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Assessment of the significance of urban vegetation in air phytoremediation: Quantitative analysis of particulate matter removed

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Abstract

Urban vegetation is widely recognised as a natural sink for atmospheric particulate matter (PM). Nevertheless, city-scale estimates of PM removal are almost exclusively based on deposition velocity () models rather than direct measurements. Here, this work presents a more precise approach to evaluating the removal of distinct PM fractions by measuring PM deposited on leaves. Five representative leaf morphologies were physically sampled throughout the year (every 4th day) and subsequently extrapolated to 20 dominant urban species to produce city-scale estimates. PM on leaf surfaces was quantified across three size categories (0.2-2.5, 2.5-11, and 11-100 µm) and then derived an estimate using species distribution and canopy attributes to determine removal on a city-wide scale. Direct physical sampling estimated that Delhi's urban forest (23.06% of city area) removed 527.43±301.37 tons of $PM_{2.5}$ and 7907.26±1079.34 tons of total PM (0.2-100 µm) during the study period. Estimates were examined in comparison with the most recent publicly accessible SAFAR emission inventory (2018). Against annual $PM_{2.5}$ emissions of 48,474.96 tons, urban vegetation removed only approximately 1.08% of emitted $PM_{2.5}$, indicating that although urban forests offer quantifiable ecosystem services, their ability to alleviate city-wide particulate pollution is fundamentally constrained. Physical measurements indicated a detectable saturation barrier to particle accumulation on leaf surfaces (as observed in Figure 2, from November-January deposition), underscoring a constraint overlooked by traditional methodologies. A comparison of physical sampling vs approach found that just ~24% of the $PM_{2.5}$ quantified by the conventional approach was in fact removed whilst the metric for PM_{10} was even lower, at ~4.6%. This study also separated wet/dry removal and leaf litter fall as additional contributing removal pathways. Elemental characterisation of deposited particles revealed distinct size-dependent composition: coarse fractions (2.5-11 µm) were dominated by crustal elements (Si, Al, Fe, Ca, and K), whereas fine (0.2-2.5 µm) particles exhibited measurable enrichments in anthropogenic trace metals, including Cr, Ni, Cu, Zn, and Pb, confirming the interception of both natural and traffic-related aerosols. Beyond improving urban liveability through carbon sequestration and urban cooling, our findings establish the first measurement-based benchmark for vegetation-mediated PM removal. The results demonstrate that urban greening should strengthen, rather than substitute for, effective emission control strategies to improve urban air quality.

1. Introduction

Urban air pollution is a worldwide issue brought on by heavy traffic, excessive industrial activity, as well as elevated population mobility [1–4]. PM, sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ground-level ozone (O_3) are examples of primary air pollutants that negatively affect human health, including respiratory and cardiovascular illnesses [5–9]. Particulate pollutants can either deposit on the canopy surface, be absorbed through stomata, or adsorption in wax of the leaves of trees, shrubs, and herbaceous vegetation [10–14].

The primary objective of the present study was to estimate PM removal by widespread urban trees in the National Capital Territory of Delhi (NCT Delhi), to characterise the city-wide PM removal capacity and chemical composition, and to identify high-performing species for effective urban air quality management. Air phytoremediation has gained recognition recently as a sustainable and economical method of diminishing urban air pollution [15,16]. The evaluation of air pollution mitigation by urban forests remains constrained in European and American regions [17–19], while limited research has been addressed in the Asian continent, especially China [20–22]. There is a notable absence of studies focusing on Indian cities, where stress factors associated with the urban environment coincide with additional constraints, such as extreme summer temperatures and varying leaf shedding patterns [23,24]. Limited repeated physical measurements can reflect seasonal fluctuations. To bridge this research gap, this study assessed the dust-removal effect of air phytoremediation by conducting temporal high-resolution physical sampling of leaves and measuring PM deposited on them.

Existing studies primarily focus on measuring the V_d of PM on leaves using leaf area index (LAI), which is leaf area per square meter projected ground area of the tree and assessing resistances on leaf surfaces, or seasonal sampling of leaves [25,26]. Model conclusions are exceptionally sensitive to assumptions regarding V_d, canopy resistance, LAI, meteorological variables, particle re-suspension, precipitation wash-off, and seasonal leaf dynamics, introducing considerable uncertainty into annual and city-scale estimates [27,28]. Research from Chicago, USA, estimated that about 234 tons of PM_{10} were removed per year by green areas covering 11% of the city area [29], and in the whole USA, about 215,000 tons of PM_{10} were removed by urban vegetation [17]. In Beijing, China, 772 tons of PM_{10} were removed by trees in the city centre [21]. Studies conducted in UK cities have shown that PM_{10} concentrations can be reduced by 2–10% if green area is increased by 25% of the available urban area [18]. As a result of urban trees huge leaf surface areas, which serve as biological filters and enhance air quality [1,30–33]. It is worth noting that the past studies estimate the PM capture capabilities by sampling leaves after a long duration without precipitation or at the end of a particular season only [13,14,20,34–38].

Prior studies have primarily focused on quantifying PM deposition on plants, with minimal chemical analysis of size-resolved leaf-deposited particles. Elemental analysis can differentiate between crustal and anthropogenic origins, offering understanding of PM sources, ecological significance, and air quality impacts [39–41]. For scientists and policymakers, creating environmental planning and policies that successfully lower these air pollutants in metropolitan areas has taken precedence [31,42–45].

For clarity PM deposited on leaves was used as representation for PM removed by vegetation. Deposited particles constitutes the suspended particles transferred from air to the leaves. Particle mass obtained through physical sampling directly represent the atmospheric PM intercepted and retained on leaves at the time of sampling. Upon deposition, particles are momentarily extracted from the airborne phase and may later persist on the leaves, be transferred to the ground by precipitation or leaf abscission, or be reintroduced into the atmosphere via resuspension. Hence, the quantified foliar PM load offers a direct

assessment of vegetation-facilitated PM retention, although adjustments for resuspension and other post-depositional phenomena are essential when calculating effective or net PM elimination. PM deposition is controlled by five mechanical processes: sedimentation under gravity, interception, inertial impaction, Brownian diffusion and turbulent impaction [28,46,47]. Dry and wet removal are two mechanisms via which PM is naturally removed apart from industrial establishments. Dry removal is the transport of gaseous and particulate species from the environment onto surfaces in the absence of precipitation. Wet removal refers to the scavenging of PM by atmospheric hydrometeors such as rain and clouds [48]. In addition to wet and dry deposition, occult deposition, achieved through fog and mist interception [49].

Apart from plant morphology [27,50,51], a plant's ability to capture PM and remove it, is controlled by environmental factors such as wind, temperature, and, most significantly, precipitation. Annual PM removal advantages of vegetation have been committed to the net PM removal capabilities of the plant species. Therefore, planting higher PM-removing species to maximize PM removal is crucial [11,52]. Precipitation washed off the captured PM and deposited it onto the ground, where inorganic PM is immobilised in the soil and the organic component can be decomposed [20]. This wash-off process is identical to filter cleaning, making the leaves ready for further PM deposition [3,15,38,53–56]. Leaf traits significantly affect PM accumulation and removal, while turbulence generated by tree structures, by altering air streamlines, may also enhance particle capture and deposition [1,11,52,57]. Many species have developed trichomes on the leaf surface, which improve PM-capturing capabilities [1,58,59].

Building upon these considerations, this work uses the city of NCT Delhi as a case study. We use high-resolution physical sampling of leaves across a full year instead of the single post-dry period or end-of-season sampling used in earlier studies. The specific research aim of this study is to quantify the net PM removal in the NCT Delhi region through vegetation and the fraction of PM removed relative to the total PM emitted from the same region. PM removal was then compared with the V_d method to quantify the efficacy of the selected methods and, finally, to evaluate species that could be preferred in urban planning for higher PM removal. Our estimation revealed that, using physical sampling, $PM_{2.5}$ removal was 527.43 ± 301.37 tons of the $PM_{2.5}$ emitted, whereas the V_d deposition method estimated 2216.94 tons of $PM_{2.5}$ removed. Both approaches indicated that the removal was significantly less than the emissions. Chemical characterisation identified signatures of both road dust and vehicular emissions in the deposited PM.

2. Results

The findings outlined below derive from an extensive dataset of physical samples gathered over the course of five representative urban plant species in Delhi. Leaf sampling was conducted from May 2022 to May 2023, spanning the full range of Delhi's seasonal PM regime. This paradigm facilitated the assessment of seasonal deposition patterns, species-specific particle retention, and the elemental composition of deposited particles across several size categories (Large: 11–100 µm, Coarse: 2.5–11 µm, and Fine: 0.2–2.5 µm), as well as the extrapolation of observed deposition to approximate yearly PM

removal by urban forests in Delhi. Sampling started in May 2022, immediately after a heavy rainfall event, which was assumed to have thoroughly cleaned leaf surfaces. This study opted for the different size fractions of PM, as they have distinct health impacts.

2.1 Emissions from the NCT region

To evaluate the estimated PM removal, the current study compares vegetation-mediated PM removal from 2022 to 2023 with the latest emission inventory from the System of Air Quality and Weather Forecasting and Research (SAFAR), which dates back to 2018. Despite not being concurrent with the research timeframe, the SAFAR inventory constitutes the most recent comprehensive sector-specific emission inventory for Delhi and was thus used as a reference for comparison. This evaluation offers an approximate magnitude instead of a direct yearly comparison, acknowledging that emissions might have fluctuated from 2018 to 2022–2023 owing to variations in activity and restrictions. Thus, the stated removal efficiencies should be regarded as a representative comparison with the most accurate emission inventory, rather than as a precise adjustment of emissions over the sampling period.

The annual $PM_{2.5}$ emissions in NCT Delhi estimated from SAFAR totalled 48,474.96 tons (Figure S1). December (4,826.25 tons) has the greatest emissions, followed by January (4,666.25 tons) and February (4,359.87 tons). Seasonal changes are shown by the fact that July has the lowest emissions (3,094.46 tons) (Table 2). The highest emissions occur during the winter months (December to February), most likely due to increased residential heating, biomass burning, and vehicular emissions. Summer (May-June): Emissions are still over 3,600 tonnes per month. However, these emissions are comparatively lower than during the winter months. Emissions were at their lowest during the monsoon months (July to September), most likely due to lower coal and biomass burning compared to winter [60]. The consistently elevated PM emissions in Delhi emphasise the need for mitigation approaches that go beyond mere emission reductions. Urban vegetation functions as a biological filter by seizing airborne particulates on foliar surfaces, limiting their atmospheric residence time, and decreasing public exposure. Measuring this ecosystem contribution is essential for determining how effectively vegetation can improve urban air quality.

2.2 Quantification of PM deposited

PM deposition on leaf surfaces was recorded to quantify the amount of atmospheric PM captured and retained by the selected plant species and to account for temporal variability in deposition throughout the study period. Throughout sampling events, species, and particle-size fractions, PM mass varied significantly. Total PM and large PM represented more dominant surface loadings than coarse and fine PM. The magnitude of deposition also varied among *Wedelia, Ailanthus altissima, Plumeria alba, Saraca asoca*, and *Cassia fistula*, indicating differences in species-specific particle capture and retention characteristics. Figure 1 illustrates the PM deposited on the surface of leaves (μg/cm^2) from May 2022 to May 2023. *Cassia fistula* had the highest averaged total PM of 197.3 μg/cm^2 over the year, followed by

Plumeria alba (191.43 µg/cm^2), *Wedelia* (184.68 µg/cm^2), *Ailanthus altissima* (179.04 µg/cm^2), and *Saraca asoca* (156.47 µg/cm^2).

As the large particle fraction (11–100 µm) dominated the total deposited mass, its distribution among species followed the same trend as that of total PM accumulation. *Plumeria alba* recorded the highest average deposition of both coarse (35.19 µg cm^{-2}) and fine (9.30 µg cm^{-2}) particles, indicating a greater capacity to capture smaller particles than the other species studied. During the sampling period, the highest total PM was captured by *Cassia fistula* (475.36 µg/cm^2), followed by *Wedelia* (442.79 µg/cm^2), *Ailanthus altissima* (430.72 µg/cm^2), *Plumeria alba* (413.36 µg/cm^2) and the lowest total was achieved by *Saraca asoca* (318.71 µg/cm^2) (Fig. 1). The fine fraction fluctuates extensively while sampling. Individual sample dates indicate substantial increases, although values are typically modest. Fine-particle retention on leaves is far more variable than coarse-particle deposition, perhaps due to particle availability and leaf-surface retention rather than cumulative accumulation. PM levels observed on the leaves fell within the range documented in other research on vegetation using identical sampling methods[61–63]. In October, sampling wasn't done. In the lack of precipitation, PM probably persisted in accumulating on leaf surfaces, with the scale of accumulation affected by species-specific deposition and retention traits, as well as ambient PM concentrations.

Throughout the sampling, PM deposition progressively escalated and attained a saturation point between November and January, aligning with a prolonged phase of no precipitation (Fig. 2). The lack of rainfall restricted the natural removal of deposited particles, resulting in ongoing accumulation on leaf surfaces until they neared their maximum capacity for particle retention. This threshold was indicated by the stabilisation of deposited PM despite consistently elevated ambient pollution levels, implying that leaf surfaces reached saturation under extended dry atmospheric circumstances. For all five species, PM appeared to plateau after about 20–30 days without precipitation, suggesting a leaf retention period beyond which further accumulation became limited (Fig. 2 lower panel).

PM deposition was lowest during the monsoon, when regular rainfall reduced particle accumulation by wet scavenging and leaf wash-off. Post-monsoon deposition increased gradually and peaked in winter due to increasing atmospheric particulate loading, restricted rainfall, and reduced atmospheric mixing. PM deposition gradually decreased in spring before rising again in summer. Unlike precipitation, which peaked during rainy season, average wind speed fluctuated more gradually over the year and remained low during PM deposition maxima in winters. The inverse relationship between cumulative precipitation and PM deposition shows that rainfall controls leaf PM accumulation, whereas wind speed regulates air dispersion and particle transit. Spearman's rank (ρ) correlation analysis showed that precipitation was the dominant meteorological factor affecting PM removal by plants. PM deposition showed a strong negative relationship with precipitation ($\rho = -0.621$, $p = 2.37 \times 10^{-10}$), indicating that rain substantially reduced particle accumulation by washing particles off leaves. In contrast, wind speed had a weaker but still significant negative correlation ($\rho = -0.383$, $p = 3.00 \times 10^{-4}$). The stronger link to rainfall suggests that rainfall is the primary meteorological driver of seasonal PM removal from vegetation, whereas wind

speed plays a secondary role. Fine PM (0.2–2.5 μm) accounted for only 6–7% of the deposited mass but remains particularly important due to its greater potential health impacts (Table 1).

An additional sampling was undertaken during the peak pollution period (November-January) to ascertain the PM deposition near the emission source. Following the regular year-round on-campus monitoring, leaf samples were collected from roadside areas off campus, where traffic emissions and road dust are significantly elevated. The *Cassia fistula* next to the roadway collected a total dust load of 728.63 μg cm^{-2}, significantly exceeding the deposition recorded in the campus environment. The deposited mass contained 457.90 μg cm^{-2} of particles above 11–100 μm, 219.64 μg cm^{-2} of particles within the 2.5–11 μm range, and 51.09 μg cm^{-2} of fine particles (0.2–2.5 μm). The large fraction (> 11 μm) constituted 62.8% of the total deposited mass, the intermediate fraction (2.5–11 μm) contributed 30.1%, and the fine fraction comprised 7.0% of the total deposition. The prevalence of coarse particles indicates that re-suspended road dust is the primary source of particulate deposition on roadside vegetation. Whereas the increased percentage of fine particles reflects the impact of automobile emissions and combustion-related pollutants (Table 1).

2.3 PM removal

The measured particle deposition data were then used to estimate PM removal by vegetation across NCT Delhi, assuming the five selected species represented regional vegetation and were evenly distributed. Drawing out leaf area from green area and LAI, and using PM deposition, the net PM reduction was estimated. The PM removal estimate used condition-specific adjustment factors to account for particle retention and resuspension. A factor of 1.0 was applied under wet conditions, assuming PM was effectively removed through precipitation and wash-off, whereas a factor of 0.5 was used for dry removals to account for resuspension, consistent with the assumption commonly applied in conventional approaches (see Sections S1 and S2). During the sampling period, *Cassia fistula* removed the maximum total PM (1696.22 ± 231.53 tons), followed by *Saraca asoca* (1665.39 ± 227.32 tons), *Plumeria alba* (1643.07 ± 224.27 tons), *Wedelia* (1551.95 ± 211.84 tons) and *Ailanthus altissima* (1350.61 ± 309.42 tons). *Plumeria alba* had the most coarse PM removed at 486.23 ± 125.82 tons, whilst *Cassia fistula* displayed the highest fine PM removal at 120.36 ± 68.77 tons (Table 1). The annual PM removal variability among the selected species was comparable across all three particle-size fractions, with coefficients of variation of 10.77%, 18.44%, and 11.12% for the large, coarse, and fine fractions, respectively, signifying a similar level of interspecific variation in PM removal.

The annual PM removal was primarily driven by the large-particle fraction, which accounts for 63.50–75.20% of the total PM removed. *Wedelia* exhibited the greatest percentage of large PM elimination (75.20%), whereas *Plumeria alba* demonstrated the lowest (63.50%); however, it contributed the most from coarse PM (29.59%). The fine PM fraction exhibited the minimal contribution across all species (5.80–7.58%), with *Ailanthus altissima* demonstrating the greatest relative fine PM elimination (7.58%). The findings indicate distinct species-specific variations in the relative capture of various PM size fractions (Table 1).

Table 1
Estimated PM removed by five selected plant species, expressed as total PM (0.2–100 μm), together with the mass and percentage contribution of large (11–100 μm), coarse (2.5–11 μm), and fine (0.2–2.5 μm) fractions.

Species	Total PM (0.2–100 μm) (tons)	Large PM (11–100 μm) (tons)	Large PM (%)	Coarse PM (2.5–11 μm) (tons)	Coarse PM (%)	Fine PM (0.2–2.5 μm) (tons)	Fine PM (%)
Wedelia	1551.95	1167.00	75.20	294.88	19.00	90.06	5.80
Ailanthus altissima	1350.61	898.39	66.51	349.81	25.90	102.41	7.58
Plumeria alba	1643.07	1043.42	63.50	486.23	29.59	113.41	6.90
Saraca asoca	1665.39	1155.02	69.35	409.18	24.56	101.17	6.07
Cassia fistula	1696.22	1165.97	68.73	409.87	24.16	120.36	7.09

Roughness, wax content, or leaf angle could be influential parameters governing deposition and removal, and these factors require further investigation [64,65]. These distinct particle deposition levels with varying aerodynamic diameters most likely reflect the various aerodynamic properties of the particles and how they interact with different leaf attributes or morphology [10,25,28,66–68].

Given that the SAFAR emission inventory was available only for 2018, we assumed that the seasonal emission trends remained largely indicative of conditions in 2022–2023. As a result, monthly emission estimates are compared with monthly vegetation-mediated PM reduction to evaluate their temporal correspondence rather than their absolute coherence. The $PM_{2.5}$ emissions for the full month are shown in Table 2. Vegetation eliminated 527.43 ± 301.37 tons of $PM_{2.5}$ throughout the year. In comparison, 2,216.90 tons of $PM_{2.5}$ were reportedly eliminated using the V_d technique, which is a far higher amount. The estimated annual removal of $PM_{2.5\text{-}11}$ by vegetation was 1949.77 ± 504.85 tons (± 25.89%). The removal percentage (physical sampling) is 1.08%, indicating a modest impact of vegetation in mitigating pollution. January shows the greatest removal rate (124.34 tonnes, 2.66%), while June has the lowest (9.49 tonnes, 0.26%). The V_d method, which accounts for deposition velocities, shows an average removal of 4.57%, peaking in November (9.85%). Despite limited winter rainfall, PM removal was higher due to greater particle accumulation on leaves; consequently, even minor wind events removed substantial PM compared with in summer.

Table 2
Monthly $PM_{2.5}$ emissions and vegetation-based and deposition velocity-based mitigation in the National Capital Territory (NCT) of Delhi.

Month	$PM_{2.5}$ emissions (tons/month)	$PM_{2.5}$ removed by vegetation (tons/month)	$PM_{2.5}$ removed (V_d method) (tons/month)	% of $PM_{2.5}$ removed (sampling method)	% of $PM_{2.5}$ removed (V_d method)
January	4666.25	124.34	431.70	2.66	9.25
February	4359.87	8.42	265.92	0.19	6.09
March	4535.93	75.33	195.74	1.66	4.31
April	3814.06	13.22	33.77	0.34	0.88
May	3969.68	12.59	10.18	0.31	0.25
June	3638.53	9.49	15.46	0.26	0.42
July	3094.46	13.16	9.26	0.42	0.29
August	3432.98	18.90	17.10	0.55	0.49
September	3542.32	88.54	105.09	2.49	2.96
October	4258.38	24.06	274.70	0.56	6.45
November	4335.25	65.96	427.20	1.52	9.85
December	4826.25	73.38	430.78	1.52	8.92

In contrast with the findings of [17,18,21,29], vegetation removes only a limited fraction of particles from the city. Results also agree with PM removal by the living wall structure [69–71]. However, the magnitude of PM removal estimated in the present study is substantially lower than that reported in earlier studies[13]. More significantly, Delhi's extraordinary PM emissions indicate vegetation-mediated reduction accounts for only a tiny proportion of the city's overall particle emissions.

The PM removal estimates presented in this study are conservative because they account only for particles retained on the leaf surface, the wax on the leaves also absorbed around 20–25% of the surface PM. This amount was not calculated in this research, but the vegetation nonetheless eliminated it [72,73]. Removal between consecutive samplings was classified as wet removal when precipitation occurred and as dry removal otherwise [74]. Despite only 32 of 85 sampling meeting the wet-removal criteria, wet removal accounted for a greater share of Total PM removal (53.39%) than dry removal (46.61%). Large and fine size fraction removals were roughly equally distributed between wet and dry removals, but coarse PM exhibited a significant contribution from wet removal (61.79% compared to 38.21%) (Figure. S2).

PM deposited on foliage may persist, be absorbed, or be removed through re-suspension, precipitation, or litterfall, subsequently transferring to the soil. The elimination of PM via litter fall was not addressed in any study (leaf abscission). NCT Delhi go through one of the hottest summers of the planet, reaching a temperature of 49.1°C (Posted On: 29th May 2024 8:45 PM by PIB Delhi, The Indian Meteorological Department (IMD), Ministry of Earth Sciences, India). As these leaves fall, they carry with them dust particles that have accumulated on their surfaces, which then settle on the ground. The decrease in LAI from 2 to 0.4 between March and April and 0.4 to 0.1 from April to May, which indicates a significant shedding of leaves (Total Leaf area reduced from 684km^2 to 34.2 km^2). It was estimated that the removal of PM by shedding contributes to the addition of 70 ± 39.99 tons of $PM_{0.2–2.5}$, 225 ± 58.25 tons of $PM_{2.5–11}$, and 945 ± 87.97 tons of $PM_{11–100}$ particles.

2.4 Comparison of physical leaf sampling and the deposition velocity ($\varvec{V}_{d}$) estimates

To assess the PM removal facilitated by the V_d method, this study used the spatially averaged PM concentration obtained from 40 CPCB monitoring sites across the city (see methodology 4.4). Considering the average observations across the monitoring network yielded a typical regional PM concentration rather than relying on a single monitoring site. This concentration was combined with the obtained V_d (see methodology 4.5) and plant attributes (LAI) to calculate the PM that settled on the vegetated surface. The derived V_d-based estimation, therefore, signifies the possible atmospheric deposition given the recorded regional PM load. To evaluate the efficacy of PM removal estimates, we compared the model-derived V_d method (Eq. 1) with direct physical sampling, examining how closely theoretical deposition predictions align with the PM actually mitigated by leaf surfaces. The total $PM_{2.5}$ and PM_{10} removed were 2216.94 tons and 42290.03 tons, respectively. Although physical sampling measured particles of 11 µm size while the emission inventory reported PM_{10}, the two fractions were directly compared, assuming that the contribution of particles between 10 and 11 µm was negligible.

The PM removal estimate obtained using the V_d method was seemingly anomalous. Restricting the comparison to the dry season (October–March), identified by limited precipitation and insignificant wash-off effects, indicates that the disparity between the V_d approach and physical sampling cannot be entirely attributed to rainfall. Instead, it is probably associated with the maximal particulate matter retention capacity of leaves. As PM loading intensifies throughout winter, leaf surfaces gradually accumulate particles until a saturation threshold is reached, beyond which additional particles are either re-suspended or fail to adhere to the surface. The Physical Sampling/ V_d ratio varied substantially, approaching unity during low-PM periods but declining to 0.15–0.38 during winter or high pollution episodes, supporting limited leaf-retention capacity under high pollution and systematic overestimation by the V_d approach.

The deposition velocity model assumes that deposition is linearly proportional to ambient PM concentration and continues to predict removal irrespective of leaf saturation (Fig. 3). This essential assumption leads to an exaggerated assessment of PM removal at consistently elevated pollution levels, underscoring a significant shortcoming of V_d-based methodologies and highlighting the benefits of

direct physical sampling for accurately measuring PM retained by urban vegetation. Following a comparison of different removal estimates, the chemical signatures of leaf-deposited PM were compared with those of ambient PM to assess their correspondence and potential source similarities.

2.5 Species- and Size-Resolved Elemental Composition of PM Deposited on Leaves

Twenty different elements, Aluminium (Al), Calcium (Ca), Chlorine (Cl), Chromium (Cr), Copper (Cu), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Sodium (Na), Nickel (Ni), Phosphorus (P), Lead (Pb), Rubidium (Rb), Sulfur (S), Silicon (Si), Strontium (Sr), Titanium (Ti), Zinc (Zn), and Zirconium (Zr), were obtained on the filter in various quantities in PM captured by the leaves (Table S1). All species leaves captured all the elements with little or no variation in quantity. Sampled filter papers were from the summer season, and in terms of quantity, Si had the highest wt% among all plant species (Fig. 4a).

The elemental profiles of the four species were identical (Pearson's $r > 0.99$), indicating negligible interspecific variability in elemental composition. Therefore, the average elemental fraction of the four species was compared with the elemental source profiles measured by Xact® 625i Ambient Continuous Multi-Metals Monitor (Table S2) [75,76]. Correlation analysis between the mean elemental composition of PM retained on vegetation and source profiles revealed that the deposited particles were dominated by soil and dust. Pearson correlation showed a very strong positive relationship with the dust-related source profile ($r = 0.947$, $p < 0.001$), indicating that re-suspended soil and road dust were the primary contributors to leaf-deposited PM. Spearman's rank correlation identified the strongest association with vehicular emissions ($\rho = 0.655$, $p = 0.004$), followed by dust-related sources ($\rho = 0.516$, $p = 0.034$) and biomass burning ($\rho = 0.507$, $p = 0.038$). These findings suggest that while the absolute elemental composition is largely governed by mineral dust, the relative elemental distribution also reflects contributions from traffic emissions and, to a lesser extent, biomass burning. Industrial emissions, secondary chloride, waste incineration, and power plant emissions showed weak or non-significant relationships with the plant deposition profile [77,78].

The heatmap displayed diverse elemental signatures across the three PM size fractions, indicating variations in their primary emission sources. Fine (0.2–2.5 µm) and coarse (2.5–11 µm) PM exhibited elevated levels of P, Mg, K, Ca, and Zn, with phosphorus attaining its peak concentration in the $PM_{2.5\text{-}11}$ category (25.01%) (Fig. 4b). In contrast, the larger fraction (11–100 µm) demonstrated significant enrichment of Fe (23.76%) and Al (12.52%), suggesting a pronounced impact from crustal elements such as re-suspended road dust, soil particles, and dust from construction activities. Calcium and titanium were uniformly identified across all fractions, reinforcing the dominance of mineral-based origins. Trace elements, including Cu, Ba, Pb, Co, and Sb, were present at significantly lower concentrations, although their contributions were validated as vehicular and other human-induced emissions [35,79]. Zn, which is associated with tyre abrasion, originates from both natural and anthropogenic sources, making it a general tracer [80]. Previous studies emphasises that non-exhaust PM is a complex mixture of brake wear, tyre wear, road surface abrasion, and re-suspended road dust [81–83]. Spearman's rank correlation analysis

showed a substantial correlation in elemental composition among the three PM size fractions, indicating that elemental abundance relative proportions were largely retained despite changes in absolute concentrations. $PM_{0·2-2·5}$ and $PM_{2·5-11}$ had the strongest connection ($\rho = 0.912$, $p < 0.001$), indicating that fine and coarse particles share a similar elemental fingerprint and are likely impacted by similar emission sources The large fraction showed significant correlations ($\rho = 0.866$ for $PM_{0·2-2·5}$ vs. PM_{11-100} and $\rho = 0.877$ for $PM_{2·5-11}$ vs. PM_{11-100}; $p < 0.001$), indicating that while coarse particles enriched in crustal elements like Fe and Al, the elemental hierarchy remained consistent across size fractions. These substantial relationships suggest that PM from urban vegetation comes from overlapping source mixtures dominated by mineral dust, traffic-related emissions, and other anthropogenic emissions [79].

2.6 The capacity of tree species to reduce PM

During the sampling period, a significant correlation was observed between the plant's maximum PM-capturing ability and sustained PM removal efficiency. This suggests that capturing ability is crucial for higher PM removal. Due to low differences, net PM removal could be represented by the maximum PM capturing capability of the plant [15,20]. The annual estimates for PM removal were developed by using five common plant species as stand-ins for Delhi's urban vegetation. To make these results more applicable, the PM retention capacities of 20 commonly found urban species were then measured and compared. This provided a more complete picture of how well each species retained PM, making it easier to identify the best species for sustainable cities and improving air quality. Leaf samples were collected for subsequent analysis at the stage corresponding to maximum PM deposition. Plant species were categorised into groups based on PM deposition intervals derived from the distribution of measured data. Species within each cluster exhibited comparable PM accumulation capacities, enabling a comparative evaluation of their efficacy in mitigating atmospheric particulate pollution. From Cluster A to Cluster D (Fig. 5), the PM deposition rises. The PM deposition levels are greatest in Cluster D and lowest in Cluster A.

For total PM (0.2–100 µm), species in Cluster D demonstrated the highest removal efficacy, varying from 528.2 to 600.1 µg cm^{-2}, with Species 15, 8, 14, 5, and 1 exhibiting the greater deposition. Cluster C had species that removed between 354.0 and 450.5 µg cm^{-2}, while Clusters B (290.1 to 343.1 µg cm^{-2}) and A (56.3 to 278.9 µg cm^{-2}) had species that removed lower amounts. The wide interspecific variation highlights the strong influence of leaf morphological characteristics on PM interception and retention. Cluster A (50–250 µg/cm^2) comprises species such as *Bougainvillaea* (2) and *Hymenocallis littoralis* (10), which demonstrate the lowest Total PM deposition, likely attributable to their smooth leaves or minimal surface roughness [84–86]. Cluster B (250–350 µg/cm^2) includes species such as *Azadirachta indica* (3), *Alstonia scholaris* (4), and *Prunus avium* (12), which exhibit moderate PM capture, potentially due to their intermediate foliage density. Cluster C (350–500 µg/cm^2), featuring *Drypetes roxburghii* (13) and *Plumeria alba* (18), consists of species with rougher surfaces or denser canopies, enhancing their effectiveness in PM capture. Cluster D (500–700 + µg/cm^2), which contains *Prosopis juliflora* (5), *Lantana* (15), and *Cassia fistula* (20), shows the highest Total PM deposition and is the most efficient in particulate matter removal. However, the species exhibiting the highest total PM deposition efficiency

may differ across particle-size fractions (0.2–2.5 μm, 2.5–11 μm, and 11–100 μm). The rearrangement of species within clusters based on particle-size categories suggests that PM capture efficiency varies with particle size, highlighting disparities in leaf structure, surface texture, trichome abundance, and cuticular properties that uniquely affect the capture and retention of both fine and coarse particles. These results show that species that remove large amounts of PM are not always the best at removing all particle types. This shows how important it is to look at particle size when choosing plants.

3. Discussion

Urban vegetation is not a substitute for emission control, it is a complementary solution. The greatest improvements in urban air quality will be achieved by reducing emissions at the source while strategically expanding green infrastructure to remove the remaining PM. Spaning 23% of the city area, Urban trees in Delhi capture around 527.43 ± 301.37 tons of $PM_{2.5}$, 1949.77 ± 504.85 tons of $PM_{2.5\text{-}11}$ and 7907.26 ± 1079.34 tons of total PM per year, representing only ~ 1.08% of the estimated 48,474 tons of $PM_{2.5}$ emitted annually in Delhi. This small contribution demonstrates that increasing urban vegetation alone is unlikely to achieve substantial reductions in $PM_{2.5}$ concentrations and must be complemented by direct emission-control strategies. Litterfall is a neglected aspect of the PM-vegetation mass balance. Despite accounting for less than 14% of the estimated $PM_{2.5}$ removal, litter fall yielded approximately 70 ± 39.99 tons of $PM_{0.2\text{-}2.5}$, 225 ± 58.25 tons of $PM_{2.5\text{-}11}$, and 945 ± 87.97 tons of $PM_{11\text{-}100}$ annually, underscoring the necessity of taking into account litterfall in assessments of net vegetation-driven PM removal. A key finding of this study is the substantial difference between PM removal estimated using V_d and PM measured directly on leaves, corresponding to a physical sampling/ V_d $PM_{2.5}$ ratio of only ~ 24%. The difference was even greater for PM_{10}, yielding a ratio of only ~ 4.6%. The V_d method typically yields greater estimates due to its assumption of uninterrupted particle deposition and its failure to adequately consider rainfall wash-off, or the leaf surface threshold. The elemental analysis provides an important distinction in species PM interactions. Leaf surfaces did not show a consistent species-specific affinity for individual elements (Pearson's r > 0.99). Instead, plant species diverged significantly in the particle-size fractions of PM they retained, the composition of the deposited material consequently varied according to the particle-size fraction captured by each species. Foliage serves as a crucial interception barrier, especially for coarse non-exhaust particles produced by brake and tyre wear and dust re-suspension, while also seizing a portion of fine exhaust-derived particles. This offers a new paradigm for species-specific vegetation, advancing from total PM reduction to size and element-focused phytoremediation of urban aerosols. In the absence of rainfall, particles accumulated progressively, indicating that vegetation serves largely as a temporary PM reservoir, while precipitation governs their subsequent transfer from the canopy to the surrounding environment.

Due to the oxidising capacity of fine particles and their interactions with other pollutants such as ozone, surface area may become more important in evaluating ecological effects [87]. Other tree attributes, such as heat mitigation potential, stress tolerance, water consumption, and aesthetic appeal, should be taken into account, as city administrators have goals beyond improving air quality alone. While certain qualities

promote services (e.g., higher leaf area is positively connected with cooling the environment), others restrict services (e.g., a high deposition capacity improves air quality but worsens plant health).

4. Methodology

The SAFAR-2018 emission inventory used as a baseline for calculating the fraction of PM emissions in NCT Delhi that could potentially be eliminated by urban vegetation. *Saraca asoca, Plumeria alba, Ailanthus altissima, Cassia fistula*, and *Wedelia* were selected to capture interspecific variability in PM deposition. Selected species are dominant tree species on the Indian Institute of Technology Delhi (IITD) campus and in NCT Delhi as well. The mass-subtraction approach used by [3] was used to quantify PM accumulation from urban regions, and the results were extended to the 342 km² green region (23.06% of NCT Delhi). While taking into account the regional heterogeneity in pollution and deposition, the observed leaf-associated PM was utilised to estimate vegetation-mediated PM removal throughout the city.

4.1 Site description and species selection

The study area covers the NCT Delhi (28°61'N, 77°23'E), spanning 1483 km^2 in northern India. As shown in Fig. 6, the sampling sites were located on the campus of the IITD in New Delhi. The sampling site is approximately 200–400 m away from an arterial road outside the campus, the nearest source of local emissions. Additional roadside sampling outside the campus was done for a comparative analysis under higher pollution exposure. Subsequently, a wider selection of prominent urban plant species was assessed to compare their PM retention capabilities and determine the most suitable species for improving PM removal in urban environments.

Atmospheric and spatial conditions were identical for all species. Species were chosen based on those commonly observed in NCT Delhi (https://forest.delhi.gov.in/forest/type-forests) and were composed of varying leaf characteristics such as leaf size, shape, and surface texture (Figure S3). All the selected species had been growing on campus for many years and were healthy, pest-free, or otherwise in good condition. Sampling sites were exposed only to environmental PM concentrations, with no nearby direct source emissions. No major point source emitters are located within the immediate vicinity of the sampling site.

4.2 Emission database for NCT Delhi

The most recent emissions for the chosen area were given by the System of Air Quality and Weather Forecasting and Research (SAFAR). SAFAR only supplied statistics for 2018. $PM_{2.5}$ emission data are obtained from the SAFAR, a high-resolution (400m × 400m) emission inventory for Delhi based on 2018 emission data, developed by the Indian Institute of Tropical Meteorology (IITM), Pune [88]. SAFAR covers city areas along with surrounding regions spanning an area of over 70 km × 65 km. A bottom-up approach was used to build the emission inventory. Twenty-six ground-level activity data of the pollution

sources were collected to prepare the emission inventory. SAFAR covers Delhi NCR; in this work, we extracted $PM_{2.5}$ emissions for NCT Delhi from the emission inventory.

4.3 Quantitative Analysis of PM

A mass subtraction approach was used to carry out a quantitative study of PM (Section S1). At the regular 4-day interval, leaf samples from each selected species were collected at a height of 1.5-2.0 m above the ground to prevail environmental PM deposition. Leaves from the outer surface of the tree canopy were chosen. Leaf areas ranging from 300 cm^2 to 400 cm^2 (3–25 leaves) from each plant were taken into consideration for the sample. The selected leaf area is adequate for accumulating the average PM mass, provides sufficient material for different PM fractions. The petiole was inspected, and the leaves were gently removed. Sampled leaves were carefully placed in Ziplock bags, labelled, and stored in a cool, dry place until analysis. Care was given to prevent the dislodgment of particles from the leaves. The leaves were collected from the trees/plants between 10:00 and 14:00 on the sampling day. Collected leaves were analysed fresh or kept stored in the refrigerator until analysed (within 24 hrs of sampling). The difference between the initial and final weights of the filter paper determined the mass of PM. Filter papers were conditioned before analysis. The filter papers were dried in the oven for 6 hrs at 60°C, then for 2 hrs in a controlled environment to stabilise the humidity of the hygroscopic filter papers before weight measurement. Pre-weight and post-weight measurements were done on Sartorius microbalance (Cubis-MSA6.6S-000-DF) (Sartorius AG-Germany). A deioniser probe (STAT-PEN) was used to remove the electrostatic charge on the filters [3,73]. Sampled leaves were placed in a glass beaker containing 500 ml of DI water and agitated with a magnetic stirrer for 60 min at 300 rpm to remove accumulated PM from the leaf surface. A magnetic stirrer was used in this work to maintain a constant agitation force, compared with the hand agitation used in previous studies. The methodological specifications were adopted and improvised from [3]. This stirrer agitation replicates the particle removal during rainfall (Figures S4 and S5). A 100 µm metal sieve was used to separate particles larger than 100 µm. After that, the water was filtered through 47-mm-diameter filter paper and a glass funnel with a stopper support assembly, then drawn through a vacuum pump. Particles are separated into three different fractions: (1) Large: 11–100 µm, (2) Coarse: 2.5–11 µm, and (3) Fine: 0.2–2.5 µm using the filters Type 91 (retention 11 µm) and next on Type 42 (retention 2.5 µm) and in the end, the final particle fraction on a PTFE membrane filter (retention 0.2 µm) (Whatman, UK), respectively. Differences between the filter's post and pre-weights yielded the PM fraction for each sample.

Images of individual species leaves were taken against a white background, and ImageJ image analysis software was used to calculate the leaf area of the sampled leaves [89]. To achieve this, a photo of the leaf lying completely flat on the work surface was captured alongside a size standard. The images were analysed by measuring the pixel count and converting it to cm^2 using the size standard. Although PM was removed from both the adaxial and abaxial surfaces of the leaves, the quantification of mass was done as per one surface of the leaf area. Similarly, one surface area analysis was used to calculate LAI values, and the other physiological studies were used in the latter part of this work. It should be noted here that some of the ultrafine particles deposited on the surface of the leaf are encapsulated in the wax

layer of the leaf. The above method of using stirrer agitation to disperse the particles in water may not work for particles that stick to the wax layer. Previous work [3,73,90] has shown that the mass of wax-encapsulated particles is about one-third to one-fourth of the surface fine PM. A strong association between the accumulation of various PM components and the amount of leaf waxes was seen. It is important to note that, some studies have reported that approximately 28% of deposited PM is water-soluble, indicating that a substantial fraction of leaf-deposited aerosol can potentially be removed from leaf surfaces through filtration [91]. Consequently, when these particles are dispersed in water, they dissolve, and their mass will not be reflected in the filter paper weight measurements. Throughout the sampling period, leaves were collected from identical plants, and their positions were kept constant. All the leaves sampled were undamaged and non-infected. Given resources and time constraints, multiple leaf sampling sets for each sampling species and date were not considered practicable for vacuum filtration and mass quantification of the filters. A limitation of filtration method is that smaller particles may become trapped on filter, introducing uncertainity in mass estimation.

However, to assess the uncertainty associated with the PM measurement method, three independent leaf samples were collected from the same tree at a single location and analysed individually. The average total deposited PM was 277.03 ± 37.82 μg/cm^2 (SD), yielding a coefficient of variation (CV) of 13.65%. The 11–100 μm particles demonstrated the least variability (218.88 ± 20.55 μg/cm^2; CV = 9.39%), succeeded by the 2.5–11 μm fraction (45.62 ± 11.81 μg/cm^2; CV = 25.89%). The finest particle fraction (0.2–2.5 μm) exhibited the greatest variability (12.53 ± 7.16 μg/cm^2; CV = 57.14%), presumably due to the comparatively low deposited mass and increased analytical uncertainty linked to fine-particle observations. The corresponding CVs for respective size fractions directly propagated into city scale PM removal estimates, such that the estimated uncertinity for each fraction reflects the observed variability in its measured leaf deposition. In addition to the replicate analysis, leaf samples were collected from multiple locations across the study area to capture spatial variability in particulate deposition (Figure S6).

4.4 Meteorological data and air quality index

Meteorological data were used to estimate the removal using the V_d approach. For that, meteorological data (rainfall and wind speed) was taken from the nearby monitoring station (https://wunderground.com/history/monthly/in/new-delhi/VIDD/date/). The daily average concentrations of PM_{10} and $PM_{2.5}$ from the 40 Central Pollution Control Board (CPCB) monitoring stations available across the entire NCT Delhi (https://cpcb.nic.in/) (Table S3 and S4). The PM_{10} and $PM_{2.5}$ ranges and national standards for air quality indices were obtained from CPCB. New Delhi encounters severe PM concentration throughout the year. The highest average $PM_{2.5}$ concentration was observed in the winter season (1st December to 15th February) at 165.60 μg/m^3 followed by spring (16th February to 31st March), post-monsoon (15th September to 30th November), summer (1st April to 30th June), and monsoon (1st July to 14th September), having concentrations of 95.04 μg/m^3, 87.79 μg/m^3, 69.96 μg/m^3, and 35.50 μg/m^3 respectively. Similarly, PM_{10} concentrations were 283.83 μg/m^3,

215.73 μg/m^3, 201.47 μg/m^3, 185.78 μg/m^3, and 89.71 μg/m^3 for winter, summer, spring, post-monsoon, and monsoon, respectively.

4.5 Dry deposition velocity and LAI data

Assuming the plant's leaf shedding and growth behaviour remain identical each year, we use the 2020 LAI reported by Maitra and Jyethi (2020) for this study in 2022-23. The total green area for the selected region was adopted from the latest report (*Delhi's Forest: At a Glance*, 2022, source:https://forest.delhigovt.nic.in/sites/default/files/Delhi's%20Forest%20at%20a%20Glance.pdf). The V_d method was used to estimate annual aerosol removal by vegetation, and this analysis was conducted to compare the physical sampling method with the V_d method. The equation to estimate PM removal using deposition velocity is as follows:

PM Removal= V_d[∑(*PM*×*LAI*×*D*)]×24×3600×*res*×*A* (1)

where V_d is the dry deposition velocity taken as 0.028 m/s for PM_{10}, and 0.0028 m/s for $PM_{2.5}$ (Table S5). *PM* is the averaged PM concentration obtained from the 40 CPCB stations in NCR-Delhi [93], *LAI* is the LAI for each month, and *D* is the number of days in that respective month, *res* is the re-suspension of particles and was taken as 0.5 and *A* is the green area of the NCR-Delhi [24].

4.6 Elemental composition of the PM captured on leaves

Energy dispersive X-ray fluorescence (EDXRF) was used to conduct the elemental compositional analysis. Aerosol-loaded filters (0.2–2.5 μm) were subjected to X-ray Fluorescence - Epsilon 4 (Malvern Panalytical, UK) for elemental determination. Analysis was performed directly on the filter papers, so no sample preparation was required, and the instrument software was used to perform all measurements. Filter papers of different size fractions were also analysed by inductively coupled plasma–mass spectrometry (ICP–MS) to identify their elemental composition. Filter papers underwent acid digestion (HNO_3:H_2O_2::9:4), and the resulting digests were measured by ICP–MS.

Declarations

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Author Contributions

S.P. and V.S. designed the research. S.P. carried out the physical sampling, PM quantification and mass analysis. R.M. conducted emission inventory analysis. Funding acquisition by V.S. and M.K. S.P. and V.S. executed data analysis and formal interpretation. S.P., R.M., M.K., and V.S. led the manuscript writing.

Data availability

Meteorological data used in this study are publicly available from Weather Underground (https://wunderground.com/history/monthly/in/new-delhi/VIDD/date/), while ambient particulate matter data are available from the Central Pollution Control Board (CPCB) (https://cpcb.nic.in/). Information on Delhi's forest and green area was obtained from Delhi's Forest: At a Glance (2022) (https://forest.delhigovt.nic.in/sites/default/files/Delhi's%20Forest%20at%20a%20Glance.pdf) and the Department of Forests and Wildlife, Government of NCT of Delhi (https://forest.delhi.gov.in/forest/type-forests). The PM quantification data generated during this study are available from the corresponding author upon reasonable request.

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Figures

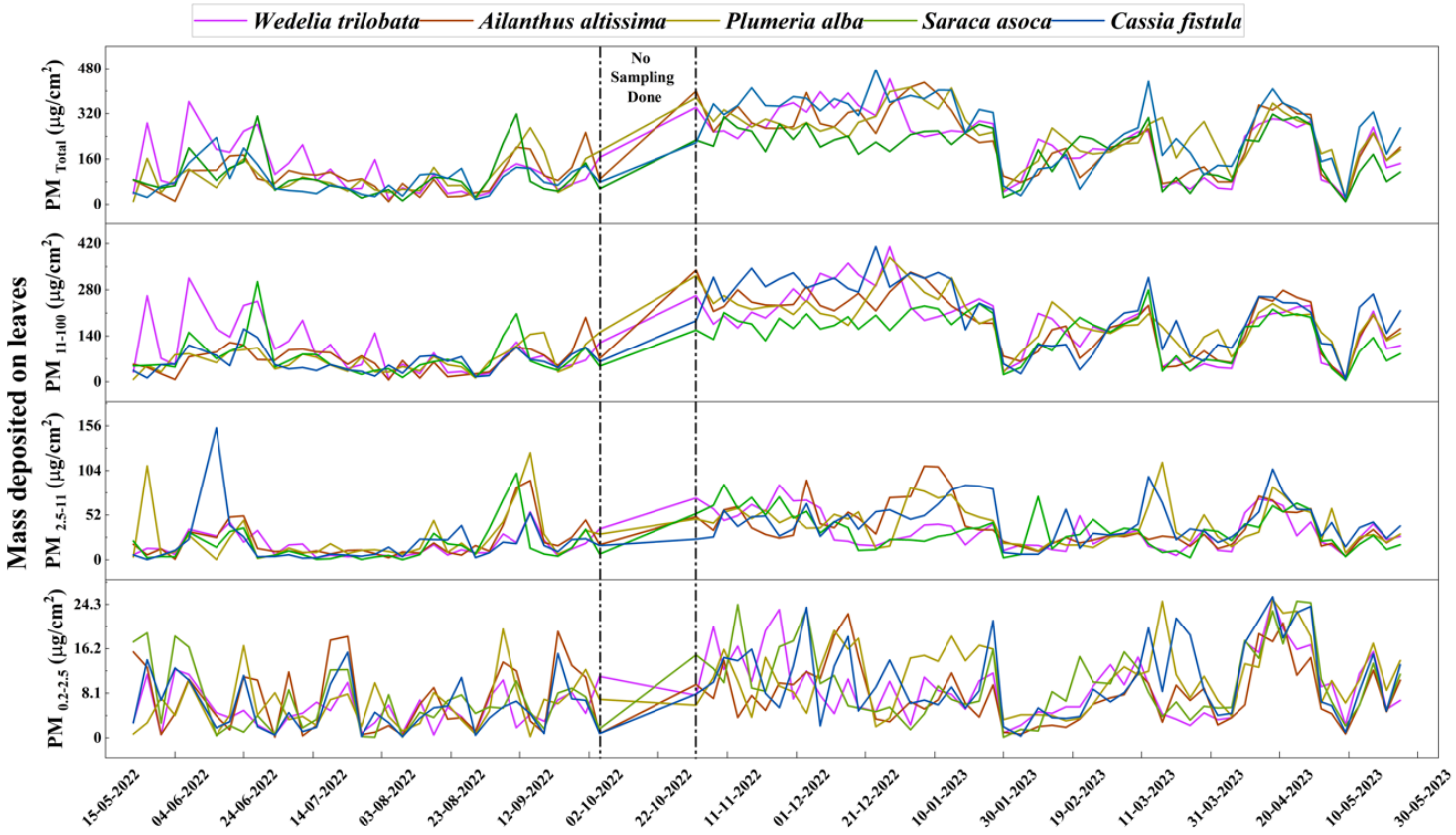


Figure 1

Temporal variation in PM deposition on leaves of the five selected plant species from May 2022 to May 2023. The figure illustrates the seasonal dynamics of total PM (0.2-100 µm) and its three size fractions: 11-100 µm, 2.5-11 µm, and 0.2-2.5 µm, accumulated on the leaf surfaces of Wedelia, Ailanthus altissima, Plumeria alba, Saraca asoca, and Cassia fistula. PM deposition is expressed as surface mass loading (µg cm^{-2}). All species exhibited similar temporal trends, with substantially higher PM deposition during the dry season and lower accumulation during rainfall-influenced periods, reflecting the combined effects of atmospheric PM concentration and precipitation-driven wash-off. Leaf samples were not collected for analyses from 5th October 2022 to 1st November 2022 due to the instrument's breakdown.

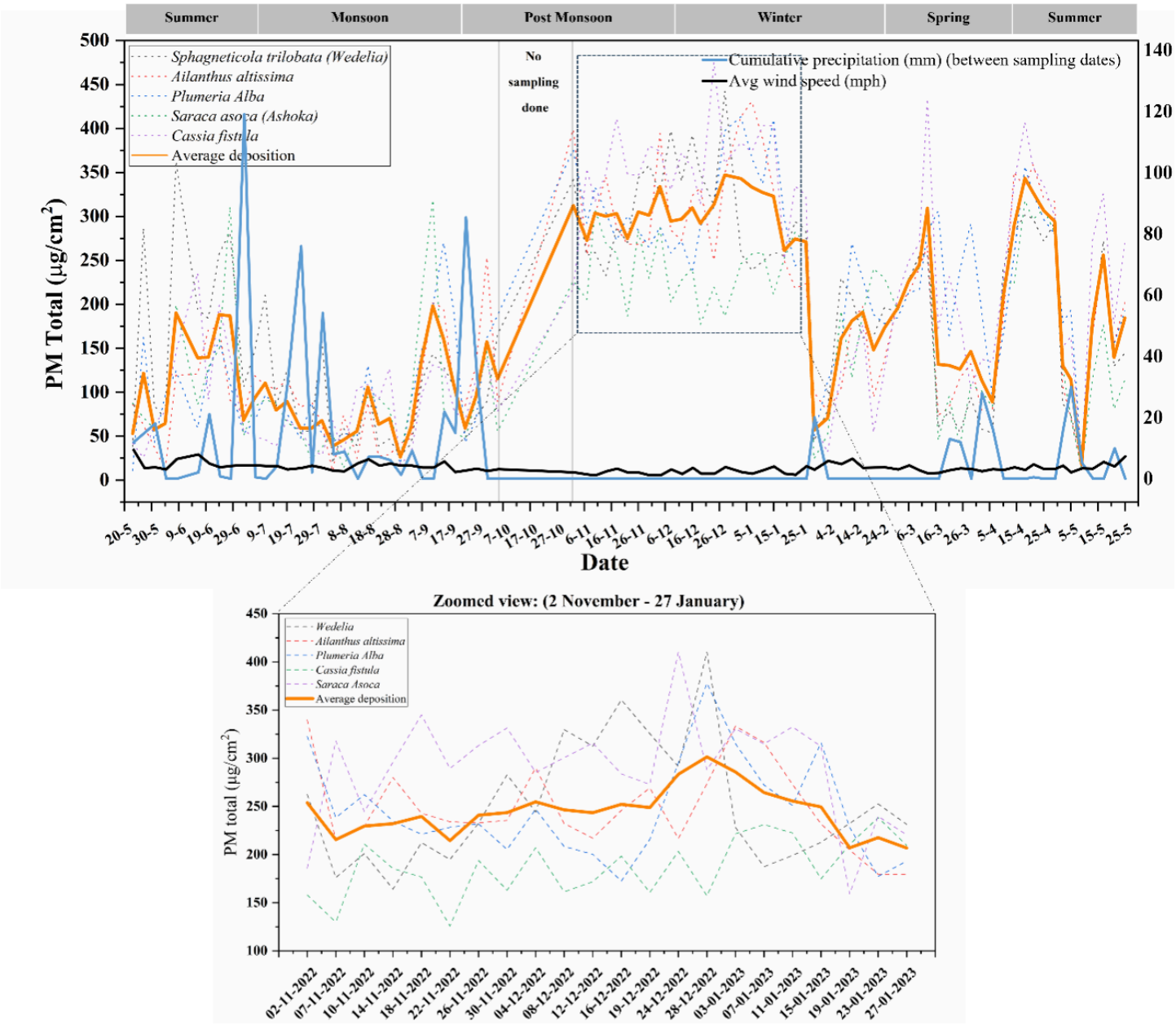


Figure 2

Seasonal variation in PM deposition and meteorological conditions across the study period (May 2022–May 2023) (Upper panel). Total PM deposition (left y-axis; µg cm⁻²) measured on the leaves of five representative urban tree species—*Spathodea campanulata (Wedelia), Ailanthus altissima, Plumeria alba, Saraca asoca, and cassia fistula*—is shown together with cumulative precipitation between consecutive sampling dates and the corresponding average wind speed (right y-axis). Orange line represents the average deposition value. Shaded bands indicate the major seasonal periods (Summer, Monsoon, Post-monsoon, Winter, Spring, and Summer). Zoomed view (2nd November 2022–27th January 2023) of temporal PM deposition (Lower panel). The winter months saw PM deposition, which reached a saturation threshold between November and January during a dry period (coefficient of variation (CoV): 10.91%). Absence of precipitation limited particle wash-off, allowing particle accumulation on leaf surfaces until leaf particle-retention capacity reached maximum.

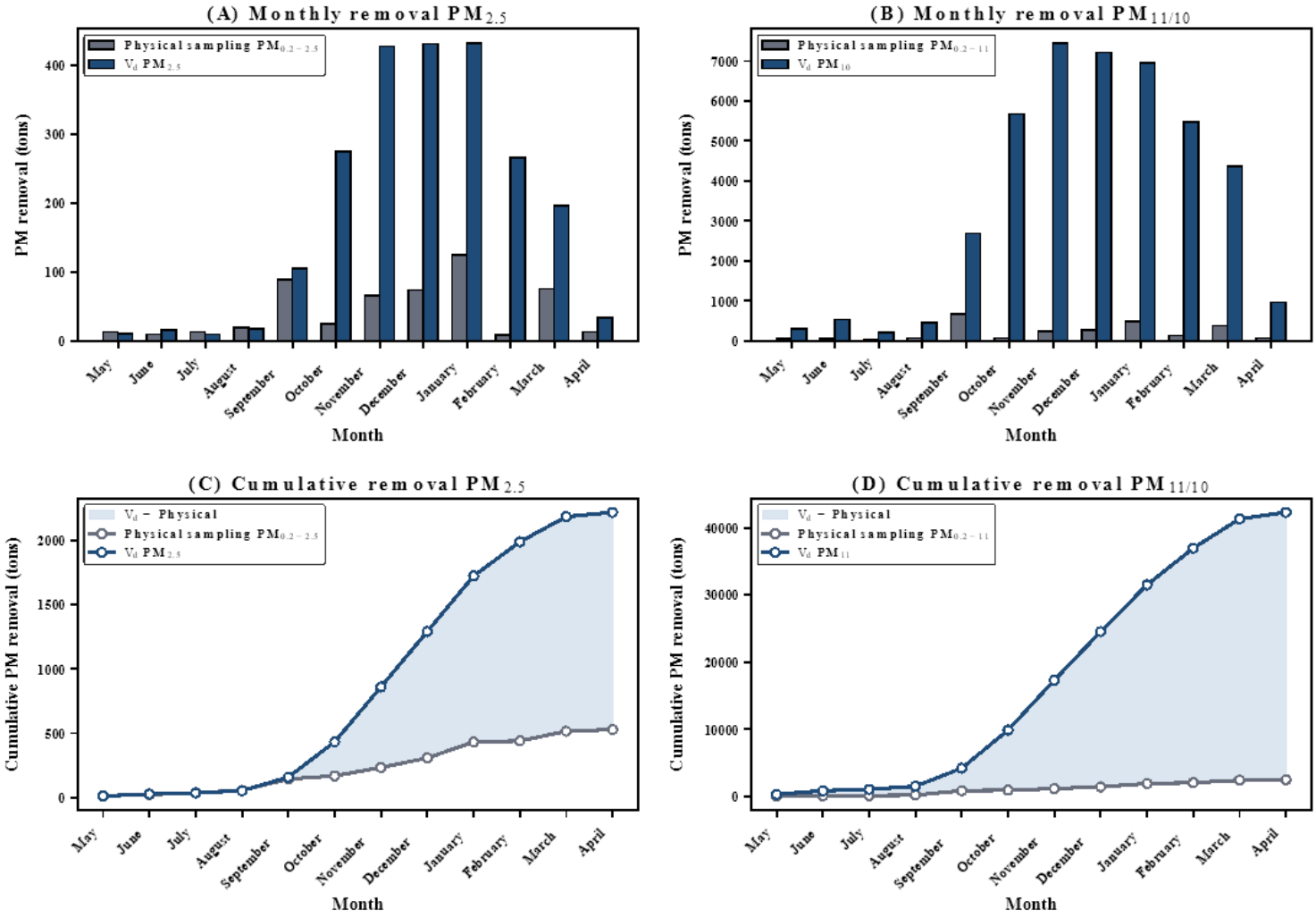


Figure 3

Comparison of monthly and cumulative PM removal estimated by physical leaf sampling and the deposition velocity (Vd) approach (A) Monthly removal of PM(0.2–2.5μm), showing physical sampling and V_d -based estimates. (B) Monthly removal of PM(11 μm)/PM10. (C) Cumulative PM(0.2–2.5μm) removal, with the shaded region representing the divergence between V_d-based and physically sampled estimates. (D) Cumulative PM11/PM10 removal and corresponding divergence between the two approaches. Both methods captured a similar seasonal trend, with minimal PM removal during the monsoon months and substantially greater removal during the winter period (October–March), which corresponds to elevated ambient PM concentrations and limited rainfall. The increasing separation between the Vd and physical-sampling estimates, particularly during the winter months, indicate progressive overestimation of vegetation-mediated PM removal by the Vd approach. This discrepancy is likely attributable to the continuous deposition assumption inherent in the Vd model, which does not account for the finite PM retention capacity of leaf surfaces or particle re-suspension after saturation.

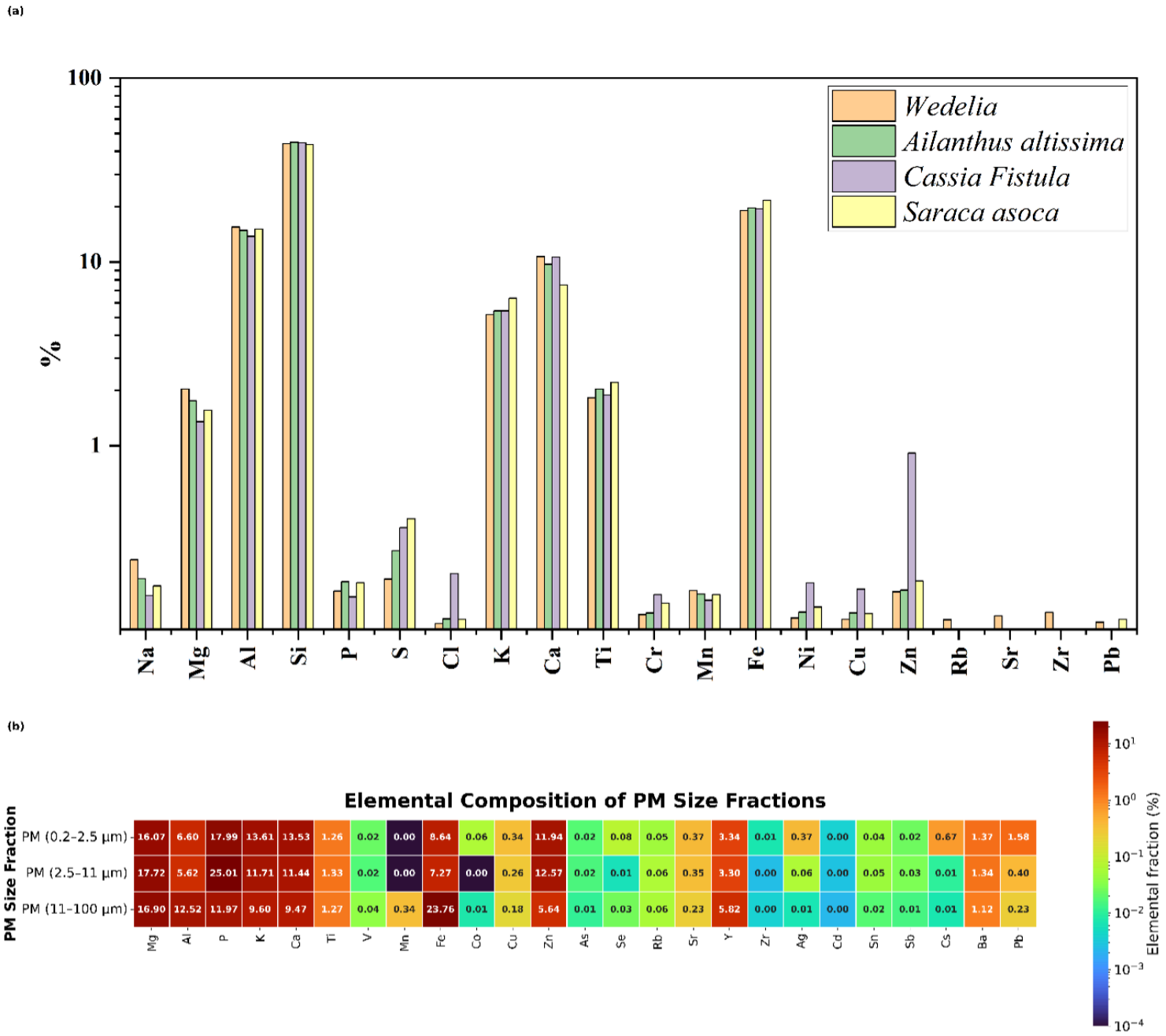


Figure 4

Elemental Composition of PM Across Plant Species and Leaf-Captured Size Fractions (a)Elemental composition of the $PM_{2.5}$ fraction deposited on leaves of the selected plant species determined by X-ray fluorescence (XRF) analysis. The relative abundance (%) of major and trace elements associated with the fine PM (0.2-2.5 µm) retained on the leaf surfaces of *Wedelia, Ailanthus altissima, Cassia fistula,* and *Saraca asoca* is presented, (b) Heatmap illustrating the elemental mass percentages (%) obtained via ICP-MS for acid-digested filter samples retrieved from three size categories ($PM_{0.2-2.5}$, $PM_{2.5-11}$, and PM_{11-100}). The heatmap illustrates the size-specific distribution of significant and trace elements, indicating an abundance of crustal elements (Mg, Al, Ca, and Fe) in larger fractions and relatively elevated levels of traffic and industry-associated trace metals (Cu, Zn, Sb, and Pb) in smaller fractions.

The detected elemental patterns yield chemical signatures for source attribution and help identify contributions from re-suspended road dust, mineral dust, and anthropogenic emissions.

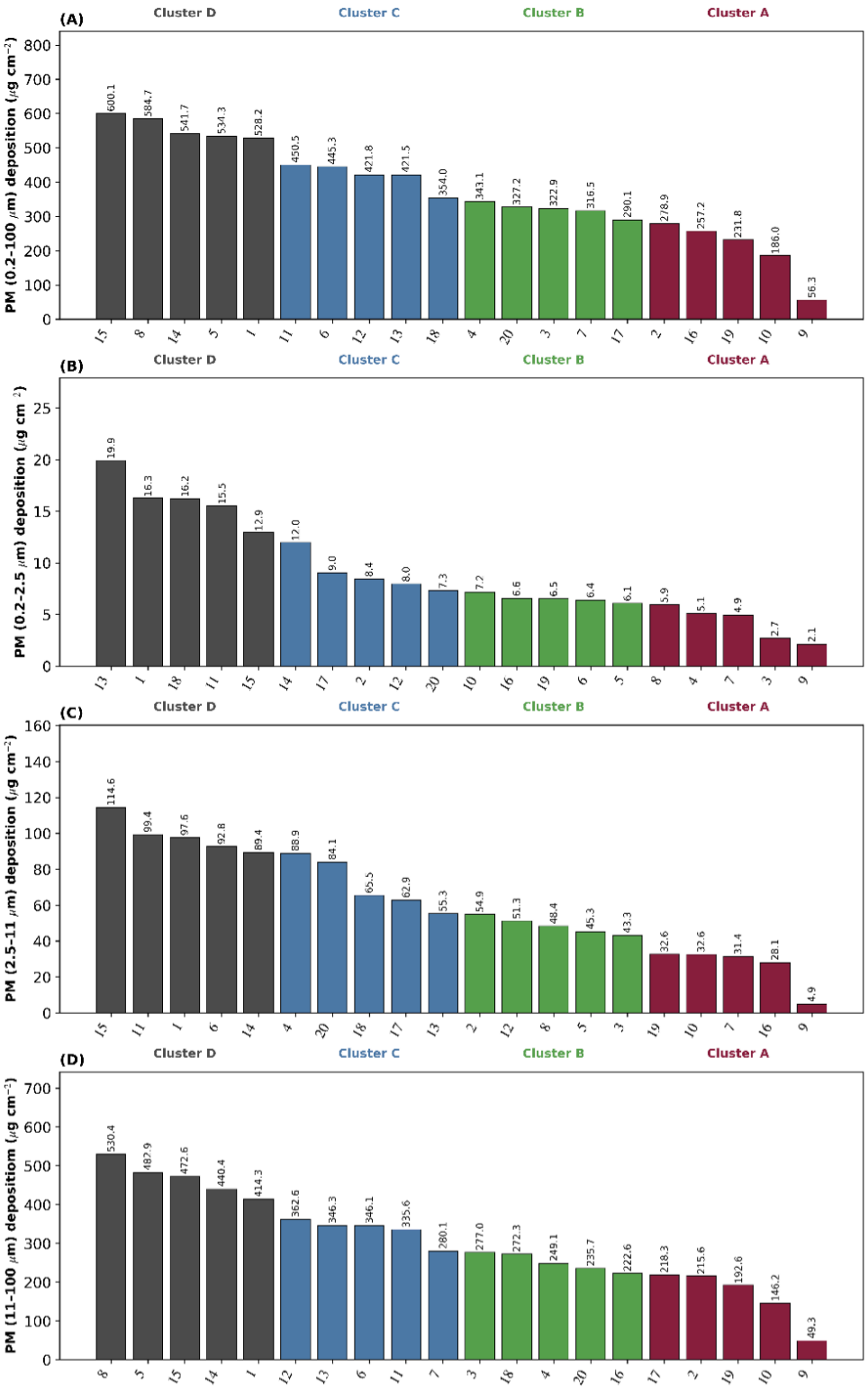


Figure 5

PM deposition capacity of twenty urban plant species at the leaf saturation (threshold) point. The bar plots presents the maximum total PM deposited on leaf surfaces (μg cm^{-2})for twenty common urban

plant species after prolonged exposure, representing the threshold beyond which little or no additional particle accumulation was observed. Species were grouped into four clusters (A–D) using hierarchical clustering analysis based on their PM retention capacity. Here, 1-Tectona grandis, 2-Bougainvillea, 3-Azadirachta indica, 4-Alostnia scholaris, 5-Prosopis juliflora, 6-Dianella tasmanica, 7-Pterospermum acerifolium, 8-Morus alba, 9-Ficus religiosa, 10-Hymenocallis littoralis, 11-Senna siamea, 12-Prunus avium, 13-Drypetes roxburghii, 14-Syngonium, 15-Lantana, 16-Wedelia, 17-Ailanthus altissima, 18-Plumeria alba, 19-Saraca asoca, 20-Cassia fistula.

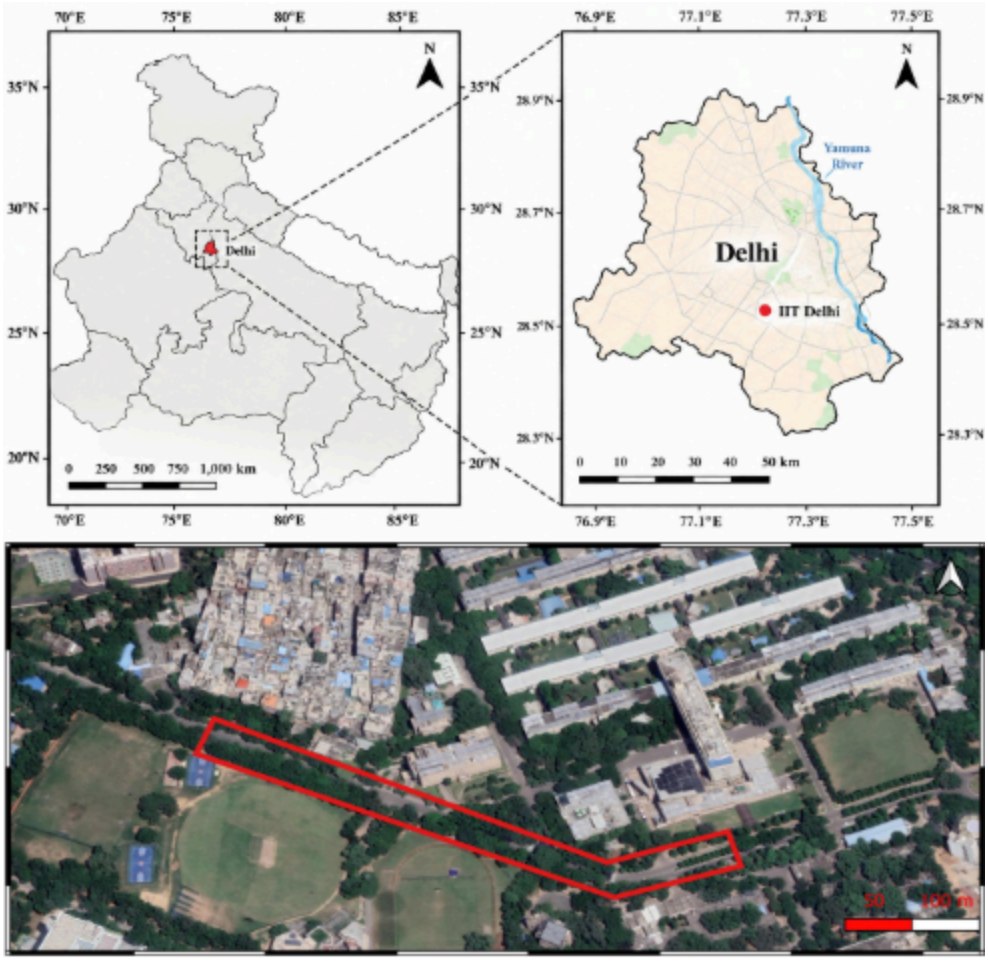


Figure 6

Location of the study area and PM sampling sites within the IITD, New Delhi, India. The top-left panel shows the location of the NCT Delhi within India. The top-right panel shows a map of NCT Delhi, with the IIT Delhi campus marked by a red dot in the southern district. The bottom panel is a high-resolution satellite image of the study area, where the red polygon delineates the vegetation sampling transect along the central road of the IIT Delhi campus.

Supplementary Files

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