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Evaluation of native Vietnamese plant species for $PM_{2.5}$ and PM_{10} removal under controlled chamber conditions

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ABSTRACT

Particulate matter (PM) pollution remains a major environmental and public-health challenge in developing countries, including Vietnam. Urban vegetation offers a promising nature-based solution, but comparative evidence for native Vietnamese plant species remains limited. This study evaluated control-corrected $PM_{2.5}$ and PM_{10} reduction rates of twenty native plant species in airtight laboratory chambers (8.0 m^3). Road-deposited dust was introduced at two concentration levels (Level 1: 150 ± 15 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ and 250 ± 25 $\mu g \cdot m^{-3}$ for PM_{10}; Level 2: 300 ± 30 and 500 ± 50 $\mu g \cdot m^{-3}$, respectively). PM concentrations were monitored hourly over six hours alongside plant-free controls. Reduction rates were corrected for background losses and normalized by one-sided leaf area and exposure time (W, $\mu g \cdot m^{-2} \cdot h^{-1}$). The highest reduction rates across both PM fractions were observed for five species: Broussonetia papyrifera ($PM_{2.5}$: 536 ± 42 and 888 ± 65; PM_{10}: 773 ± 58 and 1281 ± 94), Ficus drupacea ($PM_{2.5}$: 128 ± 11 to 273 ± 24; PM_{10}: 226 ± 19 to 483 ± 38), Dracontomelon duperreanum ($PM_{2.5}$: 161 ± 14 to 197 ± 18; PM_{10}: 259 ± 21 to 450 ± 35), Diospyros mun ($PM_{2.5}$: 96 ± 9 to 149 ± 13; PM_{10}: 167 ± 15 to 259 ± 22), and Schefflera heptaphylla ($PM_{2.5}$: 42 ± 5 to 137 ± 12; PM_{10}: 103 ± 9 to 335 ± 28), with values expressed in $\mu g \cdot m^{-2} \cdot h^{-1}$ at Levels 1 and 2, respectively. Reduction rates increased significantly at higher initial PM concentrations ($p < 0.001$). Total chamber-level PM mass removal correlated positively with total foliar area ($r = 0.78$, $p < 0.001$), while leaf-area-normalized rates were associated with species-specific foliar morphological traits. These findings highlight the potential of native Vietnamese plant species as nature-based solutions for particulate matter mitigation under controlled conditions and identify promising species for field validation and future urban greening and ecological engineering applications.

Keywords: particulate matter, $PM_{2.5}$, PM_{10}, native plant species, nature-based solutions, urban greening, ecological engineering.

INTRODUCTION

Particulate matter (PM) refers to a complex mixture of solid particles and liquid droplets suspended in the atmosphere (US EPA, 2022). Depending on aerodynamic diameter (D_a), inhalable particulate matter is commonly regulated and monitored as PM_{10} (particles with $D_a \leq 10$ μm), which encompasses both the coarse fraction ($PM_{2.5–10}$; $2.5 < D_a \leq 10$ μm) and the fine fraction ($PM_{2.5}$; $D_a \leq 2.5$ μm) (US EPA, 2022; WHO, 2021). These fractions are collectively termed inhalable particulates because their small aerodynamic dimensions allow them to bypass the upper respiratory tract, penetrate deep into the tracheobronchial and alveolar regions, and,

in the case of $PM_{2.5}$, translocate across the alveolar–capillary barrier into the systemic bloodstream (Nemmar et al., 2002; Xing et al., 2016). Short- and long-term exposure to ambient PM is associated with a wide range of adverse cardiovascular, cerebrovascular, and respiratory morbidity and mortality outcomes (WHO, 2013, 2021; McDuffie et al., 2021). Recent global burden assessments indicate that ambient $PM_{2.5}$ exposure contributes to millions of premature deaths annually worldwide, particularly in rapidly urbanizing Asian countries (McDuffie et al., 2021; Southerland et al., 2022).

PM composition varies geographically and typically includes sulfates, nitrates, ammonium, mineral ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-), organic carbon, elemental carbon, crustal dust, particle-bound water, trace metals, polycyclic aromatic hydrocarbons (PAHs), and biological fragments (WHO, 2013). Although natural dust emissions contribute significantly in arid regions, anthropogenic activities—especially fossil fuel combustion, road traffic resuspension, and industrial construction—remain the dominant sources in urban environments (WHO, 2022; Nemmar et al., 2002).

To support air quality management, the World Health Organization (WHO) has issued Air Quality Guidelines (AQGs) since 1987, most recently updated in 2021. The current WHO 2021 recommended 24-hour guideline levels are 15 μg/m³ for $PM_{2.5}$ and 45 μg/m³ for PM_{10}, with annual guideline levels of 5 μg/m³ and 15 μg/m³, respectively (WHO, 2021). While long-term trends show that $PM_{2.5}$ concentrations have declined in parts of North America, Europe, and China (Hammer et al., 2020), global urban exposure remains high: Southerland et al. (2022) estimated that approximately 86% of the world's urban population lived in areas exceeding the previous WHO 2005 annual $PM_{2.5}$ guideline level of 10 μg/m³. In Vietnam, under the updated National Technical Regulation on Ambient Air Quality (QCVN 05:2023/BTNMT), the regulatory 24-hour and annual limits are set at 50 μg/Nm³ (tightened to 45 μg/Nm³ from January 2026) and 25 μg/Nm³ for $PM_{2.5}$, and 100 μg/Nm³ and 50 μg/Nm³ for PM_{10}, respectively (MONRE, 2023), which remain substantially higher than the WHO 2021 guideline levels.

Among nature-based solutions to complement emission controls, urban vegetation has received considerable attention due to its capacity to intercept, deposit, and retain airborne particulates (Beckett et al., 1998; Janhäll, 2015). PM capture by vegetation occurs primarily through dry deposition governed by gravitational settling, inertial impaction, interception, and turbulent diffusion, which are strongly modulated by canopy architecture and leaf surface micromorphology, including epicuticular wax layers, surface roughness, venation grooves, and trichome density (Janhäll, 2015; Sæbø et al., 2012; Zang et al., 2020). Contemporary studies have evaluated the PM mitigation capacity of urban plants using atmospheric deposition models (Nowak et al., 2006; McDonald et al., 2007), field leaf-wash sampling (Beckett et al., 2000a, 2000b, 2000c; Dzierżanowski et al., 2011; Yin et al., 2011; Vigevani et al., 2022), and controlled chamber or wind-tunnel exposures (Popek et al., 2017; Jin et al., 2021; Vigevani et al., 2024).

While field sampling reflects realistic ambient exposure, it is confounded by heterogeneous meteorological conditions, fluctuating emission sources, and rainfall wash-off. Controlled chamber experiments, conversely, enable standardized comparisons of species-specific PM reduction rate under identical aerosol loading and microclimatic conditions. Despite rapid urbanization and severe seasonal PM episodes in Vietnam, urban greening programs still rely heavily on a narrow set of exotic or empirically unscreened species, and quantitative comparative data on the PM removal capacities of native Vietnamese flora remain scarce. Addressing this knowledge gap is essential for selecting ecologically adapted native species for urban air pollution mitigation.

In the present study, we selected twenty native Vietnamese plant species representing diverse foliar morphologies and growth forms based on a multi-criteria expert screening framework, and evaluated their capacity to reduce airborne $PM_{2.5}$ and PM_{10} in airtight, environmentally controlled chambers. The specific objectives of this study were to: (1) quantify and compare the control-corrected $PM_{2.5}$ and PM_{10} reduction rate normalized by leaf surface area (W, $\mu g \cdot m^2 \cdot h$) across the twenty native species under two initial PM concentration levels; (2) examine the influence of initial pollutant loading and foliar morphological traits on species performance; and (3) identify top-performing native candidates for subsequent field validation and urban greening implementation in Vietnam. To our knowledge, this study represents one of the first standardized chamber-based comparative screenings of native Vietnamese plant species for $PM_{2.5}$ and PM_{10} reduction.

STUDY MATERIALS AND METHODS

Experimental chambers and environmental control

The experimental chambers had internal dimensions of 2.0 × 2.0 × 2.0 m (internal volume V_c = 8.0 m³) and were equipped with calibrated digital sensors for continuous logging of temperature, relative humidity, and photosynthetically active radiation (PAR). The floor consisted of a reinforced concrete base finished with smooth glazed ceramic tiles. The chamber corners were reinforced with anodized aluminum frames and sealed using EPDM rubber gaskets and neutral silicone sealant to ensure airtightness. The walls were constructed from double-layer tempered glass (10 mm thickness). Four miniature axial ceiling fans (12 V DC) were installed at the four corners of the ceiling, with a perforated aluminum diffuser plate positioned 20 cm beneath the ceiling to promote uniform air circulation and prevent particle stratification (generating a gentle, uniform indoor turbulent airflow of 0.3–0.5 m/s across the canopy zone). A schematic illustration of the experimental chamber is shown in Figure 1.

Prior to the experimental campaign, chamber airtightness was verified via CO_2 tracer gas decay testing, confirming an air exchange leak rate of < 1.5%/h. During all experimental runs, chamber environmental conditions were maintained at a temperature of 26 ± 2 °C, relative humidity (RH) of 60 ± 5% (regulated using passive silica-gel desiccant trays to prevent hygroscopic particle growth and water condensation), and overhead LED illumination providing 250 μmol/m²·s PAR at canopy height. Between consecutive experimental runs, all internal glass walls, diffuser plates, and floors were thoroughly vacuumed using a HEPA-filtered vacuum cleaner, wiped twice with deionized water and antistatic microfiber cloths, and ventilated with HEPA-filtered air until baseline concentrations fell below 5 μg/m³ for $PM_{2.5}$ and 10 μg/m³ for PM_{10}.

Designing experimental models and replication

The experimental setup used to evaluate the particulate matter reduction performance of the selected plant species under laboratory conditions is presented in Figure 2.

The experimental facility comprised six identical 8.0 m³ chambers operated simultaneously as three paired blocks (three treatment chambers containing plants and three parallel plant-free control chambers). Each of the 20 species × 2 concentration levels (40 treatment combinations in total) was evaluated across three independent experimental runs (n = 3 independent replicates), using a newly prepared, unexposed set of potted plants for each replicate. The experimental unit was defined as an individual chamber run, whereas the hourly concentration readings recorded within each run constituted repeated longitudinal measurements. To minimize positional or temporal bias, species and concentration treatments were assigned to chambers in a randomized complete block schedule.

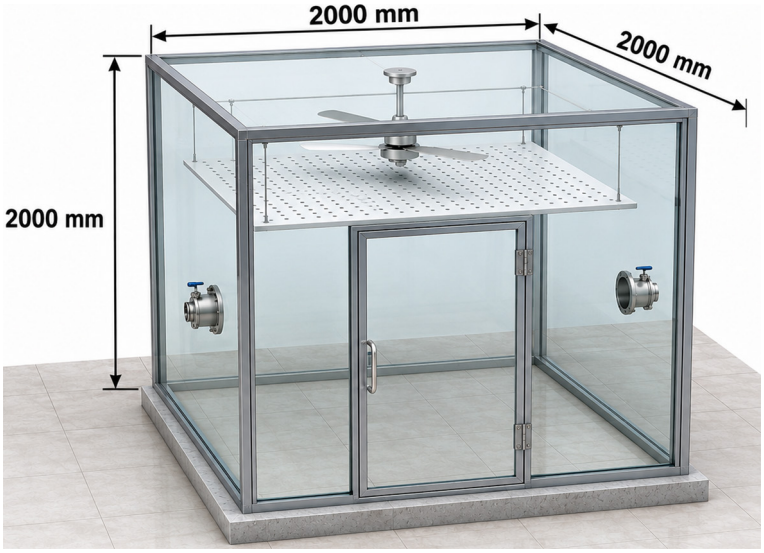

Figure 1. Design of the experimental chamber

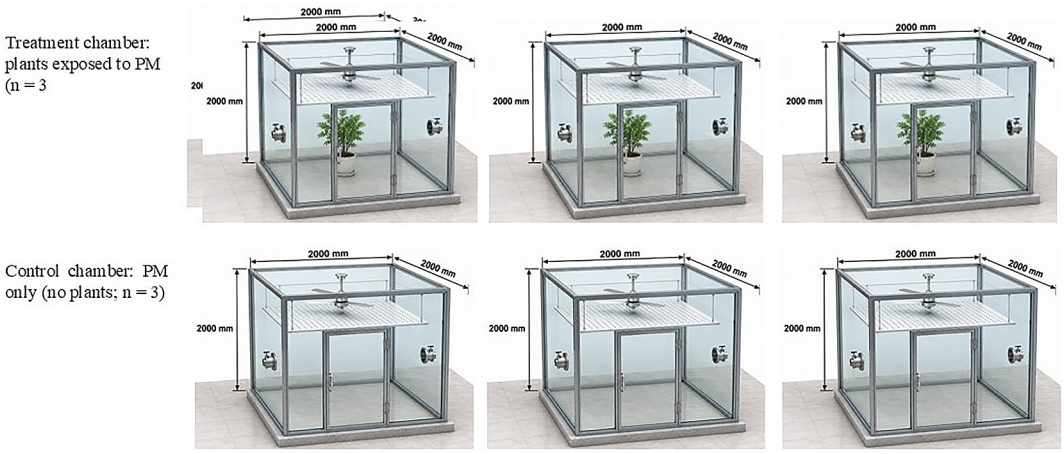

Figure 2. Experimental models

To isolate foliar and aboveground stem effects from soil or container deposition, the plastic pots and potting substrate of all test plants were completely enclosed in double-layered polyethylene bags sealed tightly around the root collar / lower stem base prior to chamber placement. In each parallel control chamber, an identical number of plastic-wrapped pots containing the same substrate (but without plants) was positioned in the same spatial arrangement to account for background particle loss via gravitational settling, turbulent wall impaction, and pot-surface deposition.

Plant species selection, acclimation, and leaf area measurement

Based on an extensive review of relevant literature and consultations with forestry and urban ecology experts, the research team established twenty (20) scoring criteria (each scored on a 1–5 scale) to screen native Vietnamese flora for urban air-quality improvement potential. Five criteria directly governing aerodynamic particle capture and urban survival were classified as highly critical and assigned a weighting factor of 2: canopy structure, degree of defoliation (evergreenness), density of leaf cover, overall foliar surface coverage, and physiological tolerance to air-polluted environments. A second group of four criteria—stem form, individual leaf size, leaf surface wettability/water-holding capacity, and plant longevity—was assigned a weighting factor of 1. The remaining eleven criteria, assigned a weighting factor of 0.5, encompassed root system safety, bark/phloem traits, growth rate, propagation/seed availability, nursery cultivation feasibility, maintenance requirements, resistance to branch/trunk breakage, absence of toxicity/allergenicity, traditional ethnobotanical uses, aesthetic value, and multifunctional urban benefits (total maximum weighted score = 97.5 points).

Following this weighted multi-criteria evaluation, twenty (20) top-scoring native plant species (19 woody tree/shrub species and 1 woody climber) were selected for chamber experimentation. Taxonomic nomenclature was verified against Kew's Plants of the World Online (POWO) and voucher specimens deposited at the Herbarium of the Vietnam National University of Forestry (VNUF). Summary information for the 20 selected species is presented in Table 1.

Healthy, pest-free potted saplings (1.5–2.0 years old; overall height 0.85–1.20 m; crown diameter 0.45–0.65 m; stem basal diameter 1.2–2.5 cm) were obtained from the VNUF nursery. Prior to PM exposure, all plants underwent a standardized two-stage chamber acclimation protocol: plants were gently washed with deionized water to remove pre-existing foliar dust, air-dried, and placed inside the chambers for a 7-day conditioning cycle (2 days sealed under controlled light/temperature, 1 day ventilated with ambient filtered air, and 4 days sealed), followed by a 7-day post-conditioning observation period to confirm normal stomatal function and zero leaf chlorosis or abscission. During this phase, qualitative and quantitative morphological traits – including leaf shape, mean leaf size, leaf coloration, canopy architecture, lamina thickness, total leaf count, adaxial/abaxial surface micromorphology (pubescent/trichome-bearing vs. glabrous; smooth vs. rugose/grooved), and plant height – were documented.

For each experimental run, between 3 and 5 potted plants of a single species (or vine trellises

Table 1. List of selected native plant species with high potential for reducing PM in Vietnam

#	Vietnamese name	Scientific name	Vietnamese family name	Scientific family name	Growth form / Mature size
1	Sấu	*Dracontomelon duperreanum* Pierre	Xoài	Anacardiaceae	Large – sized woody plant
2	Đuôi phượng	*Rhaphidophora decursiva* (Roxb.) Schott	Ráy	Araceae	Climber
3	Đáng chân chim	*Schefflera heptaphylla* (L.) Frodin	Ngũ gia bì	Araliaceae	Small– sized woody plant
4	Trám trắng	*Canarium album* (Lour.) Raeusch.	Trám	Burseraceae	Medium – sized woody plant
5	Trám đen	*Canarium tramdenum* Dai & Yakovl.	Trám	Burseraceae	Medium – sized woody plant
6	Bách xanh	*Calocedrus macrolepis* Kurz	Hoàng đàn	Cupressaceae	Large – sized woody plant
7	Dầu rái	*Dipterocarpus alatus* Roxb. ex G. Don	Dầu	Dipterocarpaceae	Large – sized woody plant
8	Sao đen	*Hopea odorata* Roxb.	Dầu	Dipterocarpaceae	Large – sized woody plant
9	Chò chỉ	*Parashorea chinensis* H. Wang	Dầu	Dipterocarpaceae	Large – sized woody plant
10	Táu nước	*Vatica cinerea* King	Dầu	Dipterocarpaceae	Large – sized woody plant
11	Mun	*Diospyros mun* A. Chev. ex Lecomte	Thị	Ebenaceae	Medium – sized woody plant
12	Nhội	*Bischofia javanica* Blume	Thầu dầu	Euphorbiaceae	Medium – sized woody plant
13	Lim xanh	*Erythrophleum fordii* Oliv.	Đậu	Fabaceae	Large – sized woody plant
14	Mý	*Lysidice rhodostegia* Hance	Đậu	Fabaceae	Medium – sized woody plant
15	Vàng anh	*Saraca dives* Pierre	Đậu	Fabaceae	Large – sized woody plant
16	Dẻ cau	*Quercus platycalyx* Hickel & A. Camus	Dẻ	Fagaceae	Medium – sized woody plant
17	Bộp lông	*Actinodaphne pilosa* (Lour.) Merr.	Long não	Lauraceae	Small– sized woody plant
18	Re hương	*Cinnamomum aff. iners* Reinw. ex Blume	Long não	Lauraceae	Medium – sized woody plant
19	Dướng	*Broussonetia papyrifera* (L.) L'Hér. ex Vent.	Dâu tằm	Moraceae	Small– sized woody plant
20	Đa lông	*Ficus drupacea* Thunb.	Dâu tằm	Moraceae	Small– sized woody plant

of equivalent height for *R. decursiva*) were placed in the center of the treatment chamber in a standardized staggered arrangement (30 cm spacing between pots) to prevent mutual crown overlap and ensure uniform airflow penetration. To determine total one-sided leaf surface area (S, m²) per chamber without destructive harvesting prior to exposure, all leaves on each test plant were counted and stratified into three size classes (small, medium, large); 15 representative leaves per size class were scanned using a portable laser leaf area meter (CI-202, CID Bio-Science, USA) to establish mean area per leaf class, which was multiplied by the respective leaf counts to obtain total one-sided foliar surface area (S ranged from 1.22 to 1.84 m² per chamber across treatments).

Particulate matter preparation and generation

This study evaluated species-specific reduction rate for inhalable particulate matter PM_{10} ($D_a \leq 10$ µm, which includes $PM_{2.5}$) and fine particulate matter $PM_{2.5}$ ($D_a \leq 2.5$ µm). Controlled aerosol exposures were conducted at two target initial concentration levels (Level 1: moderate-to-heavy urban pollution; Level 2: severe pollution episode), as summarized in Table 2.

Test dust was prepared from road-deposited dust swept from paved urban arterial roads in Hanoi, Vietnam. Raw dust was oven-dried at 105 °C for 24 h to constant mass, mechanically sieved through a 200-mesh stainless-steel sieve (< 75

Table 2. PM types and target initial concentration ranges for the experimental study

No.	PM fraction	Unit	Concentration Level 1	Concentration Level 2
1	$PM_{2.5}$ (≤ 2.5 µm)	µg/m³	150 ± 15	300 ± 30
2	PM_{10} (≤ 10 µm)	µg/m³	250 ± 25	500 ± 50

µm) to remove coarse debris, and homogenized. Aerosolization and aerodynamic size fractionation were achieved using a laboratory stainless-steel mini-cyclone separator (inner barrel diameter 50 mm, operated at a constant compressed clean-air flow rate of 30 L·min^{-1}) coupled to a Venturi dust disperser. Centrifugal force within the cyclone precipitated particles > 10 µm into the grit pot, while the suspended inhalable fraction (≤ 10 µm, verified via optical particle sizing to contain ~55–62% $PM_{2.5}$ by mass) was injected into the chamber through the side stainless-steel inlet port until the target initial concentration (Level 1 or Level 2) was reached.

Experimental assessment of plant-based PM reduction

Following dust injection, the four ceiling mixing fans were operated continuously to achieve homogeneous aerosol dispersion throughout the 8.0 m³ chamber. The initial baseline concentration (P_i in the treatment chamber and C_i in the parallel control chamber, corresponding to time t = 0) was recorded exactly 5 minutes after injection ceased, once spatial mixing had stabilized. Subsequent measurements (P_t and C_t) were recorded at 1.0-hour intervals over a standardized 6-hour exposure period (t = 1, 2, 3, 4, 5, and 6 h), or until chamber concentrations declined to the designated background stopping threshold (< 15 µg/m³ for $PM_{2.5}$ and < 25 µg/m³ for PM_{10}).

All $PM_{2.5}$ and PM_{10} mass concentrations were measured using a calibrated laser-scattering optical particle detector (HT-9600, Dongguan Xintai Instrument Co., China; measurement range 0–1,000 µg/m³, resolution 1 µg/m³, repeatability ± 10%). Prior to the experimental campaign, the HT-9600 sensors were cross-calibrated against a reference beta-attenuation particulate monitor using the same sieved road-dust aerosol (R^2 = 0.96 for $PM_{2.5}$ and R^2 = 0.94 for PM_{10}). Air sampling was conducted at a fixed central port located at 1.0 m height (mid-canopy level), with each hourly reading calculated as the mean of three consecutive 60-second measurements. Chamber relative humidity was strictly maintained at 60 ± 5% during all readings to prevent hygroscopic particle swelling from biasing optical mass estimates.

Processing experimental data and statistical analysis

Adapting the closed-chamber mass-balance framework established for phytoremediation studies (Kim et al., 2010; Aydogan and Montoya, 2011; Fooladi et al., 2019) and incorporating a parallel blank-chamber correction to account for physical aerosol settling and wall deposition (Popek et al., 2017; Jin et al., 2021), the control-corrected particulate matter reduction per unit chamber volume and unit one-sided leaf area (A) at exposure time t was calculated as:

$$A = [(P_i - P_t) - (C_i - C_t)] \times \times \frac{1}{S} \ (\mu g.m^{-3}.m^{-2}) \quad [1]$$

where: A – control-corrected amount of particulate matter reduced per unit chamber air volume and per unit one-sided leaf surface area (µg.m^{-3}.m^{-2}), P_i, P_t – particulate matter concentration (µg/m³) in the treatment chamber (with plants) at the initial baseline time (t = 0, 5 min post-injection) and after exposure time t (hours), respectively, C_i, C_t – particulate matter concentration (µg/m³) in the parallel control chamber (without plants) at the initial baseline time (t = 0) and after exposure time t (hours), respectively, S – total one-sided leaf surface area of the plants in the treatment chamber (m²), t – elapsed exposure duration from the initial baseline reading (h).

Because PM concentrations were measured at hourly intervals over the exposure period (t = 6 h) and deposition rates vary over time as chamber concentrations decline, the time-normalized volumetric reduction rate (A_t) was derived as:

$$A_t = [(P_i - P_t) - (C_i - C_t)] \times \times \frac{1}{S} \times \frac{1}{t} (\mu g \cdot m^{-3}.m^{-2}.h^{-1}) \quad [2]$$

where: A_t – control-corrected amount of particulate matter reduced per unit chamber volume, per unit leaf surface area, per hour ($\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$), t – total effective exposure time (t = 6 h).

To express the reduction rate on an absolute mass basis independent of chamber air volume, A_t was multiplied by the internal chamber volume (V_c) to obtain the average control-corrected PM reduction rate normalized by leaf area (W):

$$W = A_t \times V_c (\mu g \cdot m^{-2}.h^{-1}) \quad [3]$$

where: W – average control-corrected particulate matter reduction rate per unit one-sided leaf surface area per hour ($\mu g \cdot m^{-2} \cdot h^{-1}$).

Note that W represents the net plant-induced atmospheric PM clearance rate normalized by foliar area (which primarily reflects foliar interception/sedimentation along with minor deposition on petioles and stems), rather than a direct gravimetric leaf-wash retention measurement, V_c – internal volume of the experimental chamber (V_c = 8.0 m³).

All data are reported as mean ± standard deviation (SD) of three independent chamber replicates (n = 3). Normality of residuals and homogeneity of variance were verified using the Shapiro–Wilk test and Levene's test, respectively. A two-way analysis of variance (ANOVA) was performed to evaluate the main effects of plant species (20 levels), initial PM concentration (Level 1 vs. Level 2), and their interaction (Species × Concentration) on the control-corrected PM reduction rate (W) for both $PM_{2.5}$ and PM_{10}. Differences among species means within each concentration level were assessed using Tukey's honestly significant difference (HSD) post-hoc test at a significance level of $\alpha = 0.05$. Hourly concentration decay trajectories in treatment and control chambers were analyzed using repeated-measures linear mixed-effects models. Pearson correlation analysis (r) was used to evaluate the relationship between total chamber foliar area (S) and total chamber PM mass removed, while paired t -tests compared Level 1 and Level 2 performance within species. All statistical analyses were conducted in R version 4.3.2 (R Core Team, 2023).

RESULTS

Across all experimental runs, $PM_{2.5}$ and PM_{10} concentrations in the plant-free control chambers (C_t) exhibited a gradual, linear-to-weakly-exponential decline due to gravitational settling and wall loss, accounting for an average background reduction of 12.4 ± 2.1% for $PM_{2.5}$ and 17.8 ± 2.6% for PM_{10} over the 6-hour period. In contrast, treatment chambers containing plants (P_t) displayed a pronounced biphasic decay trajectory: a rapid exponential decline during the first 1–3 hours of exposure (accounting for 65–75% of total plant-induced clearance), followed by a slower asymptotic attenuation from hours 4 to 6 as ambient particle concentrations decreased.

Two-way ANOVA revealed highly significant main effects of plant species ($F_{19,80} = 184.6$, $p < 0.001$ for $PM_{2.5}$; $F_{19,80} = 212.3$, $p < 0.001$ for PM_{10}), initial concentration level ($F_{1,80} = 342.1$, $p < 0.001$ for $PM_{2.5}$; $F_{1,80} = 398.5$, $p < 0.001$ for PM_{10}), and the Species × Concentration interaction ($p < 0.001$) on the control-corrected PM reduction rate (W).

The mean control-corrected $PM_{2.5}$ reduction rate (W, mean ± SD, n = 3) across all 20 native plant species at Concentration Levels 1 and 2 are illustrated in Figure 3. Across the 20 species, mean $PM_{2.5}$ reduction rate ranged from 8± 4 to 536± 42 $\mu g \cdot m^{-2} \cdot h^{-1}$ at Level 1 and from 15± 4 to 888± 65 $\mu g \cdot m^{-2} \cdot h^{-1}$ at Level 2. Five species exhibited particularly high reduction rates: *Broussonetia papyrifera* (536 / 888 $\mu g \cdot m^{-2} \cdot h^{-1}$), *Dracontomelon duperreanum* (161 / 197 $\mu g \cdot m^{-2} \cdot h^{-1}$), *Ficus drupacea* (128 / 273 $\mu g \cdot m^{-2} \cdot h^{-1}$), *Diospyros mun* (96 / 149 $\mu g \cdot m^{-2} \cdot h^{-1}$), and *Schefflera heptaphylla* (42 / 137 $\mu g \cdot m^{-2} \cdot h^{-1}$) at Levels 1 and 2, respectively. The remaining 15 species exhibited lower reduction rates, ranging from 8 ± 4 to 55 ± 3 $\mu g \cdot m^{-2} \cdot h^{-1}$ at Level 1 and from 15 ± 4 to 96 ± 8 $\mu g \cdot m^{-2} \cdot h^{-1}$ at Level 2. Specifically: *Quercus platycalyx* (55 ± 3 / 96 ± 8), *Bischofia javanica* (37 ± 2 / 62 ± 7), *Lysidice rhodostegia* (33 ± 2 / 88 ± 5), *Canarium album* (32 ± 3 / 44 ± 7), *Actinodaphne pilosa* (29 ± 4 / 55 ± 11), *Erythrophleum fordii* (27 ± 2 / 40 ± 5), *Vatica cinerea* (27 ± 2 / 57 ± 6), *Hopea odorata* (27 ± 3 / 46 ± 9), *Parashorea chinensis* (20 ± 3 / 25 ± 7), *Rhaphidophora decursiva* (20 ± 2 / 74 ± 4), *Calocedrus macrolepis* (19 ± 2 / 28 ± 4), *Saraca dives* (14 ± 2 / 29 ± 5), *Cinnamomum aff. iners* (9 ± 2 / 15 ± 6), *Canarium tramdenum* (9 ± 3 / 42 ± 8), and *Dipterocarpus alatus* (8 ± 4 / 25 ± 10 $\mu g \cdot m^{-2} \cdot h^{-1}$).

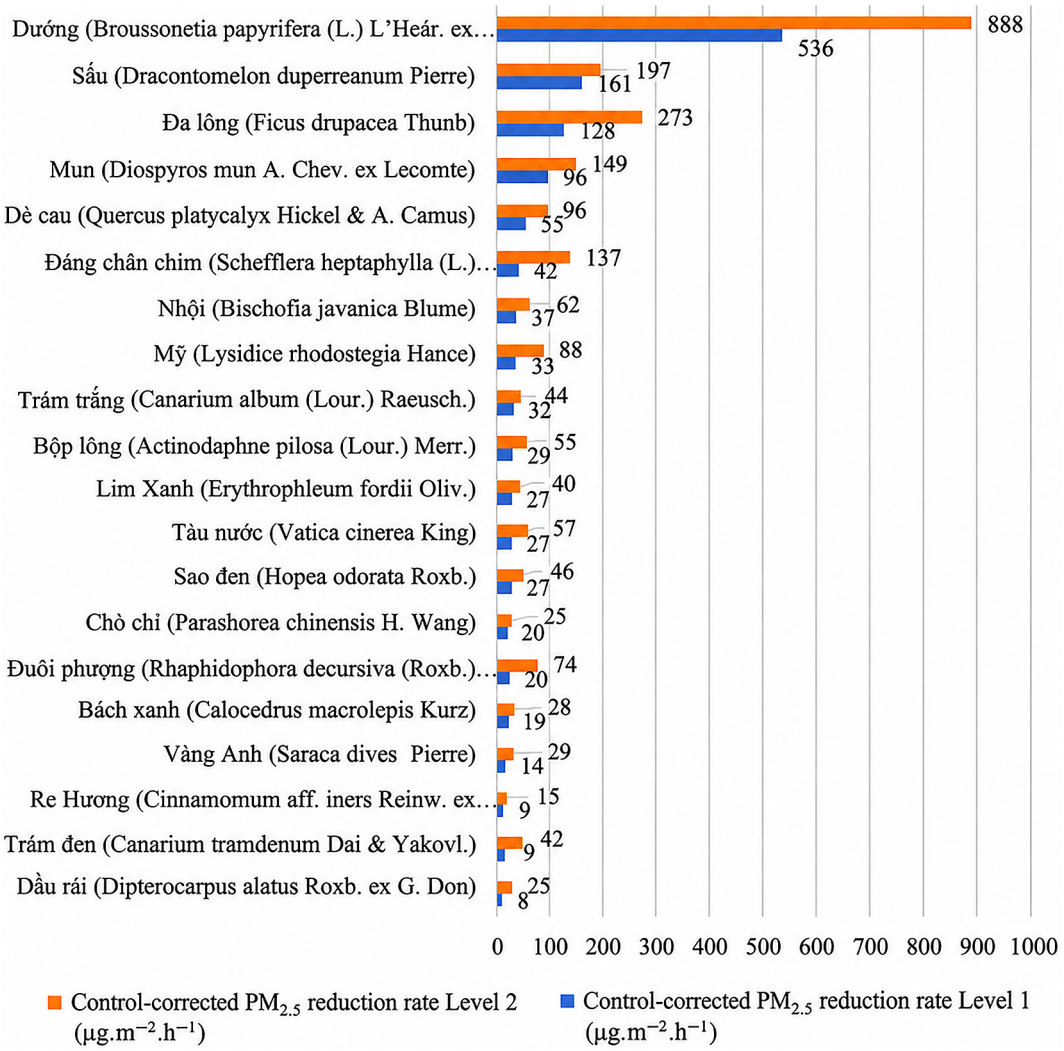

Figure 3. Control-corrected $PM_{2.5}$ reduction rate of 20 native plant species in Vietnam

Of the species evaluated, five native plants demonstrated statistically superior ($p < 0.05$, Tukey's HSD) control-corrected $PM_{2.5}$ reduction rate. Their performance metrics (mean ± SD and post-hoc statistical groupings, ordered by Concentration Level 1 ranking) are presented in Table 3.

The mean control-corrected PM_{10} reduction rate (W, mean ± SD, n = 3) of the 20 native plant species are presented in Figure 4. Among the 20 species evaluated, mean PM_{10} reduction rate ranged from 15 ± 6 to 773 ± 58 at level 1 and from 71 ± 14 to 1.281 ± 94 at level 2. Five species exhibited particularly high PM_{10} reduction rate at both concentration levels: *Broussonetia papyrifera* (773 / 1,281 $\mu g \cdot m^{-2} \cdot h^{-1}$), *Dracontomelon duperreanum* (259 / 450 $\mu g \cdot m^{-2} \cdot h^{-1}$), *Ficus drupacea* (226 / 483 $\mu g \cdot m^{-2} \cdot h^{-1}$), *Diospyros mun* (167 / 259 $\mu g \cdot m^{-2} \cdot h^{-1}$), and *Schefflera heptaphylla* (103 / 335 $\mu g \cdot m^{-2} \cdot h^{-1}$) at Concentration Levels 1 and 2, respectively. The remaining 15 species exhibited generally lower PM_{10} reduction rate, although their performance varied considerably across the two concentration levels, ranging from 15 ± 6 to 94 ± 8 $\mu g \cdot m^{-2} \cdot h^{-1}$ at Level 1 and from 47 ± 11 to 171 ± 7 $\mu g \cdot m^{-2} \cdot h^{-1}$ at Level 2. Specifically: *Actinodaphne pilosa* (98 ± 8 / 126 ± 19), *Dipterocarpus alatus* (16 ± 8 / 82 ± 17), *Hopea odorata* (47 ± 7 / 163 ± 16), *Quercus platycalyx* (94 ± 7 / 167 ± 15), *Canarium tramdenum* (15 ± 6 / 71 ± 14), *Canarium album* (60 ± 6 / 77 ± 13), *Parashorea chinensis* (44 ± 6 / 82 ± 13), *Bischofia javanica* (73 ± 5 / 123 ± 12), *Cinnamomum aff. iners* (28 ± 5 / 47 ± 11), *Vatica cinerea* (55 ± 5 / 151 ± 11), *Erythrophleum fordii* (47 ± 4 / 69 ± 10), *Saraca dives* (23 ± 4 / 48 ± 9), *Lysidice rhodostegia* (64 ± 4 / 170 ± 8), *Calocedrus macrolepis* (52 ± 3 / 61 ± 8), and *Rhaphidophora decursiva* (35 ± 4 / 171 ± 7 $\mu g \cdot m^{-2} \cdot h^{-1}$).

Of the 20 native species evaluated, the same five species exhibited the highest control-corrected PM_{10} reduction rate (Table 4). Notably,

Table 3. Top 5 experimental plant species with the highest control-corrected $PM_{2.5}$ reduction rate

No.	Experimental species	Control-corrected $PM_{2.5}$ reduction rate at Level 1	Control-corrected $PM_{2.5}$ reduction rate at Level 2	Two-level mean
1	Dướng (*Broussonetia papyrifera* (L.) L'Hér. ex Vent.)	536 ± 42 a	888 ± 65 a	712 ± 53 a
2	Sấu (*Dracontomelon duperreanum* Pierre)	161 ± 14 b	197 ± 18 c	179 ± 16 c
3	Đa lông (*Ficus drupacea* Thunb)	128 ± 11 c	273 ± 24 b	201 ± 18 b
4	Mun (*Diospyros mun* A. Chev. ex Lecomte)	96 ± 9 d	149 ± 13 d	123 ± 11 d
5	Đáng chân chim (*Schefflera heptaphylla* (L.) Frodin)	42 ± 5 e	137 ± 12 d	90 ± 9 e

Note: different lowercase letters within the same column indicate statistically significant differences among species according to Tukey's HSD test ($p < 0.05$). Unit: $\mu g.m^{-2}.h^{-1.}$

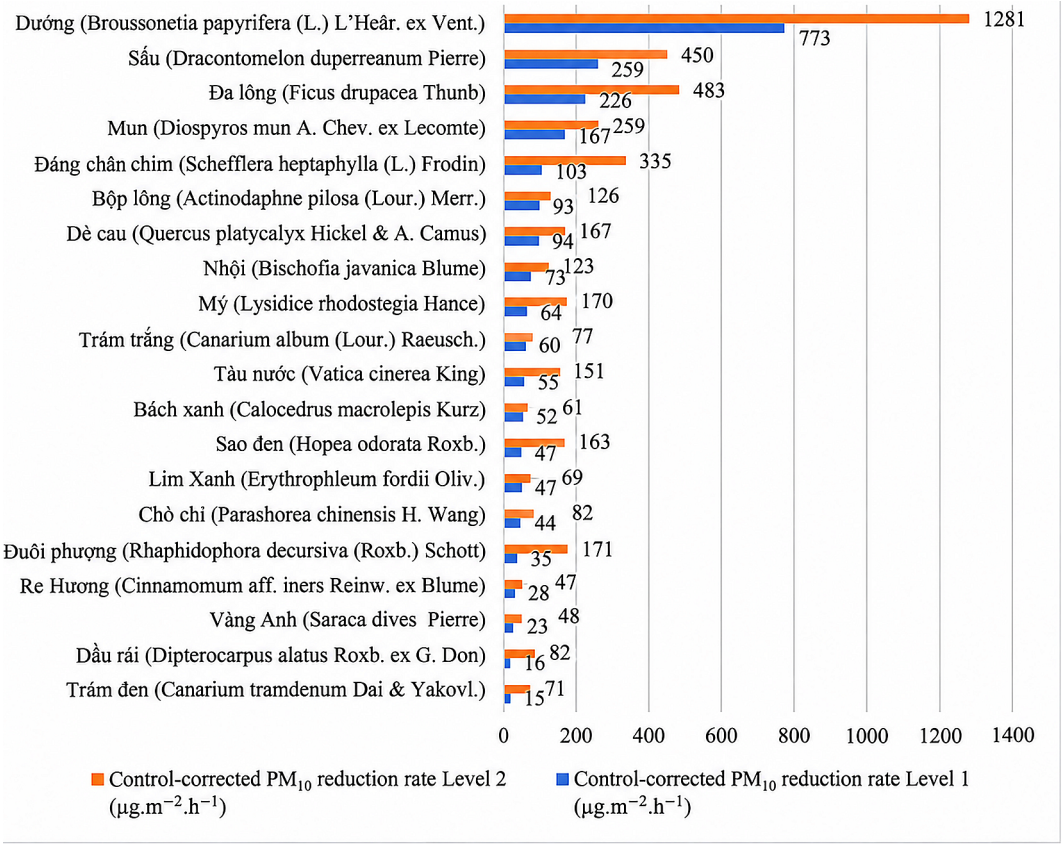

Figure 4. Control-corrected PM_{10} reduction rate of 20 native plant species in Vietnam

while Table 3 and Table 4 are ordered according to baseline performance at Concentration Level 1, where *D. duperreanum* ranked second (161 ± 14 $\mu g \cdot m^{-2} \cdot h^{-1}$ for $PM_{2.5}$ and 259 ± 21 $\mu g \cdot m^{-2} \cdot h^{-1}$ for PM_{10}) above *F. drupacea* (128 ± 11 and 226 ± 19 $\mu g \cdot m^{-2} \cdot h^{-1}$) – *F. drupacea* exhibited a steeper proportional increase at Concentration Level 2 (reaching 273 ± 24 $\mu g \cdot m^{-2} \cdot h^{-1}$ for $PM_{2.5}$ and 483 ± 38 $\mu g \cdot m^{-2} \cdot h^{-1}$ for PM_{10}), thereby surpassing *D. duperreanum* (197 ± 18 and 450 ± 35 $\mu g \cdot m^{-2} \cdot h^{-1}$) under heavy dust loading and achieving the second-highest two-level mean overall.

Across all 20 species, doubling the initial aerosol concentration from Level 1 to Level 2 resulted in a 1.22- to 3.26-fold increase in W (paired t-test, $p < 0.001$). Furthermore, total chamber PM mass removed over 6 h correlated strongly with total chamber one-sided leaf surface area S ($r = 0.78$, $p < 0.001$), confirming that larger total foliage volume removes a greater absolute mass of particulates from chamber air, whereas leaf-area-normalized rates (W) reflect intrinsic species-level surface capture efficiency.

Table 4. Top 5 experimental plant species with the highest control-corrected PM_{10} reduction rate. Unit: $\mu g.m^{-2}.h^{-1}$

No.	Experimental species	Control-corrected PM_{10} reduction rate at Level 1	Control-corrected PM_{10} reduction rate at Level 2 ($\mu g \cdot m^{-2} \cdot h^{-1}$)	Two-level Mean ($\mu g \cdot m^{-2} \cdot h^{-1}$)
1	Dướng (*Broussonetia papyrifera* (L.) L'Hér. ex Vent.)	773 ± 58 a	1,281 ± 94 a	1,027 ± 76 a
2	Sấu (*Dracontomelon duperreanum* Pierre)	259 ± 21 b	450 ± 35 b	355 ± 28 b
3	Đa lông (*Ficus drupacea* Thunb)	226 ± 19 b	483 ± 38 b	355 ± 29 b
4	Mun (*Diospyros mun* A. Chev. ex Lecomte)	167 ± 15 c	259 ± 22 d	213 ± 19 d
5	Đáng chân chim *(Schefflera heptaphylla* (L.) Frodin)	103 ± 9 d	335 ± 28 c	219 ± 19 c

Note: different lowercase letters within the same column indicate statistically significant differences among species according to Tukey's HSD test ($p < 0.05$).

DISCUSSION

The present chamber screening revealed more than a 30-fold variation in control-corrected $PM_{2.5}$ and PM_{10} reduction rate (*W*) across the twenty native Vietnamese plant species, demonstrating that intrinsic interspecific differences strongly govern aerosol depletion even under identical airflow and pollutant loading. While previous studies have evaluated urban PM removal using atmospheric transport models (Nowak et al., 2006; McDonald et al., 2007; Letter and Jäger, 2020; Zhang et al., 2021) or field leaf-wash inventories (Cavanagh et al., 2009; Abhijith and Kumar, 2020; Vigevani et al., 2022), as highlighted in the recent methodological review by Vigevani et al. (2024), empirical screening of native Southeast Asian tree species remains severely underrepresented. By standardizing chamber turbulence, relative humidity (60 ± 5%), and initial dust concentrations while subtracting parallel blank-chamber settling losses, our experimental design isolated plant-induced PM reduction from external meteorological confounding.

A key finding of this study is the exceptional performance of five broad-leaved native species as *Broussonetia papyrifera*, *Ficus drupacea*, *Dracontomelon duperreanum*, *Diospyros mun*, and *Schefflera heptaphylla* across both $PM_{2.5}$ and PM_{10} fractions. Based on our morphological observations during the conditioning phase and established foliar deposition theory (Sæbø et al., 2012; Janhäll, 2015; Zang et al., 2020), we hypothesize that specific leaf micromorphological and architectural traits explain this hierarchy:

1. *Broussonetia papyrifera* (Dướng) outperformed all other species by a factor of 3 to 4 (W = 536–888 $\mu g \cdot m^{-2} \cdot h^{-1}$ for $PM_{2.5}$ and 773 – 1281 $\mu g \cdot m^{-2} \cdot h^{-1}$ for PM_{10}). Morphologically, *B. papyrifera* possesses densely pubescent leaves covered with non-glandular trichomes on both adaxial and abaxial surfaces, coupled with a deeply reticulate, rugose venation network. Dense leaf trichomes disrupt the laminar boundary layer, increase surface roughness, and act as physical micro-traps that intercept fine and coarse particulates while preventing particle rebound and resuspension (Sæbø et al., 2012; Chen et al., 2017).
2. *Ficus drupacea* (Đa lông) and *Dracontomelon duperreanum* (Sấu) formed the second performance tier, displaying an interesting concentration-dependent rank reversal. At Concentration Level 1, *D. duperreanum* ranked second, likely due to its large pinnately compound leaves with sunken primary veins and complex multi-layered leaflet arrangement that promote inertial impaction under moderate dust loading. At Concentration Level 2, however, *F. drupacea* surpassed *D. duperreanum*. *F. drupacea* is characterized by thick, coriaceous (leathery) leaves coated with a prominent epicuticular wax layer and persistent brownish indumentum (hairs) on young foliage and twigs. Under high particulate loading (Level 2), smooth or weakly pubescent leaflet surfaces on *D. duperreanum* may experience partial saturation or particle rebound, whereas the thick waxy cuticle and fibrous indumentum of *F. drupacea* provide higher retention capacity for coarse and fine road-dust particles (Dzierżanowski et al., 2011; Popek et al., 2017).
3. *Diospyros mun* (Mun) and *Schefflera heptaphylla* (Đáng chân chim) ranked fourth and fifth, respectively. *D. mun* features a dense, compact branching architecture with coriaceous, waxy leaves that favor cuticular trapping of fine particulates, whereas *S. heptaphylla* possesses palmately compound leaves arranged in whorled clusters. This whorled compound

canopy geometry increases local drag and generates micro-eddies within the crown, enhancing gravitational sedimentation of coarse PM_{10} particles onto the adaxial lamina, consistent with the pronounced 3.25-fold surge in PM_{10} reduction observed for *S. heptaphylla* at Level 2 (335 ± 28 $\mu g \cdot m^{-2} \cdot h^{-1}$). In contrast, the woody climber *Rhaphidophora decursiva* (possessing smooth, glossy, pendulous leaves) and the scale-leaved conifer *Calocedrus macrolepis* (which had a relatively sparse juvenile crown in our sapling trials) exhibited the lowest leaf-area-normalized reduction rate.

Because these trait-performance relationships are based on qualitative morphological characterization rather than direct quantitative trait regressions (e.g., scanning electron microscopy counts of trichome density, stomatal density, or gravimetric wax extraction), they should be regarded as mechanistic hypotheses that warrant quantitative verification in future work.

Furthermore, across all 20 species, control-corrected PM reduction rates (W) were significantly higher for PM_{10} than for $PM_{2.5}$, and increased significantly from Concentration Level 1 to Level 2. Because PM_{10} encompasses both $PM_{2.5}$ and coarse particles ($PM_{2.5_10}$), the higher mass reduction rate for PM_{10} reflect the greater gravitational settling velocity and inertial impaction efficiency of coarse particles onto foliage surfaces (Beckett et al., 2000a; Janhäll, 2015). Similarly, higher ambient particle concentrations at Level 2 increase the concentration gradient across the leaf boundary layer, accelerating diffusive and impaction flux per unit leaf area (W).

Several methodological considerations and limitations must be noted when interpreting these chamber results. First, although pots and substrates were sealed in polyethylene bags and background wall/pot settling was subtracted using parallel control chambers, our mass-balance metric (W) measures net atmospheric depletion normalized by one-sided leaf area (S); thus, minor deposition onto petioles, twigs, and bark is included in the calculated rate. Second, chamber air humidity was maintained at $60 \pm 5\%$ to avoid hygroscopic swelling artifacts in optical particle counting, whereas outdoor tropical humidity in Vietnam frequently exceeds 80%, which can alter particle stickiness and leaf surface wetness. Third, over the 6-hour closed-chamber exposure, most particle clearance occurred within the first 3 hours; in open urban street canyons, continuous pollutant replenishment, variable wind speeds, rainfall wash-off, and leaf saturation dynamics will strongly modulate long-term net removal. Consequently, while controlled chamber screening provides a rigorous, standardized benchmark for ranking intrinsic species capacity, the top-performing species identified here should be regarded as priority candidates for multi-season field validation rather than a direct measure of outdoor urban air-quality improvement.

CONCLUSION

This study evaluated the control-corrected $PM_{2.5}$ and PM_{10} reduction rate of twenty native Vietnamese plant species under standardized, airtight chamber conditions. Among the species investigated, *Broussonetia papyrifera*, *Ficus drupacea*, *Dracontomelon duperreanum*, *Diospyros mun*, and *Schefflera heptaphylla* consistently exhibited statistically superior ($p < 0.05$) control-corrected PM reduction rate (W) across both particle-size fractions. Our results also demonstrated that leaf-area-normalized PM reduction rate increased significantly at higher initial PM concentrations ($p < 0.001$), while total chamber-level PM clearance correlated positively with total foliar surface area ($r = 0.78$, $p < 0.001$). The findings provide standardized comparative evidence supporting the screening of native plant species as biological interceptors for airborne particulate matter. Although these metrics reflect short-term performance in closed chambers and require long-term outdoor validation under ambient meteorological conditions, the five highest-performing species identified in this study represent promising priority candidates for field trials, urban greening, and ecological engineering programs aimed at mitigating particulate matter pollution in Vietnam.

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