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The capacity of trees to remove particulate matter and lead and its impact on tree health

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Abstract. *Yuniati R, Handayani W, Nugrahani L, Khoerunnisa I, Halimah, Putrika A, Hemelda NM. 2024. The capacity of trees to remove particulate matter and lead and its impact on tree health. Biodiversitas 25: 2541-2551.* In urban areas, common air pollutants include particulate matter (PM) and lead (Pb) particles. Plants offer a solution to mitigate both PM and Pb particles. However, PM and Pb deposition in plant leaf organs can have an impact on tree health, which can be evaluated from plant physiological aspects. A study was conducted to compare the capacity of several plant species to absorb PM and lead particles and to determine the impact of these pollutants on the physiological aspects of plants in two locations. The selected plant species were *Cerbera odollam*, *Polyalthia longifolia*, *Swietenia macrophylla*, and *Terminalia mantaly*. The four species were chosen based on their occurrence in two distinct locations: the Universitas Indonesia (UI) campus, which represents a low-pollution area, and the Bantargebang waste landfill, which represents a highly polluted area. The method employed involves using the Gravimetric Method and observing leaf morphology to evaluate the ability to capture PM, analyzing heavy metal accumulation to assess Pb particle adsorption, and examining leaf anatomy and physiology to determine tree health. Physiological aspects were observed, including chlorophyll content, carotenoid content, relative water content (RWC), and pH of leaf extract. The results showed that the highest PM deposit on plants leaf was observed in *P. longifolia,* followed by *S. macrophylla*, *C. odollam*, and *T. mantaly*. Pb analysis revealed the order of plants that accumulate Pb, from highest to lowest, is *S. macrophylla*>*P. longifolia*>*C. odollam*. The PM deposits significantly affected RWC ($r=-0.522$, $p<0.01$) and it affected the content of chlorophyll ($r=-0.28$) and carotenoids ($r=-0.017$). Of all the plants studied, *S. macrophylla* was the most impacted, with two physiological aspects affected: pigments (chlorophyll and carotenoids), and RWC. The selection of the four tree species as pollutant absorbers in Bantargebang landfill and UI Campus is appropriate, as tree health indicators, based on the analysis of leaf anatomy and physiological characteristics, detect minimal impact from environmental stress. *Polyalthia longifolia* (mast tree) would be the best performer among all the tree species.

Keywords: Air pollution, lead (Pb), particulate matter, pollutant absorber, tree health

INTRODUCTION

Particulate Matter (PM) is an air pollutant found in most locations; it consists of various other pollutants, including sulfur and nitrogen oxides (SOx, NOx), numerous elements, black carbon, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), ozone (O_3), and other substances suspended in the atmosphere (Bell et al. 2011). PM poses significant health risks to humans, particularly affecting the respiratory and cardiovascular systems (Morabet 2018). Another significant air pollutant in urban areas is heavy metals, with lead (Pb) being a particular concern. Pb, a heavy metal element, is naturally present in the soil at concentrations ranging from 2 to 200 $mg.kg^{-1}$ with an average of 16 $mg.kg^{-1}$ (Liu et al. 2023). However, anthropogenic activities have substantially elevated Pb levels beyond these natural levels in many soils. Particulate matter (PM) and lead (Pb) can originate from industrialization, urbanization, agriculture, livestock, and transportation activities (Maletsika et al. 2015).

It is now widely recognized that plants positively impact air quality in urban areas (Janhäll 2015). As PM settles on their surfaces, trees can reduce particulate matter concentrations effectively (Dzierżanowski et al. 2011). Trees for PM reduction include phytoremediation, a method aimed at purifying the environment through phytofiltration and phytostabilization mechanisms. Different lead (Pb) remediation mechanisms can be employed, including phytoextraction, phytostabilization, and phytovolatilization. Certain plant species are more effective for phytoremediation than others, as indicated by the primary coefficient, the bioconcentration factor (BCF). The BCF measures the plant's metal content ratio compared to the soil (Mocek-Płóciniak et al. 2023).

Careful selection of tree species for phytoremediation is essential to maximize their benefits and potential. The Ministry of Public Works of the Republic of Indonesia has issued Guidelines for Providing and Utilizing Green Open Space in Urban Areas, highlighting the importance of choosing plants with dense leaf masses, such as trees, herbs, or bushes, which can absorb pollutants. However, the tree's health can be affected despite its ability to clean air pollutants. In this context, 'tree health' specifically refers to the physiological or pathological aspects, defined as the tree's physiological performance in reaction to environmental factors (Jang and Leung 2022). Assessing the health of a tree involves considering various factors, including its physical appearance, growth patterns, and physiological indicators. Some common methods used to evaluate tree health include visual inspection, leaf analysis, and physiological tests. Leaf analysis by examining the leaves' color, size, and condition can reveal important clues about the tree's health. While physiological tests include chlorophyll content measurements, relative water content, or nutrient levels, they provide quantitative data regarding a tree's health and metabolic activity. Evaluating trees' abilities to remove PM and Pb particulates and assessing their impact on tree health is crucial for identifying tolerant species that can enhance urban air quality.

The Bantargebang landfill in the Bantar Gebang District of Bekasi City is a final waste disposal site. Daily, the Bantargebang landfill receives around 7,000-8,000 tons of waste from various parts of Jakarta, transported by garbage trucks (Maulana et al. 2014). Garbage trucks and waste piles become a significant source of PM and Pb in urban environments. To address this issue, the Bekasi City Environmental Service initiated reforestation efforts at the Bantargebang landfill in 2019 by planting tree species with specific physical characteristics and pollutant absorption capabilities.

This study aimed to compare the performance of four tree species, *Cerbera odollam*, *Polyalthia longifolia*, *Swietenia macrophylla*, and *Terminalia mantaly,* to remove PM and Pb and review the impact on the health of the trees. The research location involved two places: Bantargebang landfill, a highly polluted location, and the Universitas Indonesia (UI) Depok campus, a low polluted location. As the main campus, Depok campus covers approximately 320 hectares, of which 25% is designated for academic facilities, and the remaining 75% is a green area as an urban forest (Anis et al. 2018). The extensive green coverage on the UI campus shows that pollution on this campus is relatively less. Those four tree species were selected due to their presence at both study sites and the availability of a minimum of three individuals of each species at each location.

MATERIALS AND METHODS

Study area

This study was conducted from April to June 2021 in the Bantargebang landfill and Universitas Indonesia. The Bantargebang landfill is located in Ciketingudik, Bantar Gebang Sub-district, Bekasi City, West Java, Indonesia at coordinates 6°20'52.91"S, 106°59'51.48"E. Meanwhile, Universitas Indonesia is situated in Pondok Cina, Beji Sub-district, Depok City, West Java, Indonesia, at coordinates 6°18'21.63"S, 107°01'58.77"E (Figure 1). The weather and climate in Bantargebang and UI Campus at the time of data collection on May 5 and 6, 2021 were at the transition of the rainy and dry seasons. The air temperature in Bantargebang was 34°C with an air relative humidity of 54% and a light intensity of 29,925 lux. The air temperature at UI Campus was 32°C with an air relative humidity of 65% and a light intensity of 15,928 lux. The same situations occurred at both the Bantargebang location and UI Campus, where light rain fell the day prior to collecting plant samples.

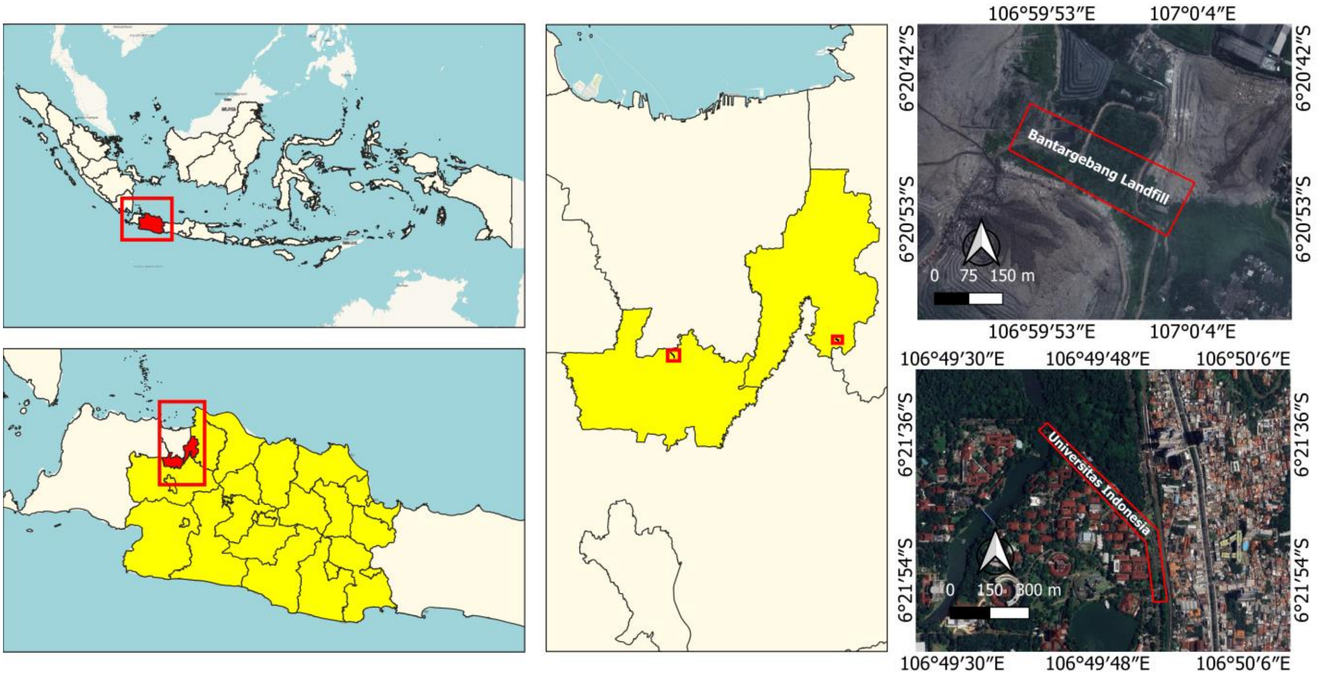

Figure 1. Research location: sampling sites in Bantargebang landfill, Bekasi City, and Universitas Indonesia, Depok City, West Java, Indonesia

Sample collection

Leaf collection for particulate matter analysis

Leaf samples were obtained from four tree species: *C. odollam* (suicide tree), *P. longifolia* (mast tree), *S. macrophylla* (mahogany), and *T. mantaly* (umbrella tree). Samples were collected in the morning from three individual plants of each species (n=3) at both the Bantargebang landfill and the UI Campus. The distance between three *C. odollam* individuals in Bantargebang is 10 m, compared to 1.5 m at UI. For *S. macrophylla* individuals, the distance is 3 m in Bantargebang and 1 m at UI. The spacing for *P. longifolia* is 2 m in Bantargebang, whereas it is 10 m at UI. Three *T. mantaly* individuals are spaced 60 m apart in Bantargebang, but only 1 m apart at UI. The sampling method employed in this study was purposive sampling; leaves samples (2-20 leaves) with a combined area ranging from 200 to 400 cm^2 were used for PM measurement in each sample (Dzierżanowski et al. 2011). The leaf area was determined using ImageJ software. One leaf was allocated for chlorophyll and carotenoid level measurement. In comparison, another leaf was designated for measuring relative water content (RWC), and 2 g of fresh leaves were used for pH measurement of the leaf extract. An additional leaf was set aside for anatomical analysis. Leaf samples were carefully stored in a sealed plastic bag, labeled, and placed in an icebox before being transported to the laboratory for analysis.

Plant sample collection for Pb content analysis

Leaves and twigs were separated based on the method by Vongdala et al. (2018), with medium to large leaves randomly taken from all tree canopies (Karmakar and Padhy 2019). Each sample, totaling approximately 120 g, was sealed in plastic bags comprising tree twigs (3-5 cm diameter) and mature leaves (11-24 cm long, 3-5 cm wide). After a one-hour drying period, the samples were resealed, weighed (around 100 g), packed into cardboard boxes, and promptly delivered to the laboratory for Atomic Absorption Spectrophotometric (AAS) analysis.

Soil sample collection for Pb content analysis

Soil samples were taken from the topsoil at 0-25 cm depths at each plant sampling site using a small shovel (Vongdala et al. 2018). After removing leaves, roots, and debris, the soil samples were air-dried for one hour. Each sample was then placed into a sealed plastic bag, weighed to approximately 100 g, packed, and transported to the laboratory for analysis using atomic absorption Spectrophotometry (AAS).

Measurement of particulate matter deposits

The PM was washed from the leaf surface according to Dzierżanowski et al. (2011) method with modifications. Each leaf sample, ranging in surface area from 200 to 400 cm^2, was washed with 150 mL of distilled water, and the resulting washing water was collected in plastic bottles. Afterward, the plastic bottles containing the washing water and the leaf samples were agitated for one hour at a rotational speed of 150 rpm using an orbit shaker (Lab-Line 3520) to ensure thorough removal of all PM from the leaf surface. The washing water containing PM was then filtered through a 120-mesh sieve (125 µm) to isolate PM measuring ≤125 µm. The surface area of the washed leaves was subsequently determined using ImageJ software. PM mass measurements were conducted following the procedure outlined by Chaturvedi et al. (2013). The filtered water containing PM was evaporated in an oven (JISICO J-300S) at 100°C, resulting in a solid fraction of PM, which was then weighed.

Preparation of leaf anatomical structure

The leaves selected were the third and fourth from the tip of the twig. A 1x1 cm square was cut from the center of each leaf. The leaf cross-section was prepared using a hand-sliding microtome according to Metusala''s method (2017), while the paradermal section was scraped. Dehydration involved a series of graded alcohol solutions (30, 50, 70, and 96%), followed by the replacement of 96% alcohol with a preservative solution of 70% alcohol and glycerin (2:3 ratio), supplemented with 1% safranin dye. For each incision preparation, a cross-section was made and examined in three different fields of view. The qualitative and quantitative features of the leaves were observed using a light microscope, with transverse sections viewed at 100x and 400x magnification. Parameters observed for leaf cross-section included adaxial and abaxial cuticle thickness, adaxial and abaxial epidermis thickness, mesophyll thickness, and palisade thickness. Meanwhile, parameters for the leaf paradermal section included the number of epidermal cells, stomata, and stomatal dimensions. The formula for calculating stomatal density and stomatal index based on Kushwaha et al. (2018):

Stomatal density = number of stomata/field of view (mm^2)

Stomatal Index (%) = stomatal density stomatal density + epidermal cell density ×100

Data were analyzed using the Independent Sample T-test.

Physiological characteristic measurement

Measurement of pigment content

The chlorophyll and carotenoid content were analyzed following the Arnon (1949) method. Leaf extraction involves 10 mL of 80% acetone and 0.03 g of calcium carbonate to prevent oxidation. After centrifugation at 500x g for 20 minutes, the supernatant was collected and diluted to 25 mL with 80% acetone. The spectrophotometer measurements at 480, 510, 645, and 663 nm are applied to the Arnon (1949) equation as follows:

$$\text{Total chlorophyll (mg/mL)} = 20{,}2\ (A_{645}) + 8{,}01\ (A_{663})$$

$$\text{Carotenoid (mg/mL)} = 7.6(A_{480}) + 1{,}49\ (A_{510})$$

Measurement of Relative Water Content (RWC)

Relative water content was carried out using the Henson (1981) method. Leaf samples, measuring 2x5 cm excluding the midrib, were initially weighed to determine their fresh weight. Thereafter, the leaves were dipped in aquades at room temperature for four hours, followed by overnight storage at 5°C to ensure full hydration of leaf cells. After removal from the water, the leaf samples were gently wiped dry with a tissue and reweighed to determine the turgid weight. The leaves were then dried in an 80°C oven for 48 hours to obtain the dry weight. The RWC value was calculated using the formula outlined by Henson (1981):

$$\text{RWC (\%)} = \frac{\text{Fresh Weight - Dry Weight}}{\text{Turgid Weight - Dry Weight}} \times 100\%$$

Measurement of leaf extract pH

The Tak and Kakde (2017) method determined the leaf extract's pH. Approximately 2 g of fresh leaf samples were ground using a mortar and pestle in 20 mL of distilled water with an initial pH of 7.12. The supernatant was separated from the extract using filter paper, and the pH was checked using a digital pH meter previously calibrated at pH 4.00 and 6.86.

Measurement of abiotic (environmental) parameter

The environmental parameters measured included soil pH using a Soil Tester 4 in 1 LCD Digital pH Meter Soil Tester Analyzer Hygrometer. Soil pH readings were taken at each specific plant growth site. Additionally, temperature, relative humidity, and light intensity were recorded. These abiotic parameters were monitored weekly from April to early May 2021 between 08.30 and 11.00 a.m. Furthermore, supplementary data on the number of vehicles at the research sites was collected between 09.30 and 09.50 a.m.

Data analysis

Data parameters regarding PM deposition in leaves and physiological plant aspects such as chlorophyll and carotenoid levels, RWC, and pH of leaf extracts were compared between plants at Bantargebang landfill and those at the UI Campus. The analysis was conducted using ANOVA, followed by Tukey's post hoc test for further examination, as described by Chaturvedi et al. (2013). We applied the Spearman correlation test to study how PM deposits relate to the observed variables. Statistical analysis was performed with SPSS Version 26.

RESULTS AND DISCUSSION

Particulate deposition capacity of the leaf

Variations in PM deposition on leaf surfaces were observed among tree species (Table 1), indicating their diverse ability to capture PM from the air.

This variability underscores the importance of selecting appropriate plant species for planting in polluted areas (Liu et al. 2012). Various leaf characteristics unique to each plant species influence the amount of PM deposited on leaves. Factors such as trichomes, rough leaf surfaces, prominent veins, and wavy leaf margins can contribute to higher PM deposits on plant leaves (Sæbø et al. 2012).

PM deposition on plant leaves at the Bantargebang site, according to the Mann Whitney test, was significantly (p=0.000) higher (113.22±39.90 μg/cm^2) compared to leaves at the UI Campus (19.31±4.07 μg/cm^2). This finding is consistent with visual observations, where leaves in Bantargebang appeared heavily covered with thick dust, unlike the shiny bright green leaves observed on the UI Campus (Figure 2).

Figure 2. *Polyalthia longifolia* leaves in (A) Bantargebang site are covered with a thick layer of dust, and (B) the UI Campus has no dust layer

Table 1. Description of plant species sampled for the study

Scientific name	Family	Average height	Canopy condition	Leaf morphology
Swietenia macrophylla	Meliaceae	± 24 meters	Dense canopy	Pinnately compound leaves, glabrous surface, prominent leaf veins, 5.5-12x2.5-4.5 cm
Cerbera odollam	Apocynaceae	± 12 meters	Rounded bushy canopy shape	Simple leaves with a smooth surface, 7.5-26x2.4-5.7 cm.
Polyalthia longifolia	Annonaceae	± 24 meters	Dense columnar canopy	Simple leaves, smooth surface, with undulating margins, 11-31x2.5-8 cm
Terminalia mantaly	Combretaceae	± 17 meters	Layered canopy	Simple leaves, glossy surface, length up to 7 cm.

In Bantargebang location, *P. longifolia* exhibited the highest PM deposition (172.71±4.52 μg/cm^2), while *T. mantaly* showed the lowest (73.33±22.95 μg/cm^2). The Kruskal Wallis test indicated significant differences (p=0.019) in PM deposits among the four plant species in Bantargebang. Further analysis using the Mann-Whitney test revealed that PM deposits in *P. longifolia* were significantly higher than in those three other trees (Figure 3). PM deposits in four plant species on the UI campus are much lower than in Bantargebang, namely in the range of 15-23 μg/cm^2. The Kruskal Wallis test showed that PM deposits in the four plant species on the UI campus were significantly different (p=0.040). At the UI Campus location, *P. longifolia* was able to deposit the lowest PM (15.18±0.40 μg/cm^2), in contrast to the Bantargebang location which showed that *P. longifolia* deposited the highest PM. This is thought to be because the location where *P. longifolia* grows is right at an intersection near the Faculty of Psychology building at the Universitas Indonesia, making it vulnerable to high-speed winds caused by passing vehicles.

The *P. longifolia* plants retained the highest levels of PM deposits, likely due to specific leaf traits such as curled leaf edges (Figure 1). Curled leaf edges or wavy margins of a leaf can help trap PM on the leaves, causing an increasing amount of PM deposit (Bui et al. 2022). These irregularities in the leaf's edge can create turbulence in the surrounding air, causing particles to become trapped or adhere to the leaf surface. Sæbø et al. (2012) state that the micro-morphology of leaf surfaces can play a crucial role in air pollution abatement capabilities. Zhang et al. (2017) demonstrated that *Acer truncatum* with a striated cuticle surface had much higher PM deposits than those with a smooth surface. Furthermore, *P. longifolia*'s short petiole, approximately 6 mm in length, reduces leaf movement caused by winds, thereby preventing PM from dispersing into the air (Leonard et al. 2016). *Swietenia macrophylla* ranked second in PM deposits, likely because its prominent leaf veins facilitate effective PM absorption (Das and Prasad 2012). Conversely, *C. odollam* and *T. mantaly* exhibited lower PM deposits than *P. longifolia* and *S. macrophylla*, possibly due to their smooth, flat leaves, which tend to accumulate less PM, as noted by Chaturvedi et al. (2013). Furthermore, effective plants in reducing particulate matter typically possess dense trichomes and serrated or scaly leaves, characteristics absent in *T. mantaly*. In summary, *Polyalthia longifolia* ranked first, but all plant species in this study demonstrate the capability to adsorb PM, as can be inferred by discerning the structural morphology of the leaves.

Accumulation of lead (Pb) in aerial plant organs

Based on the capacity of four tree species to capture PM, we selected the three most effective species to evaluate their ability to accumulate lead (Pb). The accumulation of Pb in leaves and twigs/branches exhibited lower concentrations compared to the Pb concentration in the soil. When compared between leaves and twigs, there was a tendency for Pb to be more concentrated in the leaves (Table 2).

Table 2 showed that Pb from the Bantargebang landfill soil was much greater than those from the UI campus soils. Pb accumulation in aerial plant organs (leaves and twigs) varied in Bantargebang and the UI campus but had a similar pattern. *Swietenia macrophylla* had the highest Pb accumulation in leaf organs at both study locations. The sequence of plants accumulating Pb in aerial organs (leaves and twigs) from highest to lowest in Bantargebang was *S. macrophylla*>*P. longifolia*>*C. odollam*, a pattern similarly observed on the UI campus. These discrepancies among plants can be attributed to variations in heavy metal accumulation depending on contamination sources and environmental conditions (Liu et al. 2013). Factors such as soil and plant characteristics can influence Pb uptake by roots and its translocation to aerial parts. *Swietenia macrophylla* developed a deep and extensive root system that provides stability and allows it to reach water and nutrients from deeper soil layers, enhancing its ability to absorb much higher Pb levels than the other two species.

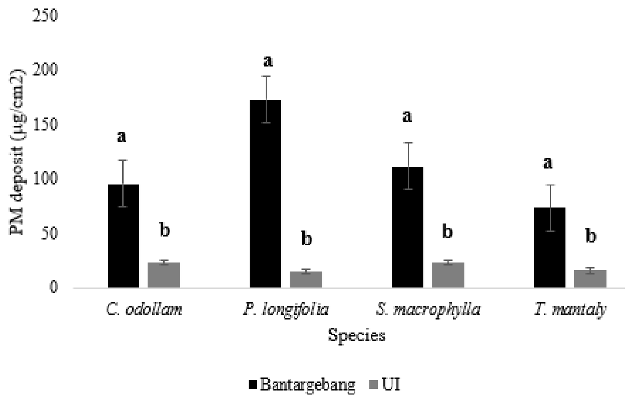

Figure 3. Deposition of PM on leaves of four tree species at both study sites during the transition period from the rainy to the dry season). Different letter notations indicate a significant difference at P<0.05

Table 2. Pb accumulation in soil and plants at Bantargebang and UI Campus of West Java, Indonesia

Plant	Research sites					
	Bantargebang (ppm)			UI Campus (ppm)		
	Soil	Leaf	Twig	Soil	Leaf	Twig
Swietenia macrophylla	18.53	6.98	4.55	15.46	9.51	2.06
Cerbera odollam	25.67	4.58	0.06	11.61	2.75	1.52
Polyalthia longifolia	15.65	3.50	4.10	14.68	3.98	1.07

Regarding Pb accumulation, The BCF determines the ratio of metal content in the plant to that in the soil. All plants examined in this study exhibited BCF values below 1 (Table 3), which indicates the plant can only absorb but not accumulate Pb. These plants possess low metal extraction potential but can still remediate soil from more widespread contamination (Hunt et al. 2014; Tow et al. 2016; Kouhi and Moudi 2020). In Bantargebang, the sequence of plants with the highest to lowest BCF values is *S. macrophylla*>*P. longifolia*>*C. odollam*. In contrast, it is *S. macrophylla*>*C. odollam*>*P. longifolia* on the UI campus.

Pb uptake and accumulation are also influenced by plant genotype, growth rate, transpiration, developmental stage, root system, nutrient requirements, competition between plants, and environmental conditions (Bakirdere and Yaman 2008). The ability of leaves to accumulate Pb is correlated with leaf anatomical parameters such as the number of stomata and stomatal index (Figures 4 and 5).

The stomatal density varies among the studied species, with *S. macrophylla* exhibiting the highest density and *C. odollam* the lowest. Significant differences in stomatal density between the two locations were observed for both *C. odollam* and *S. macrophylla*, with the higher value recorded at Bantargebang landfill than at UI Campus. The amount of stomata serves as a robust sign for assessing the collection of heavy metals in plants. Air pollutants indirectly contribute to an increase in stomatal numbers. Plants adjust their stomatal abundance to cope with heavy metals, ensuring optimal physiological and metabolic conditions. This expansion enhances the stomatal surface area, CO_2 absorption, and water accessibility. Many studies have documented that interaction with diverse heavy metals may result in elevated stomatal density in plants. Research indicates that exposure to cadmium increases stomatal count in tobacco plants, for example, to stimulate an increase in stomatal number in tobacco plants (Orcen 2017), while Arsen increases the number of stomata in soybeans (Gálusová et al. 2020). The number of stomata on the leaf surface is crucial to supply CO_2 for photosynthesis, affecting plant survival.

Stomatal density and index serve as valuable bioindicators for assessing air quality. Moreover, plants with higher stomatal density and index in polluted environments can enhance the absorption of air pollutants. The stomatal index reflects the proportion of stomata formation on the leaf surface, generally correlating with higher stomatal density (Figure 5). The stomatal index of *C. odollam* and *T. mantaly* exhibited significant differences between the two locations. Interestingly, in Bantargebang, the stomatal index of *C. odollam* was higher, whereas, on the UI Campus, the stomatal index of *T. mantaly* was higher. According to this study, the stomatal density and index of *C. odollam*, *P. longifolia*, and *S. macrophylla* are higher at Bantargebang compared to the UI Campus, suggesting the potential for these three species to serve as trees capable of absorbing pollutants.

Impact of PM deposits on tree health

Morphological performance

Quantitative parameters of the leaf paradermal section of the four tree species at two locations can be seen in Table 4. Almost all parameters for *C. odollam* showed significant differences between Bantargebang and UI Campus, except for adaxial cuticle thickness. Among the significantly different parameters, lamina thickness, adaxial and abaxial epidermis, mesophyll thickness, and palisade thickness of *C. odollam* were observed to be higher at Bantargebang than at UI Campus. For *P. longifolia*, only the adaxial thickness epidermis thickness was significantly different between the two locations with a higher value at the Bantargebang. While all parameters for *S. macrophylla* were higher at Bantargebang compared to UI Campus, the differences were not always statistically significant. *Terminalia mantaly* exhibited significant differences in lamina thickness, adaxial and abaxial cuticle, abaxial epidermis, and mesophyll thickness in both locations, but only lamina and mesophyll thicknesses were higher at the Bantargebang compared to UI Campus.

Table 3. Bioconcentration Factor (BCF) of three plant species at Bantargebang and UI Campus of West Java, Indonesia

Species	Bantargebang		UI Campus	
	Leaf	Twigs	Leaf	Twigs
Swietenia macrophylla	0.376	0.245	0.615	0.133
Polyalthia longifolia	0.223	0.261	0.271	0.072
Cerbera odollam	0.178	0.002	0.236	0.130

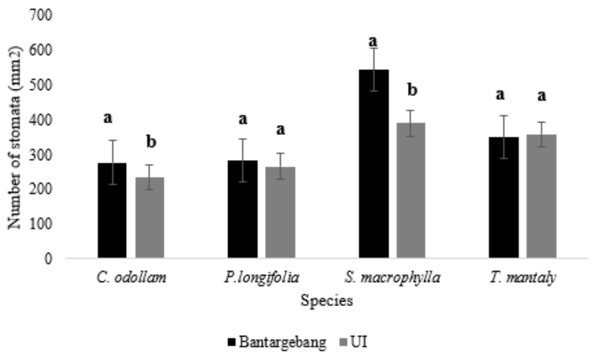

Figure 4. The average of stomatal density among all four tree species at Bantargebang landfill and UI campus. Different letter notations indicate a significant difference at P<0.05

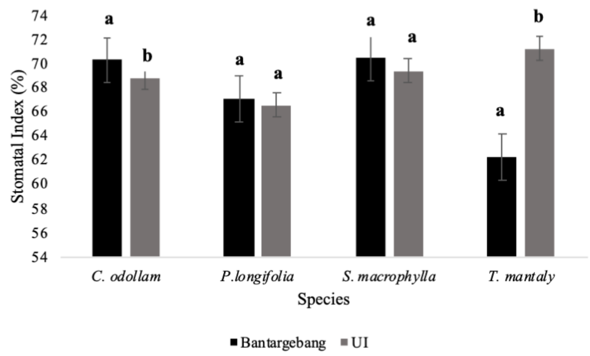

Figure 5. Stomatal Index (%)among all four tree species at Bantargebang landfill and UI Campus. Different letter notations indicate a significant difference at P<0.05

Table 4. Quantitative parameters of cross-section anatomy of the leaves of four tree species at the Bantargebang Landfill and UI Campus of West Java, Indonesia

Species	Parameter (µm)	Bantargebang	UI Campus
Cerbera odollam	Adaxial cuticle thickness	2.02[a]	2.09[a]
	Adaxial epidermis thickness	15.22[a]	10.20[b]
	Abaxial cuticle thickness	1.50[a]	1.86[b]
	Abaxial epidermis thickness	13.21[a]	9.51[b]
	Mesophyll thickness	370.53[a]	321.89[b]
	Palisade thickness	64.36[a]	56.81[b]
Polyalthia longifolia	Adaxial cuticle thickness	1.28[a]	1.43[a]
	Adaxial epidermis thickness	18.23[a]	15.65[b]
	Abaxial cuticle thickness	1.14[a]	1.26[a]
	Abaxial epidermis thickness	13.97[a]	13.60[a]
	Mesophyll thickness	142.78[a]	136.27[a]
	Palisade thickness	33.68[a]	33.37[a]
Swietenia macrophylla	Adaxial cuticle thickness	1.42[a]	1.27[a]
	Adaxial epidermis thickness	16.61[a]	11.70[b]
	Abaxial cuticle thickness	1.09[a]	0.96[a]
	Abaxial epidermis thickness	13.86[a]	10.05[b]
	Mesophyll thickness	199.74[a]	120.73[b]
	Palisade thickness	82.42[a]	36.73[b]
Terminalia mantaly	Adaxial cuticle thickness	1.42[a]	1.89[b]
	Adaxial epidermis thickness	13.69[a]	14.61[a]
	Abaxial cuticle thickness	0.99[a]	1.50[b]
	Abaxial epidermis thickness	11.55[a]	12.98[b]
	Mesophyll thickness	205.93[a]	185.98[b]
	Palisade thickness	53.06[a]	49.97[a]

Note: Average (n=18), Independent Sample T-test, and Mann-Whitney. Different letter notations on the same row indicate a significant difference at $P<0.05$

Among the quantitative parameters of the leaves, the palisade thickness most clearly demonstrates the difference in thickness between leaves from the two locations. Figure 6 represents one individual leaf from four species, showing that the palisade layer is thicker at the Bantargebang location. This increased thickness is likely a plant adaptation to cope with PM deposition on the leaf surface. Thicker palisade layers can improve the plant's ability to absorb light, which is essential in polluted environments where dust and PM can decrease the amount of sunlight available.

Pollutants like particulate matter and toxic gases likely trigger changes in the metabolism of those three species, resulting in the accumulation of secondary metabolites and other compounds that contribute to tissue thickening. These compounds enhance the plant's resilience to stress. Additionally, the plant protects itself by developing thicker epidermal layers. *Terminalia mantaly* showed only mesophyll thickness being higher at the polluted site. Regarding cuticle parameters (both adaxial and abaxial), only *S. macrophylla* exhibits greater thickness at the polluted site. In contrast, the cuticles of the other three species are thinner at the polluted location. Overall, *P. longifolia* had the fewest parameters showing significant differences between the two locations, suggesting it may have a higher resistance to air pollution caused by PM and heavy metals, which are major contributors.

A decrease in cuticle thickness is often associated with exposure to pollutants such as SO_2 and ozone gas, which can induce degradation of the cuticle layer by oxidizing fatty acid double bonds and sulfhydryl groups in membrane proteins (Elliott-Kingston et al. 2014). Research by Papadopoulou et al. (2023) revealed a reduction in adaxial and abaxial cuticle thickness in polluted regions may indicate plant sensitivity to environmental fluctuations. PM particles can physically abrade the leaf's surface, damaging and thinning the epidermal layer. Certain PM components, such as acidic particles or heavy metals, can react with the leaf surface, causing cellular damage and degradation of the epidermal cells. PM deposition can induce oxidative stress by generating reactive oxygen species (ROS) in the leaf tissues. This oxidative stress can damage cellular components, including those in the epidermal layer, leading to thinning.

Physiological performances

PM deposit and Pb accumulation significantly impact tree health, as evidenced by the lower physiological leaf traits observed in high-pollution areas compared to those in low-pollution areas (Table 5).

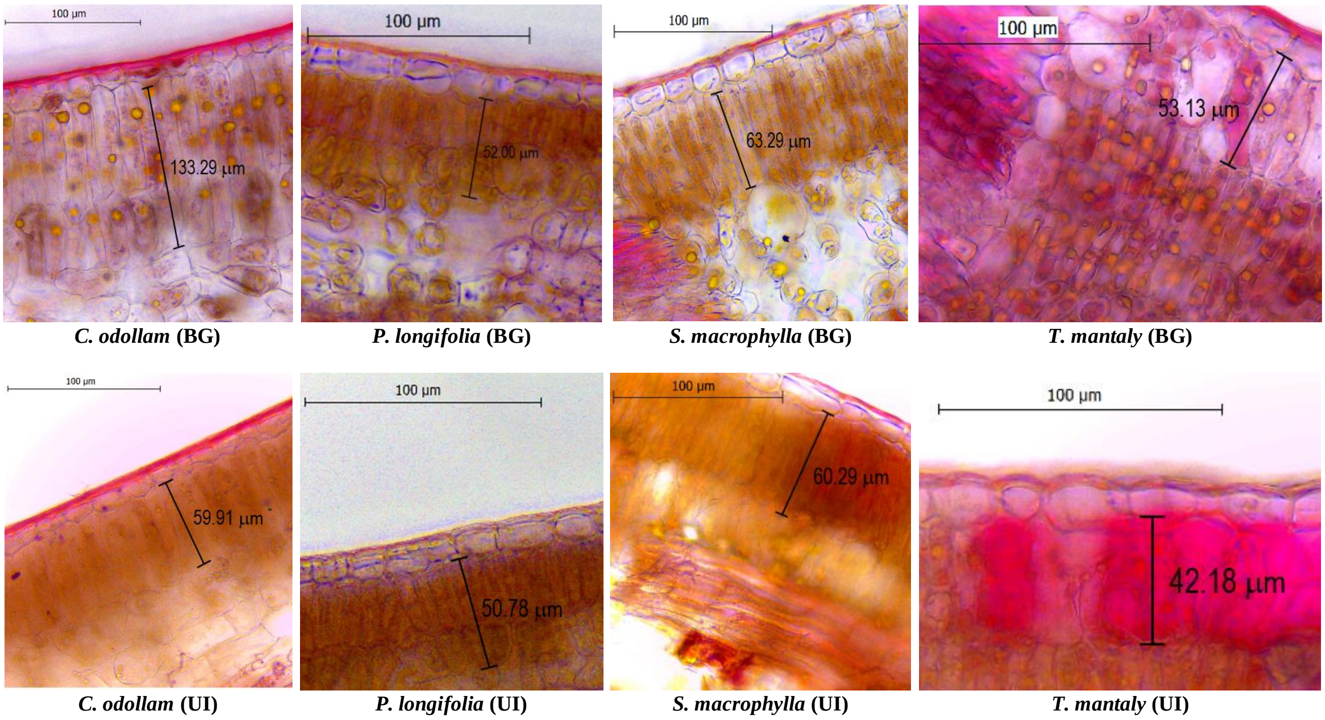

Figure 6. The palisade thickness of four leaf species (measured from a single individual, not the average of three) studied at both Bantargebang and UI campus location

Table 5. Physiological leaf traits of four tree species at two study locations in Bantargebang (BG) and UI campus (UI) of West Java, Indonesia

Species	Chlorophyll (mg/g)		Carotenoid (mg/g)		RWC (%)		Extract pH	
	BG	UI	BG	UI	BG	UI	BG	UI
C. odollam	2.65±0.22^{a}	2.69±0.32^{a}	0.81±0.06^{a}	0.83±0.08^{a}	70.09±2.21^{a}	76.97±1.11^{b}	7.42±0.18^{a}	7.23±0.12^{a}
P. longifolia	3.66±0.15^{a}	4.25±0.18^{b}	1.15±0.06^{a}	1.37±0.15^{b}	87.27±0.82^{a}	88.89±1.80^{a}	5.93±0.04^{a}	5.88±0.08^{a}
S. macrophylla	3.16±0.59^{a}	4.57±0.66^{b}	1.13±0.25^{a}	1.58±0.18^{b}	67.80±1.79^{a}	77.13±1.05^{b}	5.85±0.13^{a}	5.90±0.06^{a}
T. mantaly	2.29±0.50^{a}	2.27±0.23^{a}	0.76±0.13^{a}	0.76±0.03^{a}	89.45±3.79^{a}	95.65±0.80^{b}	5.11±0.38^{a}	5.13±0.18^{a}

Note: Mann-Whitney test was used to assess the significance of differences among leaf traits. Different letter notations on the same row indicate a significant difference at $P<0.05$

The decline in photosynthetic pigments in plants at the Bantargebang landfill is likely due to exposure to PM and Pb, which can induce a stress response prioritizing survival over growth. Consequently, chlorophyll synthesis may decrease as plants reallocate their resources to mitigate stress. Additionally, Pb toxicity can impair the biosynthesis of chlorophyll and carotenoids (Usman et al. 2020). The decline in photosynthetic pigments in plants at the Bantargebang landfill is likely due to exposure to PM and Pb, which can induce a stress response prioritizing survival over growth. Consequently, chlorophyll synthesis may decrease as plants reallocate their resources to mitigate stress. Additionally, Pb toxicity can impair the biosynthesis of chlorophyll and carotenoids (Usman et al. 2020). Plant leaves at Bantargebang landfill were heavily covered with thick PM, potentially obstructing light absorption by plants and disrupting gas exchange processes, including oxygen, by clogging stomatal apertures (Popek et al. 2018). The reduction in light and oxygen plants absorb due to PM deposits can lead to decreased pigment biosynthesis. *Polyalthia longifolia* at the Bantargebang landfill exhibited the highest PM deposits in this study. However, the difference in pigment content between the two research locations was more pronounced in *S. macrophylla* (chlorophyll 31.10% and carotenoids 28.51%) compared to *P. longifolia* (chlorophyll 14.08% and carotenoids 16.05%). According to Chaturvedi et al. (2013), plants showing significant differences in physiological aspects between polluted and unpolluted locations are considered sensitive. Therefore, *S. macrophylla* is likely more sensitive than *P. longifolia*. In contrast, *C. odollam* and *T. mantaly* exhibited relatively similar pigment levels across the two locations, possibly due to their lower PM deposits compared to *P. longifolia* and *S. macrophylla* in this study. Chlorophyll content is one of the most important chemical compounds in plants, and this compound can be utilized to forecast plant growth, development, above-ground biomass, and overall health across different environmental conditions and ecosystems (Talebzadeh and Valeo 2022). High chlorophyll content generally indicates that a tree is photosynthetically active and healthy. It directly affects the tree's ability to produce food, grow, and maintain overall vitality. Carotenoids contribute to protecting chlorophyll by absorbing excess light and providing photoprotection. However, they are secondary to chlorophyll in their direct support of photosynthesis.

Relative water content (RWC) represents the water content within plants essential for maintaining physiological balance (Hariram et al. 2018). The RWC values for *C. odollam*, *S. macrophylla*, and *T. mantaly* in Bantargebang were significantly lower than those on the UI campus (p=0.05) (Table 5). Conversely, the RWC value of *P. longifolia* did not differ significantly between the two locations (p=0.275). High water content in plants can enhance their resistance to air pollution, such as PM deposits (Rai 2016). The accumulation of particulate matter (PM) on plant leaves enhances the absorption of infrared light, leading to an increase in leaf temperature (Popek et al. 2018); this occurrence was noted in the plants at Bantargebang. Elevated transpiration may lead to substantial plant water loss, reducing their RWC (Hariram et al. 2018). The relatively stable RWC values of *P. longifolia* across both study locations indicate that it can maintain its water content despite retaining the highest amount of PM in its leaves. This suggests that *P. longifolia* remains healthy under these conditions.

Observations indicate that the pH of leaf extracts from *S. macrophylla* and *T. mantaly*, is lower at Bantargebang compared to the UI campus (Table 5). However, the Mann-Whitney test further confirmed no significant difference in the pH of leaf extracts among the four plant species across the two locations (p=0.686). The insignificant effect of PM deposits on the leaf extracts' pH is likely due to other factors affecting the pH value, such as the presence of SO_2 and NO_x gas pollutants emitted by motor vehicles at both research sites (Chen et al. 2015). pH is a sensitive indicator of air pollution (Panda et al. 2018), with acidic pollution causing decreased pH. All four plant species studied showed a pH range of 5.11 to 7.42, with *C. odollam* displaying the highest pH value. Plants with higher pH can enhance the conversion of hexose sugar to ascorbic acid, which helps increase their tolerance to environmental stress (Bharti et al. 2018).

Correlation analysis between PM deposit on observed parameters

The correlation between PM deposits and the observed parameters was analyzed using the Spearman Correlation test. This test was conducted to determine the extent of PM deposits' influence on the physiological aspects of the plants, specifically chlorophyll and carotenoid levels, RWC, and the pH of leaf extracts. The Spearman Correlation formula was applied, and the results showed that PM deposits on leaves were significantly negatively correlated with RWC (r=-0.522, p<0.01). This indicates that higher PM deposit values correspond to lower RWC values. Additionally, PM deposits had a negative correlation with chlorophyll (r=-0.28) and carotenoid (r=-0.017) levels, although these correlations were not statistically significant (p>0.05). This suggests that increased PM deposits on leaves are associated with lower chlorophyll and carotenoid levels. Conversely, PM deposits showed an insignificant positive correlation (r=0.252, p>0.05) with the pH of the leaf extract, indicating that PM deposits do not significantly impact the pH values of leaf extracts. Therefore, PM deposits on leaves are not thought to have a major impact on the pH of leaf extracts in this study.

In this study, the results related to the physiological aspects of the plant species in response to PM and lead particle deposition showed that three species (*C. odollam*, *P. longifolia*, and *S. macrophylla*) experienced a decrease in chlorophyll, carotenoid, and RWC levels. However, the pH of the leaf extract decreased only for *S. macrophylla* and *T. mantaly*. *Cerbera odollam* and *P. longifolia* may possess robust mechanisms for maintaining internal pH homeostasis, potentially through the accumulation of organic acids, buffers, or other compounds that stabilize pH despite external stress. *Swietenia macrophylla* appears quite sensitive to PM and Pb deposition, showing a decrease in all analyzed physiological aspects. *Terminalia mantaly* experienced a decrease in RWC and leaf extract pH but maintained its chlorophyll and carotenoid levels, likely because this species had the lowest ability to absorb PM and Pb. Research by Hariram et al. (2018) also indicated that *P. longifolia* has a high tolerance for air pollutants, particularly PM. Consequently, among the tree species studied, *P. longifolia* accumulates the highest PM deposits while experiencing minimal impact.

While isolated deposits of PM and Pb may seem insignificant initially and lack immediate effects, they can gradually diminish plant vigor. These pollutants accumulate over time, disturbing physiological functions and thereby influencing growth, nutrient uptake, and overall metabolism. Even minor disruptions in these processes can have lasting implications for plant health. Although it's crucial to recognize the potential negative impacts on tree health, the benefits of phytoremediation typically surpass these concerns when appropriate plant species are chosen. Additionally, regular monitoring, soil improvement, and tree maintenance strategies can mitigate the negative effects of PM deposits on tree health.

However, it is essential to recognize the limitations of this study. The methodology used to measure tree physiology may be influenced by other factors, which can restrict the generalizability of our findings. Urban trees often face stresses such as temperature fluctuations, drought, salinity, herbivores, or pathogen attacks, either individually or in combination (Loreto and Schnitzler 2010). Further research is needed to explore the combined effects of various environmental factors, beyond PM and seasonal influences, on tree health to enhance the credibility of these results. Investigating different tree species and their interactions with local meteorological conditions can offer valuable insights to optimize urban greening strategies for improving air quality.

Plants recommended for air pollution remediation should meet specific criteria: they should be low-maintenance and fast-growing, able to thrive year-round, and tolerant of air pollutants and environmental stresses like drought, cold, and pathogens (Wei et al. 2017). Species with leaf hairs, trichomes, or waxes are more effective in intercepting air pollutants (Sæbø et al. 2012; Popek et al. 2018). However, when selecting plants for roadside vegetation barriers, priority should be given to total leaf area over leaf surface characteristics (Mori et al. 2015). Ideal species for this purpose should also reach a height of 2 to 6 meters with a minimum width of 3 meters (Chen et al. 2015). Several plant species were suggested as effective absorbers of particulate matter, such as *Ulmus minor* and *Morus alba* emerged from research studies in highly polluted sites within Tehran, Iran (Elkaee et al. 2024); *Cinnamomum camphora* (Wang et al. 2023), *Pinus tabuliformis* (Zhang et al. 2018), *Taxus baccata* (Przybysz et al. 2014), *Betula pendula* (Sæbø et al. 2012). Although not specifically noted for their PM absorption capacity, Yousafzai et al. (2018) recommended *Mangifera indica*, *Ficus religiosa*, *Plumeria rubra*, *Lagerstroemia speciosa*, *Alstonia scholaris*, *Butea monosperma*, and *Polyalthia longifolia* for cultivation in and around industrial and urban areas to mitigate air pollution problems due to their tolerance, based on a study conducted in Chiang Mai City.

This study offers insights into species selection for urban areas to reduce air pollution. We identified tree species in both high and low PM accumulation groups. The high PM accumulation groups are *P. longifolia* and *S. macrophylla*. *Polyalthia longifolia* (Annonaceae) possesses physical traits that facilitate the absorption and retention of particulate matter, including wavy leaf edges, a striated cuticle surface, and short stalks. At the same time, *S. macrophylla* (Meliaceae) features prominent leaf veins that effectively trap PM on the leaf surface. The low PM accumulation groups include *C. odollam* (Apocynaceae) and *T. mantaly* (Combretaceae). This is attributed to their smooth-surfaced, generally flat leaves, which are less efficient in capturing and retaining particles. Additionally, compared to the four species, T. mantaly has the smallest leaf size. Based on the findings of this study we recommend *P. longifolia* and *S. macrophylla* should be more widely planted in urban areas, particularly in high PM pollution hotspots, such as city centers and heavily trafficked streets and roads. Conversely, *C. odollam* and *T. mantaly* should be placed in areas with lower pollution levels, such as city parks and residential neighborhoods with less traffic congestion and fewer vehicles emitting pollutants into the air.

The main conclusions that can be drawn from the presented study are as follows: all four tree species studied have the capability to remove particulate matter and Pb from the atmosphere in two locations. At the Bantargebang site, PM deposits were significantly higher compared to the UI Campus, with *P. longifolia* recording the highest (172.71±4.52 µg/cm^2) and *T. mantaly* the lowest (73.33±22.95 µg/cm^2). This variability among species was confirmed by statistical tests, highlighting *P. longifolia* as notably effective in PM capture. The descending order of the adsorptive capacities for PM of the trees in this study is *Polyalthia longifolia*>*Swietenia macrophylla*>*Cerbera odollam*>*Terminalia mantaly*. At the same time, the sequence of plants accumulating Pb from highest to lowest was *S. macrophylla*>*P. longifolia*>*C. odollam*. Physiological impacts included decreased chlorophyll, carotenoid, and relative water content (RWC) levels in *C. odollam*, *P. longifolia*, and *S. macrophylla* at polluted sites. At the same time, the pH of leaf extracts remained unaffected for most species. Notably, *P. longifolia* exhibited robust mechanisms. Despite varying sensitivities, *P. longifolia* and *S. macrophylla* demonstrated resilience under polluted conditions, maintaining physiological integrity despite high PM and Pb exposure. This study suggests *Polyalthia longifolia* and *Swietenia macrophylla* as promising candidates for high PM pollution areas due to their effective PM capture and physiological resilience. Conversely, species like *C. odollam* and *T. mantaly*, with lower PM accumulation and physiological impacts, are better suited for less polluted environments. Future research should further explore interactions between environmental factors and plant health to refine urban greening strategies to improve air quality.

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