration rate (T_r), and photosynthesis rate (P_n) of trees (a), shrubs (b), and herbs (c). “*”: $p < 0.05$; “”: $p < 0.01$; “***”: $p < 0.001$.**

a strong capability for particle retention (Lehndorff et al., 2006; Song et al., 2015; Zhang et al., 2022). Additionally, different particles exhibit distinct patterns of deposition. For example, coarse particles tend to cover the leaf surface or accumulate in stomata, while ultrafine particles can cause blockages and penetrate into stomata. However, certain heavy metal particles can penetrate the stomata and enter leaf tissue, potentially disrupting the physiological function of plants (Cui et al., 2022; Edelstein and Ben-Hur, 2018; Martín et al., 2018).

Consequently, particles retention has significant effects on plant functional traits, which can lead to changes in leaf structure and function (Chen et al., 2024), such as variations in stomatal conductance, photosynthesis rate (Popek et al., 2018), and chlorophyll content (Giri et al., 2013). In comparison, particle retention caused slight blockage of the stomata in trees and shrubs. This may be attributed to the grooves and trichomes on leaf surfaces, which provide a buffer period for the stomata to close during particle deposition. However, retained particles significantly impacted the functional traits of plants, leading to severe inhibition of the photosynthesis rate and even affecting plant growth, consistent with the results of previous studies (Lin et al., 2021; Lu et al., 2019; Popek et al., 2018). This is likely due to retained particles covering leaf surfaces and blocking the stomata, thereby inhibiting light absorption, gas exchange, and heat dissipation in plant leaves (Bukaveckas et al., 2011; Pavlík et al., 2012). This ultimately results in reduced photosynthesis, decreased transpiration rates, and increased leaf temperatures.

Furthermore, plant leaves exhibited morphological changes and coordinated functional traits under the influence of particle retention. Although chlorophyll content is closely linked to the photosynthesis rate of plants (Mänd et al., 2013), retained particles can decrease the photosynthesis rate of plant leaves, even when chlorophyll content is high (Singh et al., 2023). However, this study found varying correlations between retained particles and chlorophyll content across different plants, indicating their distinct responses and adaptations to particle retention. Surprisingly, the reduced photosynthesis rate was accompanied by a decreased specific leaf area in plants, such as the leathery-leaved tree *O. fragrans* and the papery-leaved herb *A. sessilis*. A low specific leaf area indicates that the leaf is thick, which may be related to the allocation of plant resources (Wright et al., 2004). Given the limited availability of resources, plants inevitably optimize their resource investment in functional traits, which is reflected in a series of interrelated trade-off strategies (Herben et al., 2012; Poorter et al., 2006). Additionally, plant leaves may alter stomatal conductance to adapt to the pressure of retained particles (Balasooriya et al., 2009; Kardel et al., 2013). As a result, higher stomata conductance on leaf surfaces makes it more difficult for particles to enter the stomatal cavity, leading to fewer retained particles and helping to prevent blockage.

This study serves as a reference for urban vegetation planning, suggesting that selecting plant species based on their particle accumulation capacity can help mitigate air pollution and enhance ecological benefits (Wróblewska and Jeong, 2021). The particle retention efficiency of plant species is influenced by their physiological characteristics, growth forms, and leaf functional traits (Silli et al., 2015; Yin et al.,

2022a). This study indicates that herbs in the lower strata of vegetation also significantly contribute to particle removal. In the management of urban vegetation for immobilizing particle pollution, herbs with diverse species and leaf morphologies warrant consideration. Combining plant species with different growth forms can effectively capture particles (Wang et al., 2023). For example, Niu et al. (2022) compared the particle removal capacity of different vegetation types, and found that a tree-shrub-herb configuration excelled in particle accumulation due to its intricate vegetation structure. Similarly, Chen et al. (2015) found that a tree-shrub-grass composite vegetation exhibited higher particle retention than tree-shrub or shrub-grass greenbelts, attributed to its vertical distribution of particles. Therefore, vegetation with diverse compositions and structures has a significant impact on ecosystem balance and ecological benefits, making it essential for urban green planning to select plant species that can effectively reduce particle pollution (He et al., 2020; Yao et al., 2023; Yin et al., 2022b). Furthermore, it is essential to select plant species with high ecological benefits after comprehensively assessing the particle deposition capabilities of a broader range of plants across various growth forms, which warrants further investigation.

4. Conclusions

This study investigated the particle capture abilities of six plant species (including trees, shrubs, and herbs), and examined how particle accumulation affects leaf functional traits. The results revealed that particle accumulation varied significantly based on growth form and leaf texture. Both the leathery-leaved tree *O. fragrans* and the papery-leaved herb *A. sessilis* demonstrated high competence in particle accumulation. This was likely related to leaf texture and morphologic structures, such as leaf grooves, trichomes, waxy layers, and stomata characteristics, which are closely associated with particle capture by plant species. The retained particles primarily contained Ca^{2+} , K^+ , SO_4^{2-} , NO_3^- and NH_4^+ , indicating their anthropogenic origins. Particle retention negatively affected plant functional traits by blocking stomata, decreasing photosynthesis, and reducing transpiration. Meanwhile, plant leaves adapted to the influence of retained particles by decreasing specific leaf area and altering stomatal conductance. In summary, the ability of plant species to retain particles is influenced by their growth forms and leaf textures. The significant contribution of plants, especially herbs in the lower vegetation strata, to particle removal, should not be overlooked. In summary, vegetation with a tree-shrub-herb configuration excels at particle capture, and this diverse plant arrangement contributes to mitigating particle pollution and enhancing ecological benefits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Fangmin Fei: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Siqi Chen:** Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Yaobin Song:** Writing – review & editing. **Ming Dong:** Writing – review & editing. **Hua Yu:** Writing – review & editing, Funding acquisition.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 31700475).

Appendix A Supplementary data

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jes.2024.11.031.

REFERENCES

- Abhijith, K.V., Kumar, P., 2020. Quantifying particulate matter reduction and their deposition on the leaves of green infrastructure. *Environ. Pollut.* 265, 114884.
- Balasoorya, B., Samson, R., Mbikwa, F., Vitharana, U.W.A., Boeckx, P., Van Meirvenne, M., 2009. Biomonitoring of urban habitat quality by anatomical and chemical leaf characteristics. *Environ. Exp. Bot.* 65 (65), 386–394.
- Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2000. Particulate pollution capture by urban trees: effect of species and windspeed. *Global Change Biol.* 6 (8), 995–1003.
- Bukaveckas, P.A., MacDonald, A., Aufdenkampe, A., Chick, J.H., Havel, J.E., Schultz, R., et al., 2011. Phytoplankton abundance and contributions to suspended particulate matter in the Ohio, upper mississippi and missouri rivers. *Aquat. Sci.* 73 (3), 419–436.
- Cao, Z.G., Wu, X.Y., Wang, T.Y., Zhao, Y.H., Zhao, Y.H., Wang, D.Y., et al., 2022. Characteristics of airborne particles retained on conifer needles across China in winter and preliminary evaluation of the capacity of trees in haze mitigation. *Sci. Total Environ.* 806, 150704.
- Cen, S., 2015. Biological monitoring of air pollutants and its influence on human beings. *Open Biomed. Eng. J.* 9, 219–223.
- Chen, H., Xia, D.S., Wang, B., Liu, H., Ma, X.Y., 2022. Pollution monitoring using the leaf-deposited particulates and magnetism of the leaves of 23 plant species in a semi-arid city, Northwest China. *Environ. Sci. Pollut. Res.* 29 (23), 34898–34911.
- Chen, H.Z., Yang, J., Deng, X.X., Lei, Y.J., Xie, S., Guo, S.H., et al., 2020. Foliar-sprayed manganese sulfate improves flavonoid content in grape berry skin of Cabernet Sauvignon (*Vitis vinifera* L.) growing on alkaline soil and wine chromatic characteristics. *Food Chem.* 314, 126182.
- Chen, L.X., Liu, C.M., Zhang, L., Zou, R., Zhang, Z.Q., 2017. Variation in tree species ability to capture and retain airborne fine particulate matter (PM_{2.5}). *Sci. Rep.* 7, 3206.
- Chen, S.Q., Yu, H., Xu, L., Fei, F.M., Song, Y.B., Dong, M., et al., 2024. Characterizing accumulation and negative effects of aerosol particles on the leaves of urban trees. *Environ. Pollut.* 340, 122812.
- Chen, X.P., Pei, T.T., Zhou, Z.X., Teng, M.J., He, L., Luo, M., et al., 2015. Efficiency differences of roadside greenbelts with three configurations in removing coarse particles (PM₁₀): a street scale investigation in Wuhan, China. *Urban For. Urban Green* 14 (2), 354–360.
- Cui, N., Qu, L.Y., Wu, G., 2022. Heavy metal accumulation characteristics and physiological response of *Sabina chinensis* and *Platycladus orientalis* to atmospheric pollution. *J. Environ. Sci.* 112, 192–201.
- Dang, N., Zhang, H.D., Salam, M.M.A., Li, H.M., Chen, G.C., 2022. Foliar dust particle retention and metal accumulation of five garden tree species in Hangzhou: seasonal changes. *Environ. Pollut.* 306, 119472.
- Dzierzanowski, K., Popek, R., Gawronska, H., Sæbo, A., Gawronski, S.W., 2011. Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. *Int. J. Phytorem.* 13 (10), 1037–1046.
- Edelstein, M., Ben-Hur, M., 2018. Heavy metals and metalloids: sources, risks and strategies to reduce their accumulation in horticultural crops. *Sci. Hortic.* 234, 431–444.
- Escobedo, P.J., Wagner, J.E., Nowak, D.J., De la Maza, C.L., Rodriguez, M., Crane, D.E., 2008. Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *J. Environ. Manage.* 86 (1), 148–157.
- Finer, M., Jenkins, C.N., Pimm, S.L., Keane, B., Ross, C., 2008. Oil and gas projects in the western Amazon: threats to wilderness, biodiversity, and indigenous peoples. *PLoS One* 3 (8), e2932.
- Frankowski, M., 2016. Simultaneous determination of inorganic and organic ions in plant parts of *Betula pendula* from two different types of ecosystems (Wielkopolski National Park and Chemical Plant in Lubon, Poland). *Environ. Sci. Pollut. Res.* 23 (11), 11046–11057.
- Gajbhiye, T., Pandey, S.K., Lee, S.S., Kim, K.H., 2019. Size fractionated phytomonitoring of airborne particulate matter (PM) and speciation of PM bound toxic metals pollution through *Calotropis procera* in an urban environment. *Ecol. Indic.* 104, 32–40.
- Gallagher, M.W., Nemitz, E., Dorsey, J.R., Fowler, D., Sutton, M.A., Flynn, M., et al., 2002. Measurements and parameterizations of small aerosol deposition velocities to grassland, arable crops, and forest: influence of surface roughness length on deposition. *J. Geophys. Res.* 107, 287–292.
- Giri, S., Shrivastava, D., Deshmukh, K., Dubey, P., 2013. Effect of air pollution on chlorophyll content of leaves. *Curr. Agric. Res. J.* 1 (2), 93–98.
- Gulick, S., Carrico, C.M., Frey, B., Baca, D., Dubey, M.K., 2023. Plant versus local soil inorganic ionic composition: the relationship to biomass smoke. *Sci. Total Environ.* 895, 164967.
- Gunthe, S.S., Liu, P.F., Panda, U., Raj, S.S., Sharma, A., Darbyshire, E., et al., 2021. Enhanced aerosol particle growth sustained by high continental chlorine emission in India. *Nat. Geosci.* 14 (2), 77–84.
- Han, D.H., Shen, H.L., Duan, W.B., Chen, L.X., 2020. A review on particulate matter removal capacity by urban forests at different scales. *Urban For. Urban Green* 48, 126565.
- Harrison, R.M., Yin, J., 2000. Particulate matter in the atmosphere: which particle properties are important for its effects on health? *Sci. Total Environ.* 249 (1–3), 85–101.
- He, C., Qiu, K.Y., Alahmad, A., Pott, R., 2020. Particulate matter capturing capacity of roadside evergreen vegetation during the winter season. *Urban For. Urban Green* 48, 126510.
- Herben, T., Nováková, Z., Klimesová, J., Hrouda, L., 2012. Species traits and plant performance: functional trade-offs in a large set of species in a botanical garden. *J. Ecol.* 100 (6), 1522–1533.
- Hofman, J., Bartholomeus, H., Janssen, S., Calders, K., Wuyts, K., Van Wittenberghe, S., et al., 2016. Influence of tree crown characteristics on the local PM₁₀ distribution inside an urban street canyon in Antwerp (Belgium): a model and experimental approach. *Urban For. Urban Green* 20, 265–276.

- Jacob, D.J., Winner, D.A., 2009. Effect of climate change on air quality. *Atmos. Environ.* 43 (1), 51–63.
- Janhäll, S., 2015. Review on urban vegetation and particle air pollution-deposition and dispersion. *Atmos. Environ.* 105, 130–137.
- Jiang, P., Xu, G.P., He, Y.F., Sun, T.T., Liu, C.L., Chen, C.W., et al., 2021. Complete chloroplast genome of *Alternanthera philoxeroides* by *de novo* sequencing. *Mitochondrial DNA B Resour* 6 (7), 1826–1828.
- Jiao, P., Chaoyang, L., Wenhan, Z., Jingyi, D., Yunlin, Z., Zhenggang, X., 2022. Integrative metabolome and transcriptome analysis of flavonoid biosynthesis genes in *Broussonetia papyrifera* leaves from the perspective of sex differentiation. *Front. Plant Sci.* 13, 900030.
- Kardel, F., Wuyts, K., Khavaninzadeh, A.R., Wuytack, T., Babanezhad, M., Samson, R., 2013. Comparison of leaf saturation isothermal remanent magnetisation (SIRM) with anatomical, morphological and physiological tree leaf characteristics for assessing urban habitat quality. *Environ. Pollut.* 183, 96–103.
- Kardel, F., Wuyts, K., Maher, B.A., Hansard, R., Samson, R., 2011. Leaf saturation isothermal remanent magnetization (SIRM) as a proxy for particulate matter monitoring: inter-species differences and in-season variation. *Atmos. Environ.* 45 (29), 5164–5171.
- Katata, G., Held, A., 2021. Combined measurements of microscopic leaf wetness and dry-deposited inorganic compounds in a spruce forest. *Atmos. Pollut. Res.* 12 (2), 217–224.
- Khan, M.F., Hirano, K., Masunaga, S., 2010. Quantifying the sources of hazardous elements of suspended particulate matter aerosol collected in Yokohama. *Japan. Atmos. Environ.* 44 (21–22), 2646–2657.
- Kim, J., Kim, J., Kim, Y., Go, T., Lee, S.J., 2023. Accelerated settling velocity of airborne particulate matter on hairy plant leaves. *J. Environ. Manage.* 332, 117313.
- Konczak, B., Cempa, M., Pierzchala, L., Deska, M., 2021. Assessment of the ability of roadside vegetation to remove particulate matter from the urban air. *Environ. Pollut.* 268, 115465.
- Kwak, M.J., Lee, J., Kim, H., Park, S., Lim, Y., Kim, J.E., et al., 2019. The removal efficiencies of several temperate tree species at adsorbing airborne particulate matter in urban forests and roadsides. *Forests* 10 (11), 960.
- Lehndorff, E., Ubat, M., Schwark, L., 2006. Accumulation histories of magnetic particles on pine needles as function of air quality. *Atmos. Environ.* 40 (36), 7082–7096.
- Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525 (7569), 367.
- Li, G., Wang, L.H., Sun, F.B., Wang, Y.J., Wu, H.T., Hu, Z.W., et al., 2020. Capacity of landscaping plants to accumulate airborne particulate matter in Hangzhou, China. *Pol. J. Environ. Stud.* 29 (1), 153–161.
- Li, R., Cui, L.L., Zhao, Y.L., Zhang, Z.Y., Sun, T.M., Li, J.L., et al., 2019a. Wet deposition of inorganic ions in 320 cities across China: spatio-temporal variation, source apportionment, and dominant factors. *Atmos. Chem. Phys.* 19 (17), 11043–11070.
- Li, X.L., Zhang, T.R., Sun, F.B., Song, X.M., Zhang, Y.K., Huang, F., et al., 2021. The relationship between particulate matter retention capacity and leaf surface micromorphology of ten tree species in Hangzhou, China. *Sci. Total Environ.* 771, 144812.
- Li, Y., Zhang, X.Y., Li, M.N., Yin, S., Zhang, Z., Zhang, T., et al., 2022. Particle resuspension from leaf surfaces: effect of species, leaf traits and wind speed. *Urban For. Urban Green* 77, 127740.
- Li, Y.M., Wang, S.J., Chen, Q.B., 2019b. Potential of thirteen urban greening plants to capture particulate matter on leaf surfaces across three levels of ambient atmospheric pollution. *Int. J. Environ. Res. Public Health* 16 (3), 402.
- Lin, X.T., Shu, D., Zhang, J., Chen, J., Zhou, Y.H., Chen, C.W., 2021. Dynamics of particle retention and physiology in *Euonymus japonicus* Thunb. var. *aurea-marginatus* Hort. with severe exhaust exposure under continuous drought. *Environ. Pollut.* 285, 117194.
- Liu, L., Guan, D.S., Peart, M.R., 2012. The morphological structure of leaves and the dust-retaining capability of afforested plants in urban Guangzhou, South China. *Environ. Sci. Pollut. Res.* 19 (8), 3440–3449.
- Lu, T., Lin, X.T., Chen, J., Huang, D.M., Li, M., 2019. Atmospheric particle retention capacity and photosynthetic responses of three common greening plant species under different pollution levels in Hangzhou. *Glob. Ecol. Conserv.* 20, e00783.
- Luo, D., Xu, B., Li, Z.M., Sun, H., 2021. Biogeographical divides delineated by the three-step landforms of China and the East China Sea: insights from the phylogeography of *Kerria japonica*. *J. Biogeogr.* 48 (2), 372–385.
- Maher, B.A., Ahmed, I.A.M., Davison, B., Karloukovski, V., Clarke, R., 2013. Impact of roadside tree lines on indoor concentrations of traffic-derived particulate matter. *Environ. Sci. Technol.* 47 (23), 13737–13744.
- Mänd, P., Hallik, L., Peñuelas, J., Kull, O., 2013. Electron transport efficiency at opposite leaf sides: effect of vertical distribution of leaf angle, structure, chlorophyll content and species in a forest canopy. *Tree Physiol* 33 (2), 202–210.
- Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E., 2020. Environmental and health impacts of air pollution: a review. *Front. Public Health* 8, 14.
- Martín, A., Caldelas, C., Weiss, D., Aranjuelo, I., Navarro, E., 2018. Assessment of metal immission in urban environments using elemental concentrations and zinc isotope signatures in leaves of *Nerium oleander*. *Environ. Sci. Technol.* 52 (4), 2071–2080.
- Masterson, J., 1994. Stomatal size in fossil plants: evidence for polyploidy in majority of angiosperms. *Science* 264 (5157), 421–424.
- Miao, C.P., Li, P.P., Yu, S., Chen, W., He, X.Y., 2022. Does street canyon morphology shape particulate matter reduction capacity by street trees in real urban environments? *Urban For. Urban Green* 78, 127762.
- Mitchell, R., Maher, B.A., Kinnersley, R., 2010. Rates of particulate pollution deposition onto leaf surfaces: temporal and inter-species magnetic analyses. *Environ. Pollut.* 158 (5), 1472–1478.
- Mo, L., Ma, Z.Y., Xu, Y.S., Sun, F.B., Lun, X.X., Liu, X.H., et al., 2015. Assessing the capacity of plant species to accumulate particulate matter in Beijing, China. *PLoS One* 10 (10), e0140664.
- Mu, H.N., Li, H.G., Wang, L.G., Yang, X.L., Sun, T.Z., Xu, C., 2014. Transcriptome sequencing and analysis of sweet osmanthus (*Osmanthus fragrans* Lour.). *Genes Genomics* 36 (6), 777–788.
- Nel, A., 2005. Air pollution-related illness: effects of particles. *Science* 308 (5723), 804–806.
- Nguyen, T., Yu, X.X., Zhang, Z.M., Liu, M.M., Liu, X.H., 2015. Relationship between types of urban forest and PM_{2.5} capture at three growth stages of leaves. *J. Environ. Sci.* 27, 33–41.
- Niu, X., Li, Y., Li, M.N., Zhang, T., Meng, H., Zhang, Z., et al., 2022. Understanding vegetation structures in green spaces to regulate atmospheric particulate matter and negative air ions. *Atmos. Pollut. Res.* 13 (9), 101534.
- Niu, X., Wang, B., Wei, W.J., 2020. Response of the particulate matter capture ability to leaf age and pollution intensity. *Environ. Sci. Pollut. Res.* 27 (27), 34258–34269.
- Ozdemir, H., 2019. Mitigation impact of roadside trees on fine particle pollution. *Sci. Total Environ.* 659, 1176–1185.

- Pavlik, M., Pavliková, D., Zemanová, V., Hnilicka, F., Urbanová, V., Száková, J., 2012. Trace elements present in airborne particulate matter-stressors of plant metabolism. *Ecotoxicol. Environ. Saf.* 79, 101–107.
- Perini, K., Ottelé, M., Giulini, S., Magliocco, A., Roccotiello, E., 2017. Quantification of fine dust deposition on different plant species in a vertical greening system. *Ecol. Eng.* 100, 268–276.
- Petroff, A., Mailliat, A., Amielh, M., Anselmet, F., 2008. Aerosol dry deposition on vegetative canopies. Part I: review of present knowledge. *Atmos. Environ.* 42 (16), 3625–3653.
- Poorter, L., Bongers, L., Bongers, F., 2006. Architecture of 54 moist-forest tree species: traits, trade-offs, and functional groups. *Ecology* 87 (5), 1289–1301.
- Popek, R., Gawronska, H., Wrochna, M., Gawronski, S.W., Sæbo, A., 2013. Particulate matter on foliage of 13 woody species: deposition on surfaces and phytostabilisation in waxes - a 3-year study. *Int. J. Phytorem.* 15 (3), 245–256.
- Popek, R., Przybysz, A., Gawronska, H., Klamkowski, K., Gawronski, S.W., 2018. Impact of particulate matter accumulation on the photosynthetic apparatus of roadside woody plants growing in the urban conditions. *Ecotoxicol. Environ. Saf.* 163, 56–62.
- Prusty, B.A.K., Mishra, P.C., Azeez, P.A., 2005. Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. *Ecotoxicol. Environ. Saf.* 60 (2), 228–235.
- Räsänen, J.V., Holopainen, T., Joutsensaari, J., Ndam, C., Pasanen, P., Rinnan, Å., et al., 2013. Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees. *Environ. Pollut.* 183, 64–70.
- Sæbo, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronska, H., Gawronski, S.W., 2012. Plant species differences in particulate matter accumulation on leaf surfaces. *Sci. Total Environ.* 427, 347–354.
- Salmond, J.A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., et al., 2016. Health and climate related ecosystem services provided by street trees in the urban environment. *Environ. Health* 15, 36.
- Salmond, J.A., Williams, D.E., Laing, G., Kingham, S., Dirks, K., Longley, I., et al., 2013. The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. *Sci. Total Environ.* 443, 287–298.
- Schichtel, B.A., Hand, J.L., Barna, M.G., Gebhart, K.A., Copeland, S., Vimont, J., et al., 2017. Origin of fine particulate carbon in the rural United States. *Environ. Sci. Technol.* 51 (17), 9846–9855.
- Seamans, G.S., 2013. Mainstreaming the environmental benefits of street trees. *Urban For. Urban Green* 12 (1), 2–11.
- Shao, F., Wang, L.H., Sun, F.B., Li, G., Yu, L., Wang, Y.J., et al., 2019. Study on different particulate matter retention capacities of the leaf surfaces of eight common garden plants in Hangzhou, China. *Sci. Total Environ.* 652, 939–951.
- Shi, J.N., Zhang, G., An, H.L., Yin, W.L., Xia, X.L., 2017. Quantifying the particulate matter accumulation on leaf surfaces of urban plants in Beijing, China. *Atmos. Pollut. Res.* 8 (5), 836–842.
- Sillars-Powell, L., Tallis, M.J., Fowler, M., 2020. Road verge vegetation and the capture of particulate matter air pollution. *Environ* 7 (10), 93.
- Silli, V., Salvatori, E., Manes, F., 2015. Removal of airborne particulate matter by vegetation in an urban park in the city of Rome (Italy): an ecosystem services perspective. *Ann. Bot.* 5, 53–62.
- Singh, A.K., Kumar, M., Baudh, K., Singh, A., Singh, P., Madhav, S., et al., 2023. Environmental impacts of air pollution and its abatement by plant species: a comprehensive review. *Environ. Sci. Pollut. Res.* 30 (33), 79587–79616.
- Song, Y.S., Maher, B.A., Li, F., Wang, X.K., Sun, X., Zhang, H.X., 2015. Particulate matter deposited on leaf of five evergreen species in Beijing, China: source identification and size distribution. *Atmos. Environ.* 105, 53–60.
- Subhash, N., Mohanan, C.N., Mallia, R.J., Muralidharan, V., 2004. Quantification of stress adaptation by laser-induced fluorescence spectroscopy of plants exposed to engine exhaust emission and drought. *Funct. Plant Biol.* 31 (7), 709–719.
- Tang, L., Mo, K.L., Chen, Q.W., Zhang, J.Y., Xia, J., Lin, Y.Q., 2020. An experimental study on potential changes in plant community evapotranspiration due to the invasion of *Hydrocotyle vulgaris*. *J. Hydroenviron. Res.* 30, 63–70.
- Terzaghi, E., Wild, E., Zacchello, G., Cerabolini, B.E.L., Jones, K.C., Di Guardo, A., 2013. Forest filter effect: role of leaves in capturing/releasing air particulate matter and its associated PAHs. *Atmos. Environ.* 74, 378–384.
- Tong, Z.M., Whitlow, T.H., MacRae, P.F., Landers, A.J., Harada, Y., 2015. Quantifying the effect of vegetation on near-road air quality using brief campaigns. *Environ. Pollut.* 201, 141–149.
- Vătaș, S., Gâdea, S., Vătaș, A., Chînia, D., Stoian, V., 2020. Black currant response to foliar fertilizers - modeling of varietal growth dynamics. *J. Plant Nutr.* 43 (14), 2144–2151.
- Velali, E., Papachristou, E., Pantazaki, A., Choli-Papadopolou, T., Planou, S., Kouras, A., et al., 2016. Redox activity and in vitro bioactivity of the water-soluble fraction of urban particulate matter in relation to particle size and chemical composition. *Environ. Pollut.* 208, 774–786.
- Wang, H.M., Hu, W.T., Luo, S., Liu, M.Y., Chen, J.R., Chen, Q.Z., et al., 2023. Size distribution and elemental composition of airborne particulate matter on four plant species in vertical greenery systems. *Build. Environ.* 245, 110888.
- Wang, L., Liu, L.Y., Gao, S.Y., Hasi, E., Wang, Z., 2006. Physicochemical characteristics of ambient particles settling upon leaf surfaces of urban plants in Beijing. *J. Environ. Sci.* 18 (5), 921–926.
- Wang, Y., Zhuang, G.S., Tang, A., Yuan, H., Sun, Y., Chen, S., et al., 2005. The ion chemistry and the source of PM_{2.5} aerosol in Beijing. *Atmos. Environ.* 39.
- Weber, F., Kowarik, I., Säumel, I., 2014. Herbaceous plants as filters: immobilization of particulates along urban street corridors. *Environ. Pollut.* 186, 234–240.
- Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2017. Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. *Urban For. Urban Green* 27, 173–186.
- Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2018. The impact of rainfall in remobilising particulate matter accumulated on leaves of four evergreen species grown on a green screen and a living wall. *Urban For. Urban Green* 35, 21–31.
- Wright, I.J., Groom, P.K., Lamont, B.B., Poot, P., Prior, L.D., Reich, P.B., et al., 2004. Leaf trait relationships in Australian plant species. *Funct. Plant Biol.* 31 (5), 551–558.
- Wróblewska, K., Jeong, B.R., 2021. Effectiveness of plants and green infrastructure utilization in ambient particulate matter removal. *Environ. Sci. Eur.* 33 (1), 110.
- Xu, B., Wang, J.N., Shi, F.S., 2020. Impacts of ontogenetic and altitudinal changes on morphological traits and biomass allocation patterns of *Fritillaria unibracteata*. *J. Mount. Sci.* 17 (1), 83–94.
- Xu, L.S., Yan, Q., Liu, L.W., He, P., Zhen, Z.L., Duan, Y.H., et al., 2022. Variations of particulate matter retention by foliage after wind and rain disturbance. *Air Qual. Atmos. Health* 15 (3), 437–447.
- Xu, X.W., Yu, X.X., Mo, L., Xu, Y.S., Bao, L., Lun, X.X., 2019. Atmospheric particulate matter accumulation on trees: a comparison of boles, branches and leaves. *J. Clean. Prod.* 226, 349–356.

- Xu, X.W., Zhang, Z.M., Bao, L., Mo, L., Yu, X.X., Fan, D.X., et al., 2017. Influence of rainfall duration and intensity on particulate matter removal from plant leaves. *Sci. Total Environ.* 609, 11–16.
- Xu, Y.S., Xu, W., Mo, L., Heal, M.R., Xu, X.W., Yu, X.X., 2018. Quantifying particulate matter accumulated on leaves by 17 species of urban trees in Beijing, China. *Environ. Sci. Pollut. Res.* 25 (13), 12545–12556.
- Yan, J.L., Lin, L., Zhou, W.Q., Han, L.J., Ma, K.M., 2016. Quantifying the characteristics of particulate matters captured by urban plants using an automatic approach. *J. Environ. Sci.* 39, 259–267.
- Yao, J., Chen, N.A., Liu, M., Chen, W., He, X.Y., 2023. An analysis of the co-benefits of the supply-demand for multiple ecosystem services for guiding sustainable urban development. *Ecol. Indic.* 147, 109917.
- Yin, S., Chen, D.L., Zhang, X.Y., Yan, J.L., 2022a. Review on the multi-scale interactions of urban forests and atmospheric particles: affecting factors are scale-dependent among tree, stand and region. *Urban For. Urban Green* 78, 127789.
- Yin, S., Shen, Z.M., Zhou, P.S., Zou, X.D., Che, S.Q., Wang, W.H., 2011. Quantifying air pollution attenuation within urban parks: an experimental approach in Shanghai, China. *Environ. Pollut.* 159 (8–9), 2155–2163.
- Yin, Z., Zhang, Y.X., Ma, K.M., 2022b. Evaluation of PM_{2.5} retention capacity and structural optimization of urban park green spaces in Beijing. *Forests* 13 (3), 415.
- Ysebaert, T., Koch, K., Samson, R., Denys, S., 2021. Green walls for mitigating urban particulate matter pollution-a review. *Urban For. Urban Green* 59, 127014.
- Yucedag, C., Ozel, H.B., Cetin, M., Sevik, H., 2019. Variability in morphological traits of seedlings from five *Euonymus japonicus* cultivars. *Environ. Monit. Assess.* 191 (5), 285.
- Zhang, R.W., Zheng, G.L., Li, P., 2019. Effects of foliar trichomes on the accumulation of atmospheric particulates in *Tillandsia brachycaulos*. *Open Life Sci* 14 (1), 580–587.
- Zhang, Z., Gong, J.L., Li, Y., Zhang, W.K., Zhang, T., Meng, H., et al., 2022. Analysis of the influencing factors of atmospheric particulate matter accumulation on coniferous species: measurement methods, pollution level, and leaf traits. *Environ. Sci. Pollut. Res.* 29 (41), 62299–62311.
- Zhao, S.T., Li, X.Y., Li, Y.M., Li, J.L., Liu, X.P., Duan, M.J., et al., 2024. Differential impacts of functional traits across 65 plant species on PM retention in the urban environment. *Ecol. Eng.* 200, 107184.
- Zheng, G.L., Li, P., 2019. Resuspension of settled atmospheric particulate matter on plant leaves determined by wind and leaf surface characteristics. *Environ. Sci. Pollut. Res.* 26 (19), 19606–19614.