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Autumnal particulate matter deposition on woody plant leaves reveals trait-based species selection for air pollution mitigation

Duha S. Hammad[1,3*], Kyaw Thu[1,2] and Takahiko Miyazaki[1,2]

*Correspondence:
duha.hammad@vub.be

[1] Department of Advanced Environmental Science and Engineering, Faculty of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan
[2] Research Center for Next Generation Refrigerant Properties (NEXT-RP), International Institute of Carbon-Neutral Energy Research (I2CNER), Kyushu University, 744 Motooka, Nishi-Ku, Fukuoka 819-0395, Japan
[3] Faculty of Science and Bioengineering Sciences, Vrije Universiteit Brussel (VUB), Pleinlaan 2, 1050 Brussels, Belgium

Abstract

Autumn-season particulate matter (PM) deposition on urban vegetation remains poorly understood, despite the influence of rainfall, wind variability, and leaf aging on particle retention. This study quantified coarse (10–100 µm), fine (2.5–10 µm), and ultrafine (0.2–2.5 µm) PM fractions accumulated on leaves of three common urban tree species on the Chikushi Campus of Kyushu University (Fukuoka, Japan): the deciduous *Acer palmatum* Thunb. and the evergreen *Toxicodendron succedaneum* (L.) Kuntze and *Cinnamomum camphora* (L.) J.Presl. Leaves were collected during October 2022 in two sampling campaigns separated by 14 days. Deposited PM was extracted by sequential washing (distilled water and 5% SDS) and quantified gravimetrically through stepwise filtration, with deposition expressed per unit leaf area. Leaf surface micro-topography was examined using a 3D laser measuring microscope to relate deposition patterns to leaf traits, and visible stress symptoms were documented for *A. palmatum*. Apparent species-specific differences were observed in both total PM load and size-selective retention. *T. succedaneum* showed the greatest capacity to capture health-relevant PM, with fine particles comprising 33% of the total load and ultrafine particles 18%, whereas *C. camphora* consistently exhibited the lowest retention (fine 13%; ultrafine 6.9%). *A. palmatum* accumulated moderate total PM (89.9 µg cm^{-2}) with dominance of the coarse fraction (41.4%), indicating stronger effectiveness for dust-sized particles rather than the finest fractions. Temporal responses differed by species: PM accumulation increased from the first to the second sampling event in *T. succedaneum*, while *C. camphora* decreased, consistent with wash-off and resuspension under repeated wind and rainfall. For *A. palmatum*, proximity to pollution sources did not predict higher deposition; near-road individuals accumulated less PM than semi-sheltered trees, suggesting that microclimatic exposure (solar radiation, turbulence, precipitation) can outweigh emission proximity during autumn. Leaf surface roughness and grooves enhanced retention, while glossy or leathery surfaces were less efficient for fine and ultrafine particles; *A. palmatum* also exhibited chlorosis and necrotic spotting, indicating PM-associated stress. Overall, species identity governed PM size selectivity and sampling time reflected a dynamic balance between deposition and removal, ranking mitigation potential as *T. succedaneum* > *A. palmatum* > *C. camphora*. Beyond urban ecology, the results provide a trait-based, application-oriented framework for selecting woody plant species as functional biological materials for particulate pollution control in managed and engineered green systems.

1 Introduction

Air pollution, particularly particulate matter (PM) and toxic gaseous pollutants, remains a major environmental and public health challenge in densely populated urban areas. Exposure to airborne particulate matter has been strongly associated with increased cardiovascular and respiratory morbidity and mortality. It contributes to more than 2 million premature deaths annually worldwide [2, 22, 23, 25, 33].

Particulate matter originates primarily from anthropogenic activities such as transportation, industrial processes, and fuel combustion, although natural sources also contribute [1, 5, 31]. PM is a heterogeneous mixture of solid and liquid particles with aerodynamic diameters ranging from 0.001 to 100 µm. It includes dust, ash, black carbon, heavy metals, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and other persistent pollutants capable of long-range atmospheric transport [8, 9].

Vegetation, particularly trees, plays a significant role as a natural sink for atmospheric particulate matter and contributes to air quality improvement in urban environments. PM deposition on plant surfaces occurs through multiple mechanisms, including gravitational sedimentation, interception, impaction, and diffusion. These processes are influenced by airflow dynamics and canopy structure [13, 18, 24, 27, 35, 36]. Due to their large leaf surface area and complex canopy architecture, trees function as effective biological filters capable of reducing airborne particulate concentrations [4, 6, 30].

However, most existing studies have focused on PM deposition during the active growing seasons, primarily spring and summer. During these periods, foliage is fully developed and meteorological conditions are relatively stable [12, 14, 18, 29, 37]. In contrast, autumn remains relatively underexplored despite its distinctive environmental characteristics. Autumn is typically associated with increased precipitation and variable wind regimes. It is also characterized by leaf aging or senescence in deciduous species. These factors may substantially influence PM deposition, retention, and resuspension processes [15, 17, 33].

PM accumulation on plant surfaces is strongly species-dependent and influenced by leaf morphological traits. Micromorphological features such as surface roughness, grooves, and wax structures enhance particle retention by increasing surface complexity and reducing resuspension. In contrast, smoother surfaces tend to exhibit lower retention efficiency, particularly for fine and ultrafine particles [28, 32, 34, 35] Prolonged exposure to high PM concentrations can also induce environmental stress in plants. This may lead to physiological and structural damage, including stomatal blockage, reduced photosynthetic efficiency, chlorosis, and necrotic lesions [20, 28].

Despite growing interest in species-specific PM capture, few studies have integrated seasonal context, leaf trait analysis, environmental exposure, and stress responses within a single framework, particularly during autumn. Moreover, the relative importance of leaf micromorphology compared with macro traits, as well as the influence of pollution source proximity under autumnal conditions, remains insufficiently understood.

The present study addresses these gaps by investigating autumn-season particulate matter deposition on selected urban tree species in Fukuoka, Japan. This work quantifies the deposition of coarse, fine, and ultrafine PM fractions on both deciduous and evergreen trees. It compares species-specific accumulation patterns in relation to leaf morphological traits, assesses the influence of environmental exposure and proximity to pollution sources under autumnal conditions, and evaluates visible plant stress responses associated with PM accumulation.

From an applied perspective, vegetation used in managed landscapes represents a functional biological resource whose performance depends on species traits. Trait-based selection of woody plants can therefore be viewed as a form of bio-based environmental technology, where leaf surfaces act as passive particulate filters. Understanding how seasonal conditions and leaf traits control particle capture is essential for optimizing the performance of such plant-based systems.

Based on the influence of leaf morphological traits and seasonal environmental variability on particulate matter (PM) dynamics, this study hypothesizes that: (i) PM deposition on leaf surfaces differs among species due to variations in leaf micro- and macro-morphological characteristics; (ii) evergreen species exhibit higher retention of fine and ultrafine particles compared with deciduous species; and (iii) under autumnal conditions, microclimatic exposure (e.g., turbulence, precipitation, and solar radiation) can modulate PM accumulation to an extent that may outweigh proximity to pollution sources.

2 Materials and methods

2.1 Study area and climatic conditions

The study was conducted on the Chikushi Campus of Kyushu University, located in Fukuoka Prefecture, Japan (33.52°N, 130.47°E). The campus represents an urban environment influenced by vehicular traffic, internal road networks, and mixed land use. Sampling locations were selected to represent different degrees of environmental exposure, including near-road and semi-sheltered sites, in order to evaluate the influence of pollution source proximity on particulate matter (PM) deposition.

Meteorological conditions during the sampling period corresponded to the autumn season (October 2022). According to data obtained from the Japan Meteorological Agency (2022) (Fukuoka WMO station ID: 47807) [11], the study period was characterized by warm and humid conditions with relatively high precipitation. Total monthly rainfall reached 214.5 mm, and the mean daily air temperature ranged from 9.6 to 17.6 °C. These autumnal conditions are known to influence PM wash-off, resuspension, and retention on leaf surfaces and were therefore considered critical for this investigation [10, 12, 33].

In addition, site-specific particulate matter concentrations (PM_1, $PM_{2.5}$, PM_4, and PM_{10}) and meteorological parameters (temperature, relative humidity, and atmospheric pressure) were continuously monitored using a Sensirion SPS30 optical particulate matter sensor installed within the sampling area. The sensor operates based on laser scattering principles and provides real-time measurements of particle mass concentrations across multiple size fractions. Data were recorded at regular time intervals throughout the study period and were used to characterize temporal variability in air quality and environmental conditions influencing particulate matter deposition, retention, and wash-off processes.

Descriptive statistics were used to summarize particulate matter deposition for each species and particle-size fraction. Mean values were calculated and compared across species, particle-size fractions, and sampling periods, and the results were evaluated through graphical representation.

2.2 Plant species selection and leaf traits

Three urban tree species commonly used in Japanese landscapes were selected for this study: one deciduous species, *Acer palmatum* Thunb. (Japanese maple), and two evergreen species, *Toxicodendron succedaneum* (L.) Kuntze (Japanese hazenoki) and *Cinnamomum camphora* (L.) J. Presl (camphor tree). These species were selected to represent contrasting leaf habits, surface textures, and structural traits relevant to particulate matter (PM) deposition and retention.

Leaf samples were collected from cultivated trees located on the Chikushi Campus of Kyushu University, Fukuoka, Japan (33.52°N, 130.47°E). Plant materials were taxonomically identified by the authors based on morphological characteristics, supported by mobile plant identification applications (e.g., PlantNet, PictureThis), and further verified using standard botanical references and campus vegetation records.

The collection of plant material complied with all relevant institutional, national, and international guidelines and legislation governing plant research. Leaf sampling was conducted on commonly cultivated ornamental tree species within a managed university environment using a non-destructive approach. Institutional permission to conduct the sampling was obtained through the supervising research authority at Kyushu University.

Voucher specimens were not prepared or deposited due to the non-destructive nature of the sampling and the widespread availability of the studied species. The investigated species are widely distributed and are not listed as threatened under the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, nor are they regulated under the Convention on the Trade in Endangered Species of Wild Fauna and Flora (CITES). Therefore, no additional permits or collection licenses were required.

Key morphological characteristics, including leaf type, shape, margin, surface texture, and arrangement, are summarized in Table 1 (North Carolina State University Extension

Table 1 Morphological characteristics of the analyzed urban tree species, including leaf type, shape, margin, surface texture, and arrangement, based on the North Carolina extension gardener plant toolbox [16]

Common name	Scientific species name	Leaf type	Leaf arrangement	Leaf shape	Leaf margin	Leaf surface
Camphor tree	*Cinnamomum camphora* (L.) J.Presl	Simple	Alternate	Ovate to obovate	Entire	Leathery, hairless
Japanese hazenoki tree	*Toxicodendron succedaneum* (L.) Kuntze	Compound	Alternate	Lanceolate leaflets	Entire	Glossy, leathery, hairless
Japanese maple	*Acer palmatum* Thunb	Simple	Opposite	Palmasect	Serrated	Glossy

2023). The inclusion of both deciduous and evergreen species allowed assessment of species-specific PM accumulation under autumnal conditions, when leaf aging, surface chemistry, and meteorological variability can considerably influence particle deposition [14, 33].

2.3 Sampling design and leaf collection

Leaf sampling was conducted within the lower accessible canopy to reduce variability associated with vertical gradients in particulate matter (PM) concentration [3, 30]. For *Acer palmatum*, leaves were collected at a consistent height of approximately 0.7 m above ground level. For *Toxicodendron succedaneum* and *Cinnamomum camphora*, leaves were collected between 0.5 and 3 m depending on tree architecture and accessibility, following established approaches in PM biomonitoring studies [27, 30]. Although sampling height varied slightly among species, all samples were taken from the outer canopy under comparable exposure conditions (similar light, airflow, and proximity to emission sources) to ensure consistency in environmental influence on PM deposition [14, 17].

Two sampling campaigns were conducted during October 2022 with a 14-day interval. In each campaign, 20 mature leaves per tree were randomly collected from the same marked branches within the same canopy zone, consistent with established approaches in particulate matter (PM) biomonitoring studies [19, 29]. This sampling strategy was adopted to minimize variability associated with canopy position and environmental exposure [3, 30]. Although the exact individual leaves differed between sampling events, sampling from identical branches improves temporal comparability of PM accumulation and reduces spatial sampling bias [14, 27].

Only mature and visually undamaged leaves were selected. In this study, "visually undamaged" refers to leaves without visible mechanical damage, insect herbivory, fungal infection, or severe senescence symptoms unrelated to particulate matter exposure, in line with standard leaf selection criteria in biomonitoring studies [10, 12].

Immediately after collection, samples were placed in clean paper bags, sealed, labeled, and stored at 4 °C for no longer than 24 h prior to analysis to minimize contamination or particle loss [12, 19].

The sampled trees were cultivated ornamental individuals located within a managed university campus environment. Detailed dendrometric parameters, including tree age, diameter at breast height (DBH), and crown width, were not recorded during the field campaign. However, all sampled trees were mature, well-established individuals with stable canopy structures and no visible signs of severe decline. Tree health was assessed qualitatively during sampling to ensure that leaves were collected from structurally intact and physiologically functional individuals.

Sampling was conducted following a dry period of approximately five days after the last rainfall event to minimize the influence of immediate wash-off and to allow for particulate matter re-accumulation on leaf surfaces.

2.3.1 Microscopic morphology measurement

Leaf surface microstructure was examined using a LEXT OLS4000 3D laser scanning microscope (Olympus, Japan). Prior to observation, leaf samples were air-dried at room temperature, and small sections (approximately 1–2 cm^2) were excised from the central lamina region to ensure consistency across samples. Samples were mounted flat on the microscope stage without additional coating or chemical treatment.

Microscopic observations were conducted at a magnification of × 100 to visualize surface features relevant to particulate matter (PM) deposition, including trichomes, cuticular structures, and surface irregularities. The microscope operates based on laser scanning confocal principles, enabling high-resolution three-dimensional surface imaging. Images were captured under consistent acquisition parameters, including laser intensity, scanning speed, and focus settings, to ensure comparability among samples.

The analysis was primarily qualitative, focusing on morphological characteristics associated with PM retention. Quantitative surface roughness parameters (e.g., Ra and Rq) were not calculated, as the study aimed to provide descriptive support for observed differences in PM accumulation among species. For each species, two representative samples were analyzed to ensure consistency of observed surface features.

2.4 Site mapping and documentation

The geographic locations of the sampling sites within the Kyushu University campus were documented through field observations and digital mapping tools. A schematic representation of the study area, including the relative positions of roadways and sampled trees, is presented in Fig. 1. The figure illustrates the spatial arrangement of near-road and semi-sheltered sampling locations used to evaluate the influence of environmental exposure and proximity to pollution sources on particulate matter (PM) deposition.

2.5 Methodological integration

By applying a unified sampling strategy across all species, maintaining consistent storage and handling conditions, and conducting sampling under the same autumnal meteorological context, this study enables direct comparison of PM deposition across species, leaf traits, and environmental exposure conditions. This integrated approach supports robust evaluation of autumn-season controls on particulate matter deposition in urban tree species.

2.6 Experimental PM quantification (gravimetric analysis) and statistics

Particulate matter (PM) deposition on leaf surfaces was quantified using a gravimetric method adapted from [10], which allows separation and quantification of different PM size fractions deposited on plant leaves [10]. This method has been widely applied in urban biomonitoring studies due to its reliability and reproducibility.

For each sampling campaign, 20 mature leaves per tree were used for PM extraction. Leaf samples were sequentially washed to detach deposited particles. Initially, leaves were rinsed with 250 mL of distilled water for 60 s to remove loosely attached particles. This was followed by washing with 150 mL of 5% sodium dodecyl sulfate

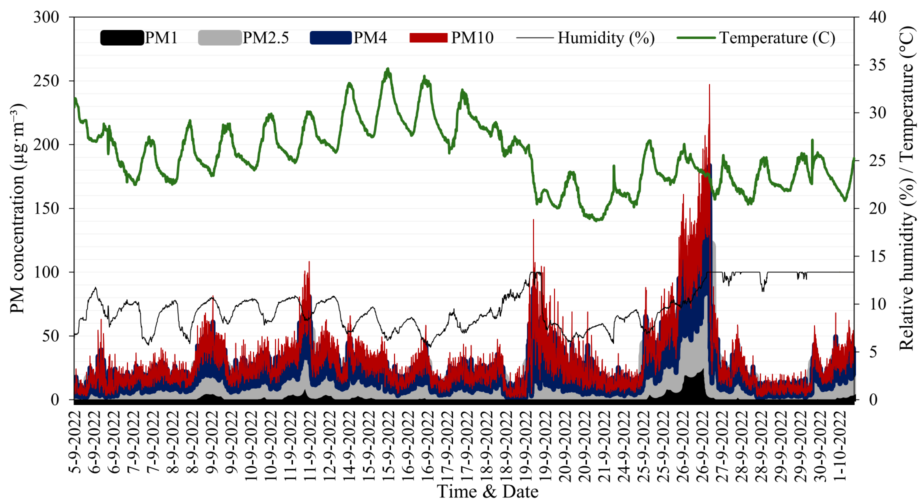

Fig. 1 Temporal variation of particulate matter concentrations (PM_1, $PM_{2.5}$, PM_4, and PM_{10}) and meteorological parameters (temperature and relative humidity) during the study period (September–October 2022). The data illustrate short-term fluctuations in air quality and environmental conditions influencing particulate matter deposition dynamics

(SDS; CH_3 $(CH_2)_{11}$ OSO_3 Na; Merck, Germany) for 60 s to extract particles more strongly adhered to the leaf surface. SDS was used as a substitute for chloroform due to safety considerations and its demonstrated effectiveness as a strong anionic surfactant for deep washing of plant tissues in previous studies [10, 24].

The resulting washing solutions were subjected to sequential filtration to separate PM into three size fractions: coarse (10–100 μm), fine (2.5–10 μm), and ultrafine (0.2–2.5 μm). Filtration was performed using a vacuum filtration system equipped with a 25 mm filter holder connected to a vacuum pump. The filtration sequence consisted of:

(i) a 106 μm polypropylene sieve (Itoh Seisakusho Manufacturing, Japan);
(ii) a 10 μm membrane filter (Omnipore, Merck Millipore Ltd., Ireland);
(iii) a 2.5 μm membrane filter (Whatman, Cytiva, Japan); and
(iv) a 0.2 μm PTFE membrane filter (Merck Millipore Ltd., Ireland).

All filters were dried at 60 °C for 30 min both before and after filtration, then stabilized in a controlled weighing room for 60 min prior to weighing. Filter masses were determined using an analytical electronic balance (HT124R, ViBRA, Japan) with microgram precision.

Total leaf surface area was determined using ImageJ software (U.S. National Institutes of Health, Bethesda, MD, USA). Leaf images were captured using a digital camera with 12-megapixel resolution under controlled lighting conditions and consistent positioning to ensure uniform image quality across all samples. Leaves were carefully flattened during image acquisition to minimize distortion, and petioles were excluded so that only the lamina area was analyzed. The measured area represents the projected one-sided leaf surface, in accordance with standard methodologies employed in particulate matter (PM) deposition studies [10, 29]. Particulate matter deposition was expressed as mass per unit leaf area ($\mu g \cdot cm^{-2}$), allowing normalization of deposition values and facilitating comparison across species, particle-size fractions, and sampling periods.

PM deposition was calculated using the following equation [10]:

$$PM\ deposition\ (\mu g.cm^{-2}) = \frac{W_{f+PM} - W_f}{A}$$

where W_{f+PM} is the weight of the filter after PM filtration (μg), W_f is the weight of the blank filter before filtration (μg), and A is the total leaf surface area (cm^2).

Following gravimetric analysis, selected leaf samples were further examined using a LEXT OLS4000 3D laser measuring microscope (Olympus, Japan) to investigate the relationship between leaf surface micro-morphological characteristics and PM deposition.

Because the study was based on a limited number of trees and focused on a single autumn period, the results should be interpreted as indicative of relative trends rather than statistically generalized differences. Future studies incorporating larger sample sizes and formal inferential statistics across multiple seasons would further strengthen these findings.

Descriptive statistics were used to summarize particulate matter (PM) deposition for each species and particle-size fraction. Mean values were calculated and compared across species, particle-size fractions, and sampling periods, and the results were evaluated through graphical representation. Formal inferential statistical analyses (e.g., ANOVA or t-tests) were not performed due to the limited sample size and the exploratory nature of the study; therefore, the results are interpreted as descriptive trends rather than statistically confirmed differences.

3 Results and discussion

3.1 Quantitative analysis and accumulation of particulate matter on leaf surfaces

3.1.1 Environmental conditions and temporal variability

Temporal variation in particulate matter concentrations (PM_1, $PM_{2.5}$, PM_4, and PM_{10}) and meteorological parameters (temperature and relative humidity) during the study period is presented in Fig. 1. PM_{10} exhibited several episodic peaks, particularly in late September, indicating short-term pollution events. These fluctuations were accompanied by variations in temperature and humidity, suggesting dynamic environmental conditions influencing particulate matter suspension and deposition processes.

Atmospheric pressure also showed notable temporal variability during the study period (Fig. 2), including a pronounced decline in mid-September, which may indicate unstable weather conditions. Such variations are associated with atmospheric mixing processes and may influence particulate matter dispersion and removal from leaf surfaces.

3.1.2 Overall capacity of trees to accumulate particulate matter

Plants, particularly trees, can influence particulate matter (PM) deposition through their canopy structure and interaction with airflow. In the present study, all analyzed species showed measurable PM accumulation; however, the magnitude and distribution of deposited particles varied considerably among species, particle size fractions, and

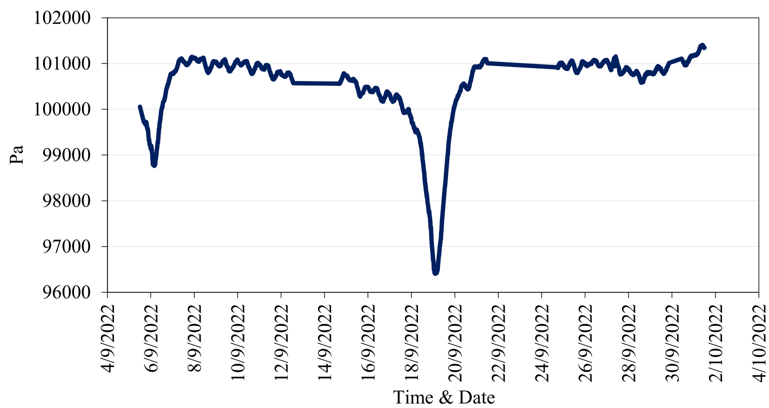

Fig. 2 Temporal variation of atmospheric pressure (Pa) during the study period. The observed fluctuations reflect changing atmospheric conditions that may influence particulate matter transport, deposition, and resuspension processes

sampling conditions. These differences indicate that PM retention is not uniform across vegetation types but is strongly controlled by species-specific traits and environmental exposure. The integration of continuous environmental monitoring provides important context for interpreting PM deposition patterns. Variations in humidity, temperature, and atmospheric pressure likely influenced the balance between particle deposition and removal processes. Periods of high humidity and precipitation promote particle wash-off, whereas elevated PM concentrations enhance deposition. These findings indicate that observed PM loads reflect a dynamic balance between accumulation and removal rather than a static filtration effect. However, these patterns should be interpreted in light of methodological constraints, particularly the absence of detailed tree structural measurements and the limited control of short-term micro-scale meteorological variability.

3.1.3 Total PM accumulation and particle size distribution

The total PM accumulated on leaf surfaces showed observable differentiation among particle size fractions. Across all analyzed samples, the fine size fraction (2.5–10 μm) represented the largest proportion of accumulated PM, with a mean value of 231.3 $\mu g \cdot cm^{-2}$, followed by the coarse fraction (10–100 μm) with 145.2 $\mu g \cdot cm^{-2}$. The ultra-fine fraction (0.2–2.5 μm) exhibited the lowest accumulation, averaging 125.3 $\mu g \cdot cm^{-2}$.

Figure 3a illustrates the total PM accumulation across the three size fractions, while Fig. 3b presents total PM accumulation for each analyzed species. These results partially contrast with earlier findings by [10, 29] who reported dominance of coarse particles, but they highlight the strong influence of local pollution sources and meteorological conditions on PM size distribution.

3.1.4 Species-specific differences in particulate matter accumulation

Noticable interspecific differences were observed in the capacity of the analyzed tree species to retain particulate matter (PM) on their leaf surfaces. *Toxicodendron succedaneum* consistently exhibited higher PM accumulation across all particle-size

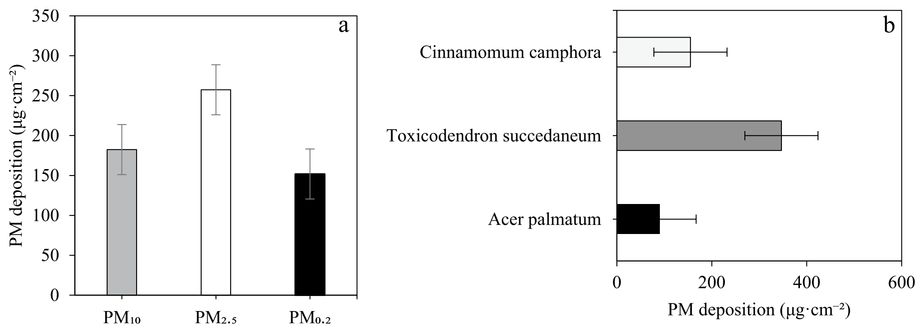

Fig. 3 **a** Total accumulation of particulate matter (PM; µg·cm^{-2}) across three size fractions (coarse, fine, and ultra-fine). **b** Total particulate matter accumulation (PM; µg·cm^{-2}) on leaves of the analyzed species. Error bars represent the standard error (SE) of the mean

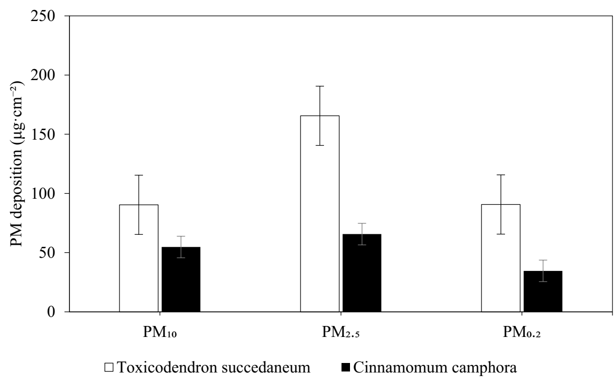

Fig. 4 Particulate matter (PM) deposition (µg·cm^{-2}) on leaf surfaces of *Toxicodendron succedaneum* and *Cinnamomum camphora* across three particle-size fractions (PM_{10}, $PM_{2.5}$, and $PM_{0.2}$). Bars represent mean PM deposition values, and error bars represent the standard error (SE) of the mean

fractions compared to *Cinnamomum camphora*. In *T. succedaneum*, the fine particle fraction (2.5–10 µm) constituted 33% of the total accumulated PM, whereas it accounted for only 13% of the total PM accumulated on *C. camphora* leaves (Fig. 4). The proportion of fine particles in *T. succedaneum* (33%) observed in this study is consistent with values reported by [29], who found fine particle contributions ranging between 25 and 40% in urban tree species.

Similarly, the ultrafine fraction (0.2–2.5 µm) contributed 18% of the total PM load in *T. succedaneum*, compared with only 6.9% in *C. camphora*. These results indicate a higher apparent capacity of *T. succedaneum* to retain fine and ultrafine particles, which are considered the most hazardous PM fractions due to their ability to penetrate deeply into the human respiratory system and bloodstream.

Acer palmatum Thunb. also demonstrated substantial PM accumulation, with a total PM load of 89.9 µg·cm^{-2}, comparable to values reported by [7]. However, in contrast to *T. succedaneum*, PM deposition on *A. palmatum* leaves was dominated by the coarse particle fraction (10–100 µm), which accounted for 37.2 µg·cm^{-2} (41.4%) of the total accumulated PM. The ultrafine fraction represented 26.52 µg·cm^{-2} (29.5%), while the fine fraction contributed 26.1 µg·cm^{-2} (29.1%) of the total PM load.

This distribution pattern aligns with the findings of [30], who reported higher retention of coarse particles on broadleaf species, but contrasts with the observations of [10, 27], who reported a predominance of ultrafine particle deposition. The accumulation of PM across the three particle-size fractions on *A. palmatum* leaves is illustrated in Fig. 5, with error bars representing variability among samples.

3.1.5 Species-specific and temporal differences in PM accumulation capacity

Distinct interspecific differences were observed in both the magnitude and temporal dynamics of PM accumulation. Toxicodendron succedaneum exhibited the highest overall PM retention capacity. Fine particles (2.5–10 µm) accounted for 33% of its total accumulated PM, which is approximately 2.5 times higher than that recorded for Cinnamomum camphora (13%). Similarly, the ultrafine fraction (0.2–2.5 µm) contributed 18% of the total PM load in T. succedaneum, compared to 6.9% in C. camphora.

In addition, T. succedaneum showed an increase in PM accumulation in the second sampling event compared with the first (Fig. 6). In contrast, C. camphora consistently showed the lowest PM accumulation across all particle-size fractions and exhibited a decline in PM retention during the second sampling event.

3.1.6 Spatial and temporal variation in PM accumulation in Acer palmatum Thunb.

Spatial variation in PM accumulation was evident between near-road and far-from-road sampling locations. Near-road samples were dominated by fine particles (2.5–10 µm), which accounted for 12 $\mu g \cdot cm^{-2}$ (40.9%) of the total PM. In contrast, individuals located farther from the road exhibited a higher contribution of the coarse particle fraction (10–100 µm), representing 29.2 $\mu g \cdot cm^{-2}$ (48.3%) of the total PM load [17].

Notable temporal differences were observed between the two sampling events at near-road sites (Fig. 7). The second sampling event showed higher total PM accumulation (16.8 $\mu g \cdot cm^{-2}$) compared with the first (12.5 $\mu g \cdot cm^{-2}$). In both samples, the fine particle fraction constituted the largest portion of accumulated PM, contributing 7.5 $\mu g \cdot cm^{-2}$ (25.7%) in Sample 2 and 4.5 $\mu g \cdot cm^{-2}$ (15.1%) in Sample 1.

Trees located farther from the road exhibited higher total PM accumulation (36.9 $\mu g \cdot cm^{-2}$) than near-road trees (Fig. 7). The second sampling event showed higher PM accumulation than the first. In the second sample, the coarse particle fraction

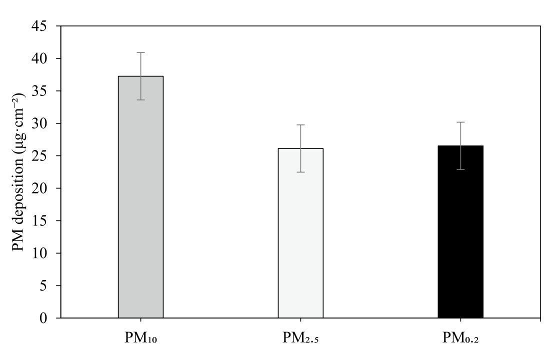

Fig. 5 Total accumulation of particulate matter ($\mu g \cdot cm^{-2}$) on leaves of *Acer palmatum* across coarse, fine, and ultrafine particle fractions. Error bars represent the standard error (SE) of the mean

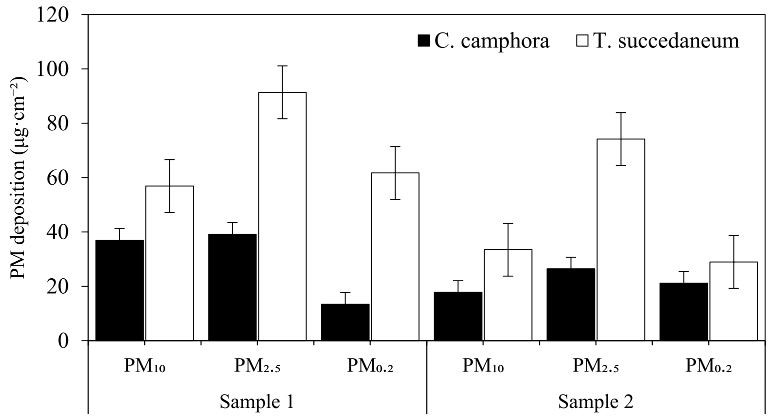

Fig. 6 Particulate matter (PM) deposition (µg·cm^{-2}) on leaf surfaces of the evergreen tree species *Cinnamomum camphora* and *Toxicodendron succedaneum* across three particle-size fractions (PM_{10}, $PM_{2.5}$, and $PM_{0.2}$) during two sampling campaigns (Sample 1 and Sample 2). Error bars represent the standard error (SE) of the mean

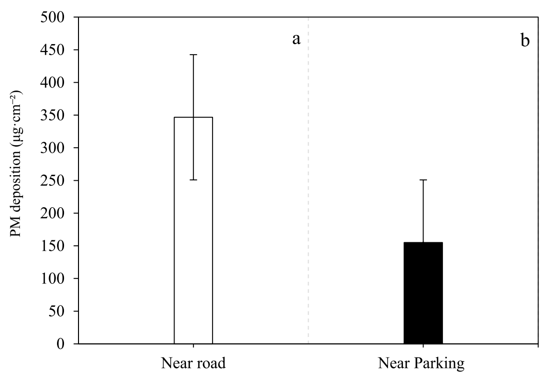

Fig. 7 Particulate matter accumulation (µg·cm^{-2}) on leaves of the analyzed tree species at different locations: **a** *Toxicodendron succedaneum* and **b** *Cinnamomum camphora*. Error bars represent the standard error (SE) of the mean

accounted for 32.5% of the total PM load. In contrast, the first sample showed a higher contribution of the ultrafine fraction, which reached 11.9 µg·cm^{-2} (19.7%).

3.2 Differences among species and locations

Identifiable differences in particulate matter (PM) accumulation were observed among the analyzed species, reflecting the combined effects of species-specific characteristics and location relative to pollution sources.

3.2.1 Comparison between Toxicodendron succedaneum and Cinnamomum camphora

Marked differences in PM deposition were observed between *Toxicodendron succedaneum* and *Cinnamomum camphora*, which can largely be attributed to differences in their locations, surrounding environments, and species-specific traits. *T. succedaneum* was located near internal campus roads with frequent transportation activity, whereas *C. camphora* was situated close to a car parking area and surrounded by different types of vegetation. These contrasting site characteristics likely contributed to the observed variation in PM accumulation between the two species, as illustrated in Fig. 7.

The majority of particles deposited on *T. succedaneum* leaves belonged to the fine particle fraction, indicating strong exposure to traffic-related emissions. In contrast, PM accumulation on *C. camphora* leaves showed a more balanced distribution, with coarse and fine particles contributing nearly equally to the total deposited PM. Coarse particles generally originate from natural sources and anthropogenic activities such as soil resuspension and mechanical abrasion, whereas fine particles are predominantly associated with urban environments and are mainly emitted from transportation and industrial activities, particularly through fossil fuel combustion [7, 9, 26].

The observed differences between *Toxicodendron succedaneum* and *Cinnamomum camphora* can be attributed to the interaction between site-specific environmental exposure and leaf structural characteristics. The higher proportion of fine particles on *T. succedaneum* suggests stronger exposure to traffic-related emissions, whereas the more balanced particle distribution on *C. camphora* reflects a mixed contribution from both anthropogenic and natural sources. These patterns indicate that local environmental conditions play a key role in shaping particle size composition, while species-specific leaf traits determine the efficiency of particle retention [10, 17, 29, 30].

3.2.2 Location effect on PM accumulation in Acer palmatum

Previous studies have reported a positive relationship between traffic density and PM accumulation on plant leaves. Muñoz et al. (21), for example, demonstrated a correlation between PM deposition on *Platanus orientalis* leaves and traffic flow, indicating that vegetation located close to emission sources can function as an effective particle scavenger. Accordingly, trees growing near pollution sources are generally expected to accumulate higher PM loads than those located farther away.

However, for *Acer palmatum*, the present study revealed an inverse pattern. Individuals located near the pollution source accumulated a lower total PM load (29.3 $\mu g \cdot cm^{-2}$) compared with those situated farther from the road, which accumulated 60.5 $\mu g \cdot cm^{-2}$ (Fig. 8). This finding indicates that, for *A. palmatum*, proximity to the pollution source alone does not necessarily translate into higher PM retention on leaf surfaces.

The reduced particulate matter (PM) accumulation observed in near-road *Acer palmatum* individuals, despite their proximity to emission sources, can be explained by local microenvironmental and aerodynamic conditions. Trees located close to the road are typically exposed to higher wind speeds, enhanced turbulence, and stronger mechanical air mixing generated by vehicular movement. These factors reduce deposition efficiency and increase particle resuspension, particularly for fine and ultrafine particles that are more sensitive to turbulent transport [17, 27]. In addition, wind and precipitation events can enhance wash-off processes, limiting the net accumulation of particles on exposed leaf surfaces [10, 33]. Increased solar radiation and surface heating in exposed roadside environments may further promote thermal convection and boundary-layer instability, enhancing particle removal. Solar radiation may also alter the chemical composition of deposited particles by degrading organic compounds such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), facilitating their volatilization and removal from the leaf surface.

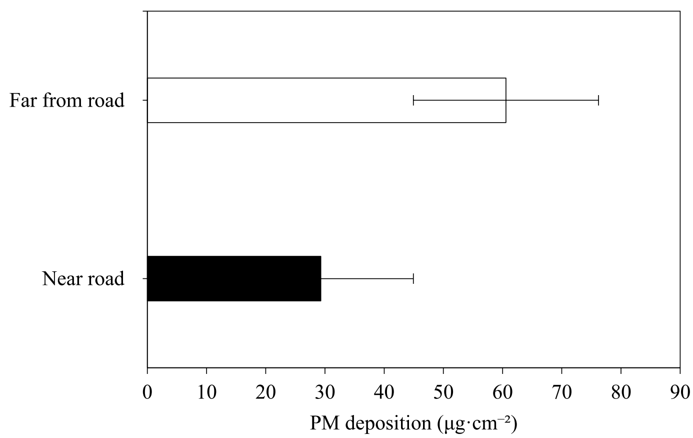

Fig. 8 Differences in total particulate matter accumulation (µg·cm^{-2}) on leaves of *Acer palmatum* according to location relative to the pollution source (near-road vs far-from-road). Error bars represent the standard error (SE) of the mean

In contrast, *A. palmatum* individuals located farther from the road were generally more sheltered from direct environmental stressors, resulting in lower turbulence intensity and reduced resuspension, which allowed particles to persist longer and accumulate over time. Similar patterns have been reported in previous studies, where vegetation in sheltered environments exhibited higher PM retention than highly exposed roadside vegetation [14, 15].

Overall, these findings demonstrate that PM accumulation is governed by a dynamic balance between deposition, adhesion, and removal processes, and that under autumnal conditions, microclimatic exposure can outweigh the effect of proximity to pollution sources in controlling PM retention. This highlights the importance of site-specific environmental conditions when evaluating the effectiveness of tree species for particulate pollution mitigation.

3.3 Species leaf traits and PM accumulation

3.3.1 Leaf traits influencing PM accumulation in Acer palmatum

Particulate matter (PM) accumulation on leaf surfaces is controlled by a combination of environmental conditions and species-specific leaf traits. Micromorphological characteristics can either enhance PM capture or reduce particle resuspension during meteorological disturbances. For example, the presence of surface hairs and other hydrophobic features has been linked to improved PM capture through electrostatic attraction of charged particles [20]. In addition, leaf margin characteristics can limit PM loss during rainfall and wind events.

Figure S2 illustrates the main leaf traits of *Acer palmatum* that influence PM accumulation. The species is characterized by a serrated (toothed) leaf margin, which may play an important role in preventing particulate matter from being washed off the relatively glossy leaf surface. Unlike some other species, *A. palmatum* lacks pronounced surface features such as hairs, grooves, or trichomes; therefore, the serrated margin appears to be the primary structural trait contributing to PM retention by reducing particle displacement during precipitation and air turbulence.

Leaf shape and surface area showed no direct relationship with PM accumulation in *A. palmatum*. Notably, leaves of near-road individuals had a larger average surface area (51.3 cm^2 per leaf) than those of far-from-road individuals (17.9 cm^2 per leaf), yet PM accumulation was lower at the near-road site. This indicates that leaf surface area alone is not a reliable predictor of PM deposition for this species.

However, stem characteristics may indirectly influence PM retention. [4, 24, 27] reported that plants with thicker stems capture PM more effectively than those with narrow stems, potentially due to reduced air turbulence around the foliage. This mechanism may partly explain the observed PM accumulation on *A. palmatum* leaves, as reduced turbulence can limit particle resuspension and promote longer PM residence time on leaf surfaces.

3.3.2 Leaf surface characteristics and PM accumulation in Toxicodendron succedaneum and Cinnamomum camphora

Leaf surface morphology has been identified as a critical factor governing PM accumulation efficiency [12, 29, 35, 36]. From a physical perspective, surface roughness modifies the leaf boundary layer by reducing airflow velocity near the surface, thereby increasing particle residence time and enhancing deposition probability. In contrast, smoother surfaces promote airflow continuity, which facilitates particle removal and limits retention, particularly for fine and ultrafine particles. The higher PM retention observed in *T. succedaneum* is consistent with its rough and grooved leaf surface, which enhances particle interception and reduces resuspension. In contrast, the smoother, leathery surface of *C. camphora* provides fewer microscale trapping sites, leading to lower retention of fine and ultrafine particles. Fine and ultrafine particles are more susceptible to removal through wash-off and resuspension processes, whereas coarse particles tend to reaccumulate more readily under changing environmental conditions.

In the present study, apparent differences in surface morphology were observed between *Toxicodendron succedaneum* and *Cinnamomum camphora* (Fig. 9). *T. succedaneum* exhibited a rough leaf surface with pronounced grooves, whereas *C. camphora* showed a smooth, leathery surface. These contrasting surface characteristics help explain the differences in PM deposition observed between the two species. Grooved and rough surfaces increase the contact angle (θ) between rain droplets and the leaf surface, thereby reducing PM wash-off and limiting particle resuspension during precipitation events. In contrast, the leathery surface of *C. camphora* favors retention of coarse particles but appears less effective in capturing fine and ultrafine PM fractions.

In addition to surface roughness, leaf shape and arrangement further influenced PM accumulation. The lanceolate leaves of *T. succedaneum* enhanced PM capture efficiency, consistent with [17], who reported that lanceolate leaf forms are more effective in accumulating PM than other leaf structures. Conversely, the simple leaf arrangement of *C. camphora* likely reduced air turbulence around the leaf surface, thereby limiting PM interception and resulting in lower overall PM deposition [27].

Leaf surface area did not show a positive relationship with PM accumulation. Despite having smaller leaves (6.5 cm^2 per leaf), *T. succedaneum* accumulated more PM than *C. camphora*, which had larger leaves (13.4 cm^2 per leaf). This supports previous findings

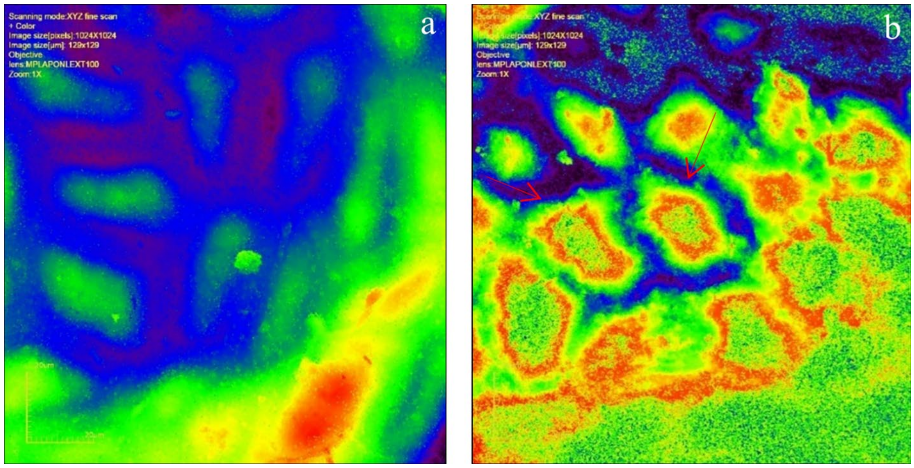

Fig. 9 Leaf surface topography observed using a 3D Laser Measuring Microscope (100 × magnification) for **a** *Cinnamomum camphora* and **b** *Toxicodendron succedaneum*

that smaller leaves may be more resistant to climatic disturbances such as wind and rain, leading to improved PM retention under variable environmental conditions [14, 17].

The enhanced PM retention observed on rough and grooved leaf surfaces can be explained by fundamental principles of particle–surface interaction and boundary-layer aerodynamics. Increased surface roughness promotes turbulence at the microscale, reducing airflow velocity near the leaf surface and increasing the probability of particle interception and impaction [27]. Rough surfaces also create micro-depressions and sheltering zones that trap particles and protect them from shear forces, thereby reducing resuspension.

From a surface science perspective, roughness increases the effective contact area between particles and the leaf surface, enhancing adhesion through van der Waals forces and electrostatic interactions. In contrast, smooth or waxy surfaces exhibit lower friction and weaker particle adhesion, making deposited particles more susceptible to removal by wind or rainfall [12, 29]. These mechanisms collectively explain the higher PM retention efficiency observed in species with complex surface morphology.

3.4 Environmental stress effects on *Acer palmatum*

Environmental stress can induce pronounced physiological and structural alterations in plants, many of which are directly observable in leaf tissues [8]. In the present study, *Acer palmatum* exhibited clear and progressive stress symptoms associated with exposure to airborne particulate matter (PM), particularly under conditions of elevated pollution levels and prolonged exposure. Consistent with previous reports, plant responses to environmental stressors vary according to species-specific tolerance thresholds and the intensity of stress exposure [20].

The deposition of fine and ultrafine PM on *A. palmatum* leaf surfaces adversely affected key physiological processes. Fine particles are capable of obstructing stomatal apertures, which play a critical role in gas exchange, light utilization, and overall metabolic activity. Such obstruction can limit CO_2 diffusion, reduce photosynthetic efficiency, and ultimately result in decreased chlorophyll content [8, 20, 28]. In this study, chlorophyll degradation was visually manifested as chlorosis, characterized by yellowing and brown discoloration of leaf tissues, particularly toward the end of the growing season [20].

In addition to pigment loss, PM-associated toxic constituents, including nitrates, sulfates, organic compounds, and trace elements, can cause both physical and chemical injury to leaf tissues. In *Acer palmatum*, this damage was evident in the form of necrotic spots, defined as localized dead or discolored regions on the leaf surface, indicating cellular damage and tissue necrosis [20]. Moreover, under elevated PM exposure, stressed leaves exhibited a noticeable reduction in size compared with healthy, fully developed leaves (Fig. 10), suggesting inhibited growth and disrupted developmental processes [20, 28].

These responses reflect the adverse physiological effects of particulate pollution, including impaired photosynthesis, cellular damage, and reduced metabolic activity [8, 28]. Overall, these findings demonstrate that PM exposure not only promotes particle accumulation on *Acer palmatum* leaves but also compromises leaf physiological integrity and overall plant health. Consequently, when considering *A. palmatum* for urban green infrastructure or air-purification applications, its sensitivity to particulate pollution and the manifestation of associated stress symptoms should be carefully evaluated, particularly in environments characterized by elevated PM concentrations [20].

3.5 Implications for functional plant selection and managed green systems

Although this study was conducted in an urban setting, the findings have broader relevance for the selection of woody plant species as functional components of managed green systems. Leaf surfaces can be considered passive biointerfaces whose structural traits determine their efficiency in capturing airborne particles. From this perspective, species such as *Toxicodendron succedaneum* represent high-performance biological materials for fine and ultrafine particulate interception, whereas *Acer palmatum* may be

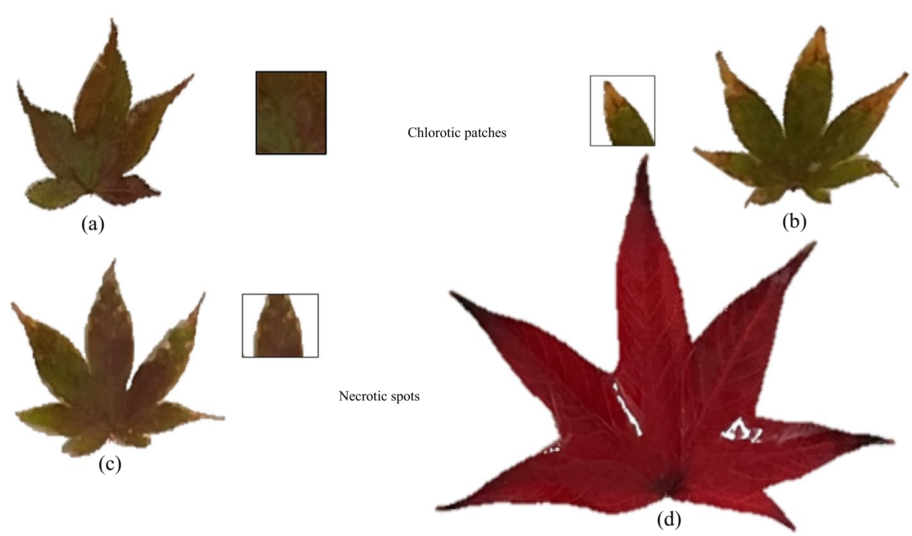

Fig. 10 Differences among *Acer palmatum* Thunb. leaves under environmental stress: **a** and **b** chlorotic patches, **c** necrotic spots associated with particulate matter injury, and **d** healthy leaf structure

more suitable for controlling coarse dust fractions. The accumulation characteristics and mitigation roles of the analyzed species are summarized in (Table 2).

Trait-based selection of plant species offers a scalable and low-energy approach to air quality management that can complement engineered filtration technologies. The autumnal dynamics observed in this study further highlight the importance of seasonal performance when evaluating plant-based systems intended for long-term deployment. These insights support the development of evidence-based frameworks for selecting woody plants as functional components of nature-based solutions for air pollution mitigation.

3.6 Study limitations

This study has several limitations that define the scope of the findings. First, the analysis was restricted to a single autumn sampling period, and therefore seasonal variability beyond autumn was not assessed. Second, detailed tree structural parameters (e.g., age, diameter at breast height, and crown width) were not quantified, and sampling height varied slightly among species due to differences in tree architecture, although efforts were made to ensure comparable environmental exposure. Third, the number of sampled trees per species was limited, which may constrain representation of intraspecific variability. In addition, leaves were collected from the same branches, but individual leaves were not tracked, introducing potential variability at the leaf scale. Plant stress assessment was based on visible symptoms without quantitative physiological or biochemical measurements. Furthermore, formal inferential statistical analyses were not performed due to the exploratory nature of the study and sample size constraints; therefore, the results should be interpreted as indicative of relative trends rather than statistically generalized differences. Finally, although environmental monitoring was conducted, short-term micro-scale meteorological variability was not fully controlled; however, sampling was performed after a dry period of approximately five days following rainfall events to minimize immediate wash-off effects. Despite these constraints, the study provides consistent comparative insights into species-specific PM deposition under autumn conditions. Future studies incorporating multi-season sampling, larger sample sizes, and quantitative physiological and statistical analyses would further strengthen these findings.

Table 2 Summary of particulate matter (PM) accumulation characteristics and mitigation roles of the analyzed urban tree species, showing total PM retention, dominant particle-size fraction, relative contributions of fine and ultrafine PM, and their functional role in urban air pollution control

Species	Total PM	Dominant fraction	Fine PM (%)	Ultrafine PM (%)	PM control role
T. succedaneum	High	Fine	33%	18%	Best for health protection
C. camphora	Low	Coarse	13%	6.9%	Least effective
A. palmatum	Moderate	Coarse	29.1%	29.5%	Dust control

4 Conclusions

This study evaluated autumn-season particulate matter (PM) deposition on three common urban tree species on the Chikushi Campus of Kyushu University (Fukuoka, Japan) by quantifying coarse (10–100 μm), fine (2.5–10 μm), and ultrafine (0.2–2.5 μm) particle fractions on leaf surfaces. The results demonstrate that autumn is a dynamic period for PM capture, during which fluctuating meteorological conditions, including rainfall, wind, and exposure, strongly influence deposition, wash-off, and resuspension processes, in some cases overriding the expected effects of proximity to pollution sources.

In Acer palmatum, near-road individuals accumulated lower total PM than semi-sheltered individuals, indicating that increased turbulence, solar radiation, and precipitation exposure can reduce net PM retention despite higher emission intensity. Leaf surface morphology contributed to interspecific differences in PM capture, with rough and grooved surfaces enhancing particle retention, while smooth or leathery surfaces showed lower efficiency, particularly for fine and ultrafine fractions. In addition, A. palmatum exhibited visible stress symptoms (chlorosis, necrotic spots, and reduced leaf size), suggesting that PM exposure during autumn may affect leaf physiological condition and should be considered alongside capture efficiency in species selection.

Overall, PM accumulation reflects a balance between deposition, removal, and re-accumulation processes under variable environmental conditions. Based on both total PM retention and fine and ultrafine particle capture, the species ranked in PM mitigation potential as: T. succedaneum > A. palmatum > C. camphora. Among the studied species, T. succedaneum appears to be the most suitable candidate for mitigating fine and ultrafine particulate pollution in urban environments, while A. palmatum may be more effective for controlling coarse particles.

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Authors' contributions
Duha S. Hammad: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing–original draft. Kyaw Thu: Supervision, Validation, Writing–review and editing. Takahiko Miyazaki: Supervision, Validation, Writing–review and editing.

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Data availability
The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
The collection of plant material complied with all relevant institutional, national, and international guidelines and legislation governing plant research. Leaf samples of ***Acer palmatum*** Thunb., ***Toxicodendron succedaneum*** (L.) Kuntze, and ***Cinnamomum camphora*** (L.) J. Presl were collected from cultivated trees located on the Chikushi Campus of Kyushu University, Fukuoka, Japan.Sampling was conducted within the premises of Kyushu University on cultivated trees, with institutional permission obtained through the supervising research authority at Kyushu University. Due to the non-destructive nature of sampling, no formal collection permits or licenses were required.The sampling involved non-destructive collection of leaves from commonly cultivated urban tree species within a managed environment. No endangered or protected species were involved in this study. The investigated species are not listed under the International Union for Conservation of Nature (IUCN) Red List of Threatened Species and are not regulated under the Convention on the Trade in Endangered Species of Wild Fauna and Flora (CITES). Therefore, no additional collection permits or licenses were required.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form.

Competing interests

The authors declare no competing interests.

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