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Wind-Induced Resuspension and Net Removal of Particulate Matter ($PM_{1–10}$) on Urban Shrub and Climbing Species

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Abstract

Elevated particulate matter (PM) concentrations pose severe health risks, necessitating green infrastructure mitigation. While deposition is well documented, wind-induced remobilization remains insufficiently quantified. This study establishes a size-fractionated ($PM_{1–2.5}$ and $PM_{2.5–10}$) wind-induced resuspension and net removal values for six Central European shrub and climbing species (*Parthenocissus quinquefolia*, *Hedera helix*, *Viburnum opulus*, *Viburnum lantana*, *Ligustrum ovalifolium*, and *Cornus mas*) under controlled laboratory conditions. Following standardized aerosol chamber loading, leaves were subjected to constant, laminar airflow velocity of 3 m/s. Numerical quantification of particle counts per unit area (cm^2) was performed via scanning electron microscopy with backscattered electron signal processing. Results demonstrate significant interspecific variations. *Parthenocissus quinquefolia* was most efficient, retaining the highest particle counts (121.6×10^3 particles/cm^2 for $PM_{2.5–10}$) and achieving net removal rates of 46.3% and 60.5% for $PM_{1–2.5}$ and $PM_{2.5–10}$, respectively, relative to initial deposition. *Cornus mas* exhibited the lowest net removal efficiency for coarse particles (21.2% for $PM_{2.5–10}$), while *Hedera helix* showed the highest fractional resuspension rates ($k = 1.93 \times 10^{-4} \cdot s^{-1}$ and $2.01 \times 10^{-4} \cdot s^{-1}$, respectively). These species-specific traits are vital for optimizing urban green infrastructure. Ultimately, these findings provide actionable recommendations for targeted plant selection to maximize urban air purification.

Keywords: particulate matter; wind-induced resuspension; net removal; urban green infrastructure; air quality management

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1. Introduction

Elevated concentrations of atmospheric particulate matter (PM) represent a significant health challenge, specifically in urban areas [1–3]. Consequently, the World Health Organization (WHO) updated its guidelines in 2021, leading to the revised EU Ambient Air Quality Directive in 2024 [4]. While these new EU limits align with the Zero Pollution objective of the European Green Deal 2050, they remain less stringent than WHO recommendations.

Current data from the European Environment Agency highlights a critical gap. In 2024 59% of monitoring stations exceeded WHO annual PM_{10} recommendations, and 93%

failed the $PM_{2.5}$ threshold [2]. Projections indicate that without drastic reductions, the mandatory 2030 limits will be missed by a wide margin [2,5].

As nearly all exceedances occur in urban areas [6], the EU actively promotes green infrastructure alongside emission-reduction strategies in transport and industry [5,7]. Beyond ecosystem restoration, the primary objectives are enhancing public health and achieving the "Zero Pollution Vision 2050", where adverse health effects from air pollution are entirely avoided [7].

1.1. Role of Vegetation in Particulate Matter Mitigation

The difference between the amount deposited on the leaf surface and the amount resuspended is defined as net removal, representing the quantity of PM effectively retained by the leaf surface under specific dynamic forces [8].

To fully evaluate the air mitigating efficiency of urban greenery, plant–PM interactions must be understood as a dynamic, four-stage conceptual cycle: initial deposition, wind-induced resuspension, rain-induced wash-off, and long-term or ideally permanent sequestration. While initial deposition determines the immediate dust-capture potential, wind-induced resuspension acts as a continuous counter-mechanism that remobilizes a fraction of these particles back into the air. The remaining net load on the leaf is either subjected to wash-off via precipitation events—which cleanses the canopy and resets its capture capacity—or undergoes extended sequestration within the epicuticular wax layer or leaf microstructures.

In fact, there are significantly fewer scientific publications addressing resuspension from plant surfaces compared to the number of deposition studies [9]. Available studies demonstrate that highly diverse, non-standardized methodologies currently prevail, utilizing optical particle counters [10], gravimetric weighing [11,12], magnetic susceptibility [13–15], or particle counting via SEM [16–21]. An analytical limitation in the existing literature is the major reliance on field-based sampling, which inherently conflates wind remobilization with dynamic ambient fluctuations and unknown baseline loads [11,12,22]. Conversely, while laboratory wind-tunnel frameworks effectively isolate specific meteorological variables within short timeframes [10,23,24], previous quantitative efforts remain limited by heterogeneous experimental designs.

The quantity of PM resuspended from the plant surface depends heavily on various plant physiological factors such as leaf shape, surface roughness (grooves or pits), stomatal density, and trichomes [8,25–28]. Structural features like lanceolate shapes or revolute margins enhance particle retention by inducing localized air turbulence or sheltering particles [29], while an increased amount of epicuticular wax allows for a greater number of particles to be tightly immobilized within the surface layer [25,29,30]. Mechanically, fractional resuspension rates and the total duration of wind exposure are positively correlated [11], exhibiting a distinct time dependency where initially high resuspension rates rapidly decrease over time due to particle detachment fatigue [10,23]. Furthermore, aerodynamic remobilization exhibits a distinct size dependency. Coarse fractions (10–100 μm) settle predominantly on outer leaf areas and are easily remobilized [30], whereas the resuspension thresholds of smaller particles (approximately 5 μm) are more strongly influenced by humidity and capillary forces. Controlled wind-tunnel trials have reported highly variable fractional resuspension rates depending on the selected species and particle typologies. Early monoculture frameworks by Ould-Dada and Baghini (2001) isolated mechanical detachment using artificial silica particles (1.85 μm) on the conifer *Picea abies*, yielding a low mean resuspension rate of 4.88×10^{-7} s under a constant wind speed of 5 m/s [23]. When transitioning to broad-leaved species and multi-speed regimes (1 to 10 m/s), subsequent studies tracked PM modifications gravimetrically. For instance, Li et al. (2022) recorded $PM_{2.5}$ resuspension fractions between 32.02% (*Robinia pseudoacacia*) and

61.38% (*Abies holophylla*), with rates ranging between 8.24×10^{-4}/s and 2.65×10^{-4}/s [14]. Similarly, Zheng et al. (2019) evaluated real-world, roadside atmospheric dust (0 to 500 μm) on four urban plant species, reporting resuspension rates between 1×10^{-4}/s and 8×10^{-4}/s under highly variable initial surface loads (0.45 to 11.05 g/m²) [12].

Analytically, these contrasting results—specifically the significant deviations between artificial monoparticles on conifers [23] and polydisperse road dust on large forest trees [11,12]—highlight a fundamental research gap. Previous quantitative approaches have focused almost exclusively on large woody species or conifers under varying, and often under higher, wind velocities. However, standardized laboratory studies isolating the purely mechanical detachment processes of fine and coarse particle fractions ($PM_{1–2.5}$ and $PM_{2.5–10}$) on widespread Central European shrubs and climbing plants are completely lacking. This is precisely where the present study sets in: by utilizing a controlled exposure chamber followed by high-resolution numerical SEM-BSE particle counting, this research bridges the gap for urban hedge or vertical greening infrastructure. In alignment with the previous literature, our work confirms the pronounced size dependency of particle remobilization while simultaneously demonstrating that under moderate airflow, species-specific leaf traits remain the decisive factor in maximizing net particle retention.

1.2. Research Question

The utilization of vegetation and green infrastructure to reduce airborne particulates is increasingly discussed as a promising approach to improving air quality. While numerous studies have examined the capacity of various plant species for PM deposition, the issue of wind-induced resuspension of previously deposited particles remains a critical yet overlooked factor in achieving air purification. A comprehensive review by Vitaliano et al. (2024) emphasizes that the resuspension of pollutants from plant surfaces remains an under-researched topic [31]. Similarly, Zheng and Li (2019) point out that evaluating the effectiveness of plants in air purification should not rely solely on their capture capacity, but also on their propensity for resuspension [12]. In this context, Setiawan et al. (2025) mention the limitations of PM deposition studies regarding specific plant species [32].

To accurately interpret the air filter efficiency of urban greenery, these isolated processes must be integrated into a comprehensive, dynamic conceptual cycle consisting of four distinct stages, which are initial deposition, wind-induced resuspension, rain-induced wash-off, and semi-permanent immobilization within leaf microstructures. While initial deposition and subsequent wash-off or long-term immobilization are documented more often, the wind-induced resuspension phase represents a missing link in evaluating net air purification efficiency.

A thorough review of the literature reveals only a limited number of studies explicitly addressing plant-based PM resuspension in general or at the laboratory scale. While preliminary data exist for some plant species, no information is available for others, as discussed in the Discussion section. Most resuspension studies are field-based, where external conditions—such as location, pollutant concentration, wind, precipitation, and seasonality—have been proven to be decisive factors [33,34] for both deposition levels and resuspended quantities. Moreover, most studies of this type focus on wash-off efficiency [9,19,35,36] rather than wind-induced resuspension.

Against this background, the present study systematically investigates the resuspension dynamics of six common Central European shrub and climbing species at a laboratory scale. The primary objective is to quantify net removal—here operationally defined as the fraction of particulate matter retained on the leaf surface after being subjected to a specific wind exposure, calculated relative to the initially deposited particle load. We mention that this parameter is conceptualized specifically for laboratory-scale investigations within a controlled environment to isolate the immediate relationship between deposition and wind-induced resuspension. To address existing research gaps, a specialized experimental framework was developed to isolate physical resuspension mechanics. The practical and novel value of this study lies in translating these controlled insights into actionable urban planning guidelines. By establishing a comparative hierarchy of species-specific net retention, these findings allow landscape architects and municipal authorities to transition to a highly targeted botanical selection. Specifically, this data helps optimize green barrier designs along high-exposure zones—by avoiding species prone to high wind-induced remobilization. Ultimately, this research provides a reproducible framework for vegetation strategies aimed at optimizing urban air quality through targeted, cost-effective, and sustainable green infrastructure.

2. Materials and Methods

The following sections describe the plant species utilized and the methodological approach employed. All plant materials were obtained from local commercial garden centers, Starkl GmbH, Vienna, Austria. The study complied with relevant institutional, national, and international guidelines. None of the investigated species are listed as endangered or protected under the CITES convention or the Convention on Biological Diversity.

Figure 1 shows a schematic illustration of the methodological approach. The precise description of the methodology is explicitly explained in the subsequent chapters.

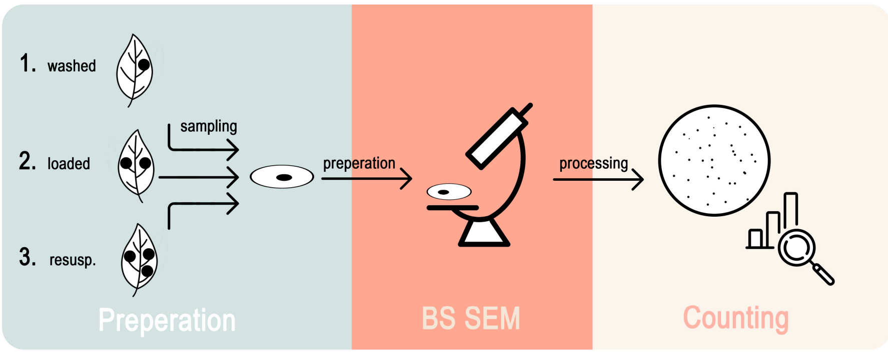

Figure 1. Schematic illustration of the methodological approach.

2.1. Plant Material

The plant species selected for this study to evaluate their net particle retention capacities were *Parthenocissus quinquefolia*, *Hedera helix*, *Viburnum opulus*, *Viburnum lantana*, *Ligustrum ovalifolium*, and *Cornus mas*. To ensure methodological reproducibility and account for biological variability, all investigated specimens were sourced as healthy, container-grown plants aged between 2 and 3 years, exhibiting a vital physiological condition free of visible pathogen stress or nutrient deficiencies. For each species, one plant was utilized. Mature, fully expanded and healthy leaves were collected during August in 2025. Individual leaves of the species investigated are shown in Figure 2.

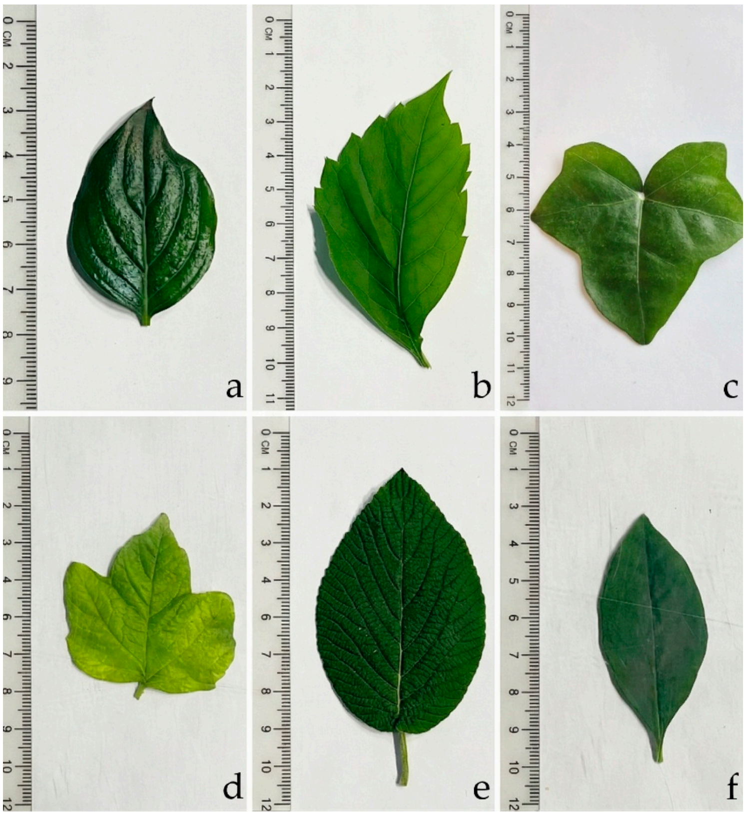

Figure 2. Individual leaves of the plant species investigated. (**a**) *Cornus mas*, (**b**) *Parthenocissus quinquefolia*, (**c**) *Hedera helix*, (**d**) *Viburnum opulus*, (**e**) *Viburnum lantana*, (**f**) *Ligustrum ovalifolium*.

2.2. Experimental Procedure for Resuspension

Cleaning the leaves was conducted by rinsing the foliage with deionized water in a controlled, dripping manner to remove superficial contaminants while maintaining the integrity of the epicuticular wax structures. This condition is hereafter defined as the initial state. To ensure the validity of the experimental loading, the particle count of each sample was documented in this state prior to the aerosol exposure. This serves as a qualitative baseline to verify pre-existing PM numbers after cleaning. By establishing this baseline, it is ensured that the observed resuspension dynamics primarily reflect the interaction between the leaf surface and the standardized incense-derived PM introduced during the study.

All experiments were conducted in a climate-conditioned laboratory where the ambient relative humidity was strictly monitored and controlled at a constant level of 40 ± 5%. Because no additional moisture was introduced into the experimental PM chamber, the microclimate inside the box directly mirrored these stable laboratory conditions.

The leaves were then pinned onto a sample holder with a diameter of 50 mm. While fixing the leaves prevents natural leaf movement in the wind, this approach was chosen to eliminate confounding variables from erratic foliage motion and non-uniform deposition conditions. This procedure ensures a standardized and reproducible framework necessary for a reasonable species comparison. A potential concern regarding the use of detached leaves is the onset of desiccation during the following procedure. However, the structural integrity of the epicuticular wax layer—the primary interface for particle adhesion—is largely independent of the leaf's internal turgor pressure over such short-term intervals. As shown [37], these wax crystals form a rigid physicochemical barrier that remains stable even as the underlying mesophyll tissue begins to shrink. The use of detached leaves in controlled laboratory environments is a well-established methodological approach in aerosol research [33,38].

The holder was placed inside the same test chamber utilized by Streit et al. (2025) [39]. Each sample was positioned 15 cm from the air inlet, centered and orthogonal to the direction of the airflow at the height of the tube's center point within the chamber (see Figure 3). During this experimental phase, no other items, plants, pots, or desiccant (calcium chloride) were present in the chamber, except for the PM sensors used to monitor the introduced PM concentrations. The specifications of the chamber and sensors regarding accuracy, reproducibility, and calibration are described in detail by Streit et al. (2025) [39]. Following sample placement, particulate matter was introduced into the chamber for 1 min and 25 s using incense sticks (Pajoma brand, manufactured by Ingo Steyer GmbH & Co. KG, Hemmoor, Germany). The aerosol generated by the incense sticks is characterized by a well-documented, unimodal particle size distribution [40]. The stable emission profile ensures a highly reproducible mass concentration. This resulted in a relatively high PM concentration of 1000 ± 50 μg/m^3. If the concentration within the chamber fell outside this target range, the entire procedure described up to this point was repeated. This specific concentration was selected based on preliminary tests, which indicated that such levels are necessary to achieve sufficient PM deposition within some hours. The samples remained in the test chamber for three hours to allow for PM loading at a constant airflow velocity of 0.3 m/s. This condition is hereafter referred to as the loaded state.

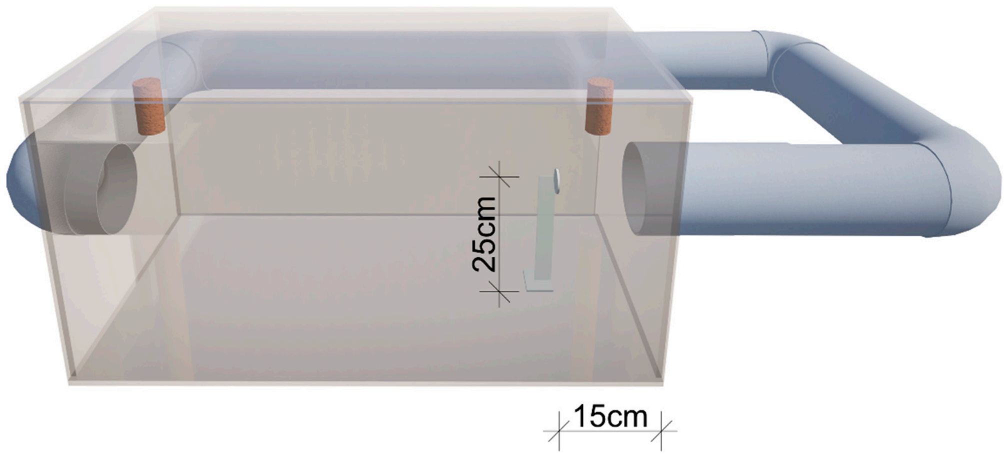

Figure 3. PM Experimental setup: PM loading chamber showing the sample holder relative to the air inlet.

Following the loading process, the sample holder containing the leaf was removed from the test chamber and placed in front of a fan (Noctua NF-A14, manufactured by Noctua GmbH, Vienna, Austria). The fan operated at a rotational speed of 3000 rpm, generating an airflow of 3 m/s immediately in front of the unit. The plants were exposed to this airflow for a total duration of one hour. The wind speed was selected because similar velocities have been investigated in previous studies, thereby ensuring comparability. Furthermore, at wind speeds exceeding 5 m/s, resuspension rates no longer correlate with species-specific leaf traits such as trichomes, grooves, or surface roughness [11,12].

Concerning the exposure duration, it is established that resuspension rates are time-dependent and exhibit a negative correlation over time [11,41]. This process is characterized by an immediate high-flux particle release that rapidly transitions into a stable plateau due to detachment fatigue. By maintaining a continuous 1 h exposure, the experimental setup bypasses this volatile initial transient phase, ensuring that the documented particle retention reflects a more stable state suitable for a reliable interspecific comparison.

This condition is hereafter referred to as the resuspended state. To determine the air velocities during the resuspension process, an anemometer (Testo SE & Co. KGaA, Titisee-Neustadt, Germany; Model 0635 1032) was utilized. This step was conducted in a laboratory environment rather than inside the test chamber. Ambient PM concentrations in the laboratory were monitored using a separate PM sensor of the same model installed in the test chamber (AirGradient Open Air, model O-1PST, manufactured by AirGradient Ltd., Mae Rim, Thailand) with a measurement interval of 0.7 min. During the resuspension period, the average ambient concentrations were 2.7 μg/m^3 and 3.6 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively.

To evaluate the particle distribution, representative mature and healthy leaves were selected for each plant species. The investigation was conducted at three stages: after initial cleaning, following the three-hour PM loading, and after the 60 min resuspension process. For each stage, leaf discs (10 mm diameter) were carefully extracted using a hole punch, sampled adjacent to the central leaf vein (midrib). These samples were mounted onto aluminum stubs using conductive carbon adhesive (EM-tec C33, Micro to Nano, Haarlem, Netherlands) and stored in airtight containers until analysis to prevent contamination. To account for intra-leaf variability, six independent SEM micrographs were captured per sample as technical replicates and subsequently averaged to represent the specific leaf surface characteristics. As one representative mature leaf was selected per species due to the resource-intensive nature of high-resolution SEM-BSE quantification, the true biological sample size is $n = 1$ per species, with the averaged technical replicates forming the basis for the subsequent comparative analysis. Figure 4 illustrates a pinned leaf after sampling and an adhered sample disc.

Figure 4. Pinned leaf with punched-out holes for sampling (**left**) and samples glued with conductive carbon adhesive for SEM analysis (**right**); technical replicates $n = 6$.

To ensure a standardized and reproducible comparison, the analysis focused on the adaxial leaf surface. This prioritization is supported by previous research indicating that the adaxial leaf surface represents the primary interface for atmospheric particle deposition. Consequently, the adaxial side typically exhibits significantly higher PM deposition compared to the abaxial surface, making it the most critical and relevant site for evaluating wind-induced resuspension [18].

The specific selection of the $PM_{1–2.5}$ and $PM_{2.5–10}$ fractions was justified by two main factors: first, they strictly comply with the international classification of particle size fractions used in environmental standards. Second, they match the particle size distribution generated by the incense sticks used.

2.3. SEM Imaging and Quantitative Analysis

The entire sample surface was rendered conductive by sputter coating with a gold-palladium alloy at a 60:40 ratio. Utilizing physical vapor deposition with a sputter coater

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(Quorum Technologies Ltd., Laughton, UK; Q150T S), a layer approximately 4 nm thick was applied to the sample surface. Imaging and elemental analysis were performed using a scanning electron microscope (FEI Company, Hillsboro, OR, USA; Quanta 250 FEG) equipped with a backscattered electron (BSE) detector. SEM micrographs were acquired at an acceleration voltage of 5.00 kV. For secondary electron imaging, an Everhart–Thornley detector was employed. The BSE detector was specifically used to enhance the contrast between the particles and the leaf surface, thereby facilitating more efficient particle counting.

From each sample SEM micrographs were taken from randomly selected locations on the adaxial surface, resulting in total 6 SEM pictures from each species. Figure 5 illustrates an SEM micrograph of *Parthenocissus quinquefolia* in its loaded state on the left. The right side shows the corresponding BSE image after processing. The color-coding of the particles enables further quantitative analysis by the software, as can be seen in Figure 5.

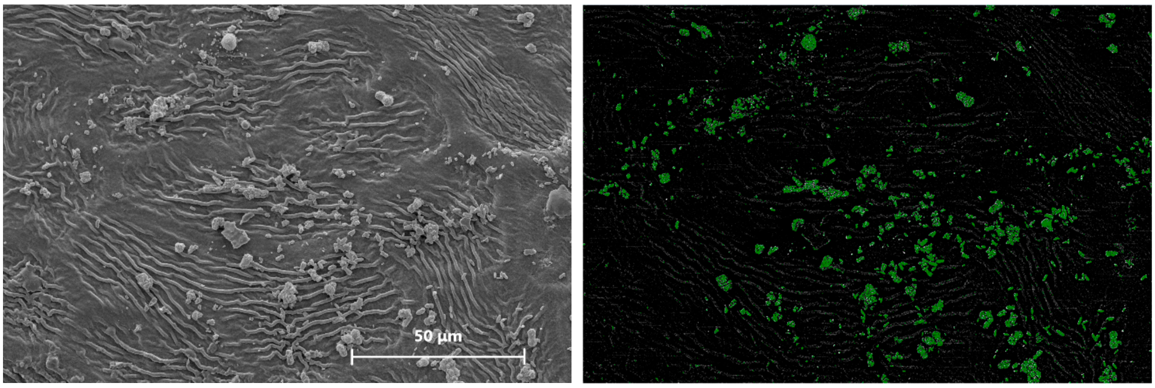

Figure 5. Presentation of *Parthenocissus quinquefolia* as an SEM image (**left**) and with color-coded particles after BSE image processing (**right**) in the loaded state.

The images were processed using Digital MicrographTM software (Version 3.6.1, Gatan Inc., Pleasanton, CA, USA). Based on pixel-based scale calibration, the software enables the quantification of particles and provides data on their size in terms of area and diameter. Using a consistent threshold, only particles with a geometric diameter between 1 µm and 10 µm were included in the analysis. The measurement results refer exclusively to the geometric diameter of the particles. To specify the aerodynamic diameter, the density of the particles would need to be determined. The measured particle counts were subsequently extrapolated to an area of one square centimeter to facilitate comparison with other publications. The application of a geometric or material-specific particle size correction factor was explicitly omitted. This is primarily justified by the high material contrast of the BSE signal, which allows for a precise differentiation between particles and leaf structures [42].

The evaluation of efficiency—whereby a highly efficient species is defined as one that captures a significant amount of PM while minimizing resuspension—requires detailed consideration and was calculated using two distinct approaches. First, the resuspension rates k (s^{-1}) were evaluated. This parameter describes the reduction in immobilized particles as a function of the initial loading and time, according to Formula (1).

$$k = \Delta N / N_I \cdot \Delta t \quad (1)$$

K: Resuspension rate (s^{-1}).

ΔN: Number of resuspended particles removed by airflow (n).

N_I: Initial number of particles present on the surface at the beginning of the respective time interval.

Δt: Time interval (s).

Secondly, the net removal was determined by calculating the difference between the particle counts before and after the resuspension process, as presented in the following figures.

2.4. Data Management and Statistical Analysis

For the statistical analysis of particle loading, a one-way analysis of variance (ANOVA) was performed for each state (initial, loaded, and resuspended) across both particle size classes. Prior to conducting the ANOVA, the assumptions of normality and homogeneity of variances were mathematically verified using Shapiro–Wilk and Levene's tests, respectively [43]. The six technical replicates (SEM micrographs) captured per sample were averaged to generate a single representative mean value for each leaf surface. Consequently, the statistical unit for the ANOVA is the average species-specific mean ($n = 1$ biological unit per species), ensuring that the high intra-leaf variability does not inflate the degrees of freedom or create significance of the comparisons. A Tukey-HSD post hoc test was subsequently applied to facilitate pairwise comparisons ($\alpha = 0.05$), visualized via a compact letter display (CLD). Given the exploratory laboratory nature of this framework, the ANOVA and subsequent Tukey-HSD post hoc test were utilized strictly as comparative tools to identify baseline differences in surface-level retention dynamics. All statistical calculations and visualizations were executed using Python statistical software (Python Software, version 3.12.7), primarily utilizing the SciPy (https://scipy.org) [44] and Statsmodels (https://www.statsmodels.org) [45] libraries.

2.5. Utilization of Artificial Intelligence

During the preparation of this study, the AI model Gemini Pro (Google) was utilized to assist translation from German to English and to support the conceptual development of the data evaluation strategy. The authors conducted a rigorous manual review of all AI-generated suggestions to ensure scientific accuracy. The final interpretation of the data and the formulation were performed solely by the authors.

3. Results

The following chapter describes the results obtained from the resuspension experiments.

3.1. Statistical Analysis

The analytical results for the different states—initial, loaded, and resuspended—were subjected to a one-way ANOVA. For both particle size fractions ($PM_{1–2.5}$ and $PM_{2.5–10}$), the calculated *p*-values were below the threshold of 0.05 ($p < 0.001$), classifying the interspecific differences as highly significant.

The Tukey-HSD post hoc test reveals a clear differentiation in binding capacity. In the loaded state, *Parthenocissus quinquefolia* formed a statistically distinct group for both fractions, exhibiting the highest values (group a). This indicates a significantly higher affinity for particle uptake compared to all other species. Conversely, *Cornus mas* consistently ranked in the lowest significance groups (group d for $PM_{1–2.5}$ and group c for $PM_{2.5–10}$), demonstrating the lowest binding efficiency.

For the fine fraction ($PM_{1–2.5}$), no significant differences were found between *Ligustrum ovalifolium* and *Viburnum opulus*, which both share group b. In the larger fraction ($PM_{2.5–10}$), however, *Viburnum opulus* showed significantly higher loading than *Ligustrum ovalifolium*, as evidenced by their assignment to distinct significance groups.

3.2. Quantification of Resuspended Particulate Matter

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Figure 6 presents the determined particle numbers after initial cleaning, following the loading process, and after the resuspension procedure. The resuspended amount can be determined from the difference between the PM count after loading and the count remaining after resuspension. The number of particles that remain on the leaves after the resuspension process represents the net retained particle load, from which the net removal efficiency is calculated. These values are derived from the SEM analyses and are expressed per cm².

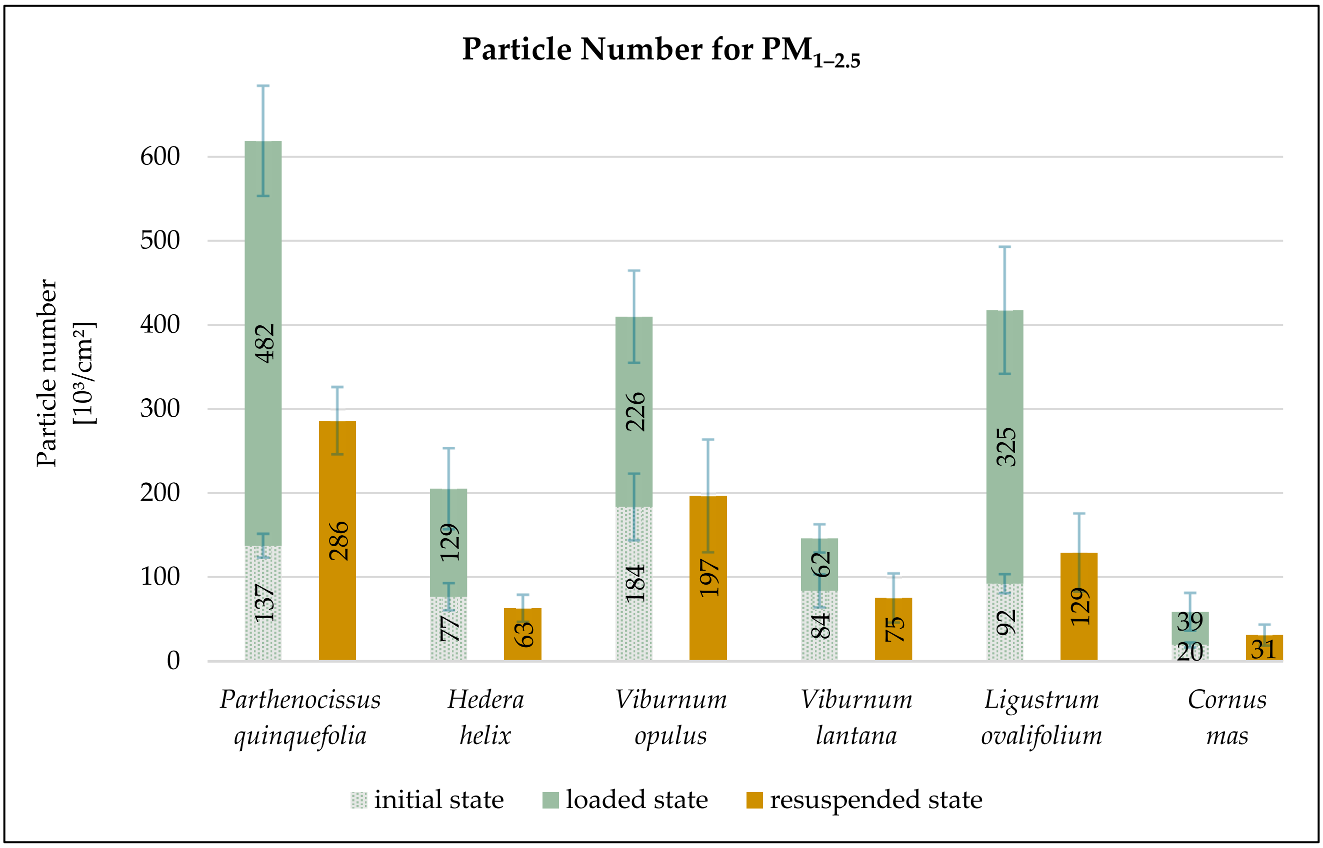

Figure 6. Particle number of initial, loaded and resuspended state with resuspension time of 1 h for $PM_{1–2.5}$.

It can be observed that *Parthenocissus quinquefolia* exhibits the highest particle counts following the loading process for both investigated PM fractions. Furthermore, this species shows the highest amounts of retained PM after the resuspension procedure. It demonstrates both a high binding capacity and a high degree of retention for both particle fractions presented. The second-highest PM counts were recorded for *Ligustrum ovalifolium* and *Viburnum opulus*. Notably, these two species did not differ significantly in their loading levels for these PM size fractions. *Hedera helix*, *Viburnum lantana* and *Cornus mas* proved to be less efficient regarding PM loading, in descending order of effectiveness.

Parthenocissus quinquefolia exhibits a significantly higher net removal value than all other species, followed by *Viburnum opulus*, which also differs significantly from the remaining values. The lowest net removal was observed for *Cornus mas*. There were no significant differences in net removal among the other investigated plant species.

Figure 7 shows that *Parthenocissus quinquefolia* and *Viburnum opulus* exhibit the highest deposition amounts; however, no statistically significant difference was found between these two species regarding the loading of the $PM_{2.5–10}$ fraction. The same applies to the next highest deposition levels, which were recorded for *Viburnum lantana* and

Ligustrum ovalifolium. For the remaining plant species, the deposition amounts for the $PM_{2.5–10}$ fraction followed the same trend as observed for the smaller particle size fraction.

Parthenocissus quinquefolia also exhibited the highest PM counts following the resuspension process, with 121.6 × 10^3/cm^2. This value differs significantly from that of *Viburnum opulus* 72.1 × 10^3/cm^2, which in turn is significantly different from the remaining PM resuspension amounts.

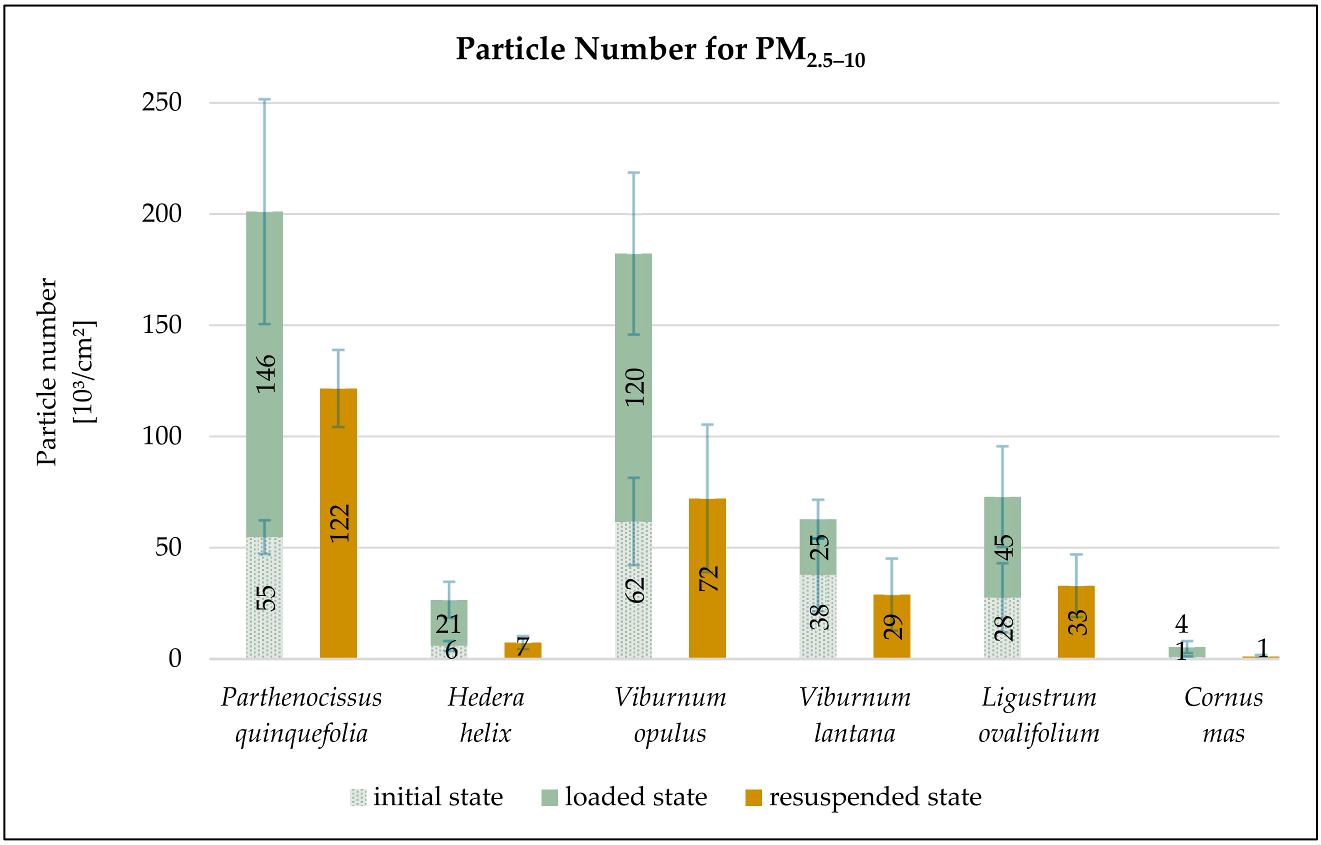

Figure 7. Particle number of initial, loaded and resuspended state with resuspension time of 1 h for $PM_{2.5–10}$.

Notably, the standard deviation for the $PM_{2.5–10}$ fraction is comparatively larger than for the $PM_{1–2.5}$ fraction. This results from a lower absolute particle count and a more non-uniform deposition pattern across the leaf structures. As each individual large particle carries a higher statistical weight, local hotspots lead to greater variance compared to the more homogeneously distributed fine fraction.

Table 1 presents the resuspension rates, the resuspended amounts, and the net removal amount for both size fractions. Regarding the resuspension rate, a higher rate corresponds to a larger proportion of the PM deposited on the leaf being resuspended. The data collected indicate that, overall, *Hedera helix* exhibits the highest resuspension rates. For the larger fraction, *Parthenocissus quinquefolia* shows the lowest resuspension rate at $1.11 \times 10^{-4} \cdot s^{-1}$.

The absolute number of resuspended particles initially depends on the deposited amount; consequently, *Parthenocissus quinquefolia*, *Ligustrum ovalifolium*, and *Viburnum opulus* exhibit the highest absolute resuspension quantities. For the $PM_{1–2.5}$ fraction, there is approximately a factor of 10 difference between the highest and lowest resuspension rates. The percentages of particles remaining on the leaf after resuspension provide a clear indication of the retention capacity of each species. In the $PM_{1–2.5}$ fraction, the *Viburnum species* and *Parthenocissus quinquefolia* show the highest percentage of retained particles and net removal, respectively. Similarly, *Cornus mas* exhibits high retention percentages. However, due to its low initial deposition number, this results in low absolute quantities and, thus, low net removal efficiency. *Parthenocissus quinquefolia* shows the highest percentage of retained $PM_{2.5–10}$. In combination with the highest deposition counts and high net removal rates of 46.3% and 60.5% for the respective fractions, *Parthenocissus quinquefolia* demonstrates the highest efficiency for both deposition and net removal.

Table 1. Resuspension rate, resuspension number and net removal $PM_{1–2.5}$ and $PM_{2.5–10}$.

	Parthenocissus quinquefolia	*Hedera helix*	*Viburnum opulus*	*Viburnum lantana*	*Ligustrum ovalifolium*	*Cornus mas*
k $PM_{1–2.5}$	1.49	1.93	1.45	1.34	1.92	1.30
k $PM_{2.5–10}$	1.11	2.01	1.68	1.48	1.52	2.20
res.$PM_{1–2.5}$	332.5	142.5	213.3	70.7	288.5	27.4
res.$PM_{2.5–10}$	79.5	19.2	110.1	33.8	40.0	4.2
nr $PM_{1–2.5}$	46.3	30.6	48.0	51.6	30.9	53.2
nr $PM_{2.5–10}$	60.5	27.7	39.6	46.1	45.1	21.2

k ($10^{-4}\cdot s^{-1}$) is the resuspensions rate; res.PM ($10^{3}\cdot cm^{-2}$) is the number of resuspended particles per cm^2; nr is the number of retained particles on the leaf surface for different size fractions (%) calculated in % from initial loaded PM divided by the amount after resuspension; each for 1 h resuspension time.

The particle size distribution on the investigated leaves, made possible by the chosen methodological approach, is illustrated in Figure 8. Both the PM counts in the loaded state and after the resuspension process are shown. As expected, the finer PM fractions constitute the majority in terms of total numbers. Due to the use of smoke as a PM source, predominantly smaller particles in the range of 1–2.5 μm were injected into the test chamber. Accordingly, smaller fractions were primarily detected on the leaf surfaces. As anticipated, the particle count as a function of particle size follows a negative exponential trend across all species. The fraction with a geometric diameter of 1–2.5 μm in diameter is the most abundant in all species. Interestingly, differences emerge in the larger fractions: *Hedera helix* and *Cornus mas* exhibit practically few to no particles in the larger size classes. This is evident in both Figure 8 and in the SEM micrograph in Figure 9.

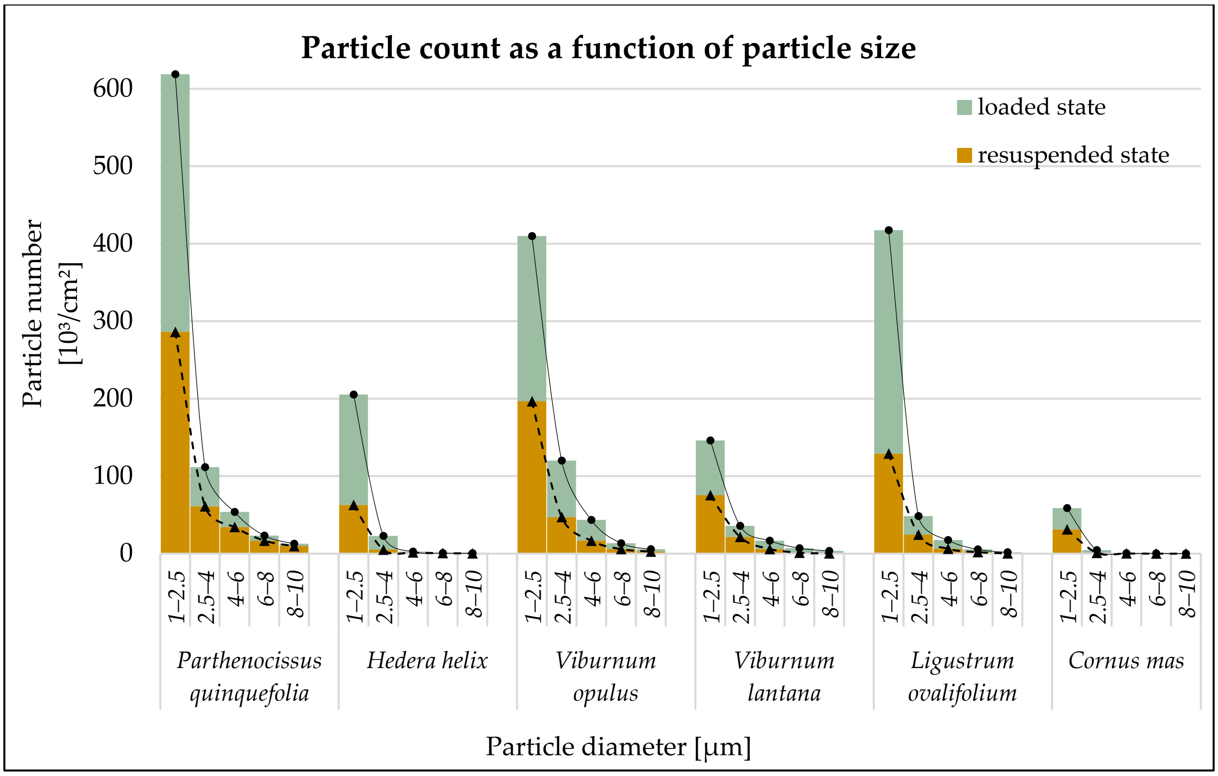

Figure 8. Particle number distribution based on geometric diameter, categorized by different size fractions for different species; solid and dashed lines represent the interpolated particle counts for loaded and resuspended state, respectively.

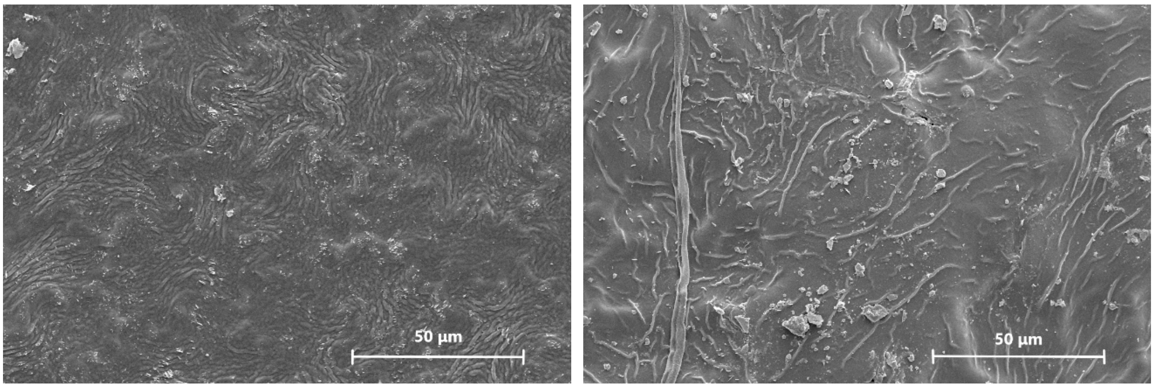

Figure 9. Variation in particle deposition on *Hedera helix* (**left**) and *Viburnum opulus* (**right**) in the loaded state. Note the higher density of coarse particles on the structured surface of *Viburnum opulus*.

Figure 9 illustrates the varying loading levels and differing affinities for larger particles. The image of *Hedera helix* on the left shows a predominance of very small particles. In contrast, the micrograph of *Viburnum opulus*—which features a more highly structured surface—reveals significantly more large particles, measuring up to approximately 10 µm. These morphological differences directly account for the variations in deposition amounts and, subsequently, the resulting resuspension quantities.

Analyses and raw data can be found in the supplementary material Table S1.4. Discussion

The following section discusses the results as well as the methodology employed in this study.

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4.1. Methodology and Experimental Approach

The deposition process within the PM chamber and the subsequent resuspension trials can be completed within a single day for each plant species. Furthermore, compared to field sampling, this laboratory-based approach is independent of weather conditions. However, the experiments must be conducted during the growing season when the plants are in leaf—a limitation that applies equally to field-based studies. Another significant advantage is that the initial PM loading on the samples is known prior to the experimental loading process and can be varied accordingly.

The selection of PM within the laboratory test chamber has not been, but could be, varied and adapted to specific requirements. Depending on the research question, it is possible to employ different PM sources and concentrations. In this context, the particle size of the PM is controllable, which distinguishes this approach from field studies where, as is well known, local PM—often consisting of highly diverse types—is deposited on the plants.

A noteworthy advantage of particle counting via SEM and digital image processing is the ability to represent detailed particle size distributions [46,47]. In comparison, when determining PM loading on leaves using the wash-off method, the resolution of particle sizes is typically less refined due to the filters employed [11]. Furthermore, the loading is often determined as weight per unit area rather than as a size distribution [12]. The approach used in this study, however, enables the investigation of the behavior of distinct particle size fractions. As the numerical SEM-BSE data were not cross-validated with gravimetric measurements, the mass-based net removal fluxes cannot be directly inferred. To enhance comparability and account for variables such as particle coagulation, future research could implement a dual methodological approach that combines microscopic particle tracking with gravimetric estimates.

Regardless of the chosen methodology, the use of the resuspension rate enables a direct comparison between different experimental results. However, this rate does not provide information on the absolute quantities of resuspended PM, as it is derived from the ratio between initial and final loading. Therefore, the inclusion of absolute values is mandatory. Simply reporting PM deposition or deposition efficiency alone does not allow for conclusions to be drawn regarding absolute resuspension behavior. Consequently, it is insufficient to report only the loading after wash-off or the initial state; rather, it is essential to determine the difference between the loaded and post-resuspension states [13,18,19].

The focus on the adaxial leaf surface is justified by its role as the primary interface for atmospheric PM interaction [18]. While the abaxial surface also traps particles, deposition and resuspension rates are naturally lower on the underside due to its protection from direct gravitational settling and laminar airflow. Notably, the experimental setup and SEM-BSE methodology applied here are fully applicable to abaxial surfaces as well. By prioritizing the most relevant deposition pathway, this study provides a reproducible framework, while the standardized approach remains open for future whole-leaf assessments.

The assessment of inter-individual biological noise is inherently limited by the specific leaf selection used in this experimental framework. Due to the necessary technical effort and the resource-intensive nature of high-resolution SEM imaging and subsequent digital particle quantification, the number of samples had to be restricted. Consequently, because the true biological sample size was restricted to $n = 1$ per species due to these high-resolution technical constraints, the quantitative variance primarily reflects intra-leaf positioning rather than macro-scale biological variance. To account for intra-leaf variability, six independent SEM micrographs were captured per sample and averaged. However, this setup primarily captures micro-surface variations and remains limited in its ability to map broader intraspecific variability driven by plant-to-plant or leaf-to-leaf biological noise. To achieve a more comprehensive understanding of species-specific retention properties and to account for broader interspecific variance, further research should incorporate a larger range of biological replicates. This would further bolster the overall robustness of the data and validate the observed trends across diverse environmental conditions.

Furthermore, the constant relative humidity maintained during the experiments (40 ± 5%) provided a stable environment that minimized moisture-induced changes in particle–leaf interaction mechanics. Relative humidity is well known to critically influence leaf adhesion and interparticle cohesion. Consequently, the quantitative findings of this study are valid within this specific, moderate humidity range, as higher or lower environmental moisture could shift the absolute resuspension thresholds.

The empirical data obtained in this study depicts the outcomes of a laboratory-scale investigation. To ensure the practical application of these findings, a next step could focus on scaling these results up into macro-scale urban modeling frameworks. It is essential to integrate such empirical datasets into numerical simulation models, which currently frequently utilize static deposition velocities that under-represent wind-induced particle remobilization. This integration ultimately enables more accurate simulations of localized concentration reductions and their subsequent impact on mitigating human population exposure in high-exposure urban zones.

4.2. Comparison of Deposition and Resuspension Results

The plant species investigated in this study are commonly used in Central Europe and represent popular choices for urban greening in parks, courtyards, and gardens. It is, therefore, all the more surprising that few studies have addressed wind-induced resuspension for these specific species. However, as noted by several authors, this is a crucial aspect for evaluating and understanding the relative particle retention potential of plants and, consequently, their overall efficiency in PM mitigation [12,31,32].

No studies on wind-induced resuspension were found for *Parthenocissus quinquefolia*, despite its common use in urban greening and existing research on its deposition patterns. PM deposition and physicochemical leaf characteristics of *Parthenocissus quinquefolia* have been investigated in urban environments [48,49], showing high deposition levels of up to 36 $\mu g/cm^2$ on the adaxial surface and 17 $\mu g/cm^2$ within the wax layer. These high levels are attributed to the species' significant wax content, making it one of the most efficient plants for PM deposition. The results of the present study support these findings, as *Parthenocissus quinquefolia* exhibited the highest PM deposition counts after the loading process for both particle fractions. While simulated rainfall experiments have already demonstrated effective removal of deposited PM [32], Setiawan et al. (2025) argue that the combination of high deposition and good washability makes *Parthenocissus quinquefolia* a suitable species for urban air purification. Building on these insights, the results of this study further demonstrate that, in addition to high deposition and washability, *Parthenocissus quinquefolia* also exhibits high net removal rates of 46.3% and 60.5% for $PM_{1–2.5}$ and $PM_{2.5–10}$, respectively. Consequently, the suitability of this species for highly effective initial particle capture and subsequent wind-induced retention is rated as very high.

The deposition amounts for *Hedera helix* observed in this study align with findings from the previous scientific literature. In the present study, the species showed comparatively low PM counts following the loading process. Similarly, Dzierzanowski et al. (2011) found that *Hedera helix* exhibited the lowest PM deposition levels, both on the leaf surface and within the wax layer [30]. Conversely, this climber is highly adaptable and thrives in diverse urban environments; for instance, studies along roadsides have shown high deposition loads of up to 2.9×10^{10} $PM_{2.5}$ particles per m^2 [46]. Field studies indicate that *Hedera helix* retains high PM loads—predominantly coarse particles (10–100 μm)—while smaller particles are incorporated into the epicuticular wax to a lesser extent compared to other species such as conifers [30,33]. These varying results do not constitute a contradiction. Firstly, the PM used in this laboratory study primarily consisted of particles with diameters smaller than the 10–100 µm range frequently found in the field. Secondly, the leaf physiology may not be able to immobilize small particles within the superficial wax layer during the short duration of a laboratory experiment. Nevertheless, *Hedera helix* remains an effective species for PM mitigation due to its evergreen nature, allowing for particle binding even during the cold season when deciduous species are leafless. Due to these properties, *Hedera helix* is widely used in urban greening where space for trees is limited [50].

The deposition efficiency of *Viburnum opulus* is described heterogeneously in the literature, with assessments ranging from low [51] to high [13] PM deposition levels. Notably, Muhammad et al. (2020) identified this species as highly efficient among 96 tested species [13]. This observation is consistent with the present study, in which *Viburnum opulus* exhibited the second-highest deposition values after *Parthenocissus quinquefolia*. Unfortunately, no studies on wind-induced resuspension are currently available for this species. Regarding the net removal value, however, *Viburnum opulus* shows significant potential. With a net removal rate of 48.0% for $PM_{1–2.5}$, it is suggested to be a highly promising species in shrub form for effective PM mitigation.

Muhammad et al. (2020) investigated the deposition efficiency of *Viburnum lantana*, ranking it as the second highest among 96 species [13]. Such high deposition efficiencies were not observed in the present study, which may be explained by differing methodological approaches. Muhammad et al. (2020) [13] utilized a wash-off method to quantify leaf-surface PM, potentially leading to higher reported values in comparison. In contrast, the SEM particle counting in this study focused on undisturbed leaf areas. As *Viburnum lantana* exhibits dense leaf trichomes, these structures were not captured during SEM counting, whereas the wash-off method accounts for all particles trapped within the trichome layer when washed of. Figure 10 displays a leaf hair of *Viburnum lantana*, showing particles adhering to and near the hair structure. The beneficial effect of leaf hairs on PM deposition is well documented [20,25,26,28]. Notably, the species exhibited a high net removal value of 51.6% for $PM_{1–2.5}$. The amount of PM remaining on the leaf after cleaning, relative to the initial loading, is significantly high compared to the other species. This suggests a protective effect provided by the hairs during the cleaning or resuspension process. It indicates that, while the initial deposition counts might not rank in the top tier within this specific SEM-based setup, the retention capacity in the presence of water or airflow is high.

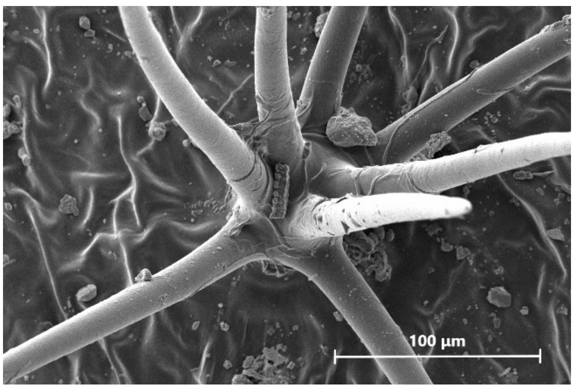

Figure 10. SEM micrograph of a trichome on *Viburnum lantana* with adhering particles of various sizes.

Species of the genus *Ligustrum* have been frequently investigated in PM deposition studies. However, no data on the resuspension of *Ligustrum ovalifolium* are currently available. Previous research has shown that following rain or strong wind events, PM loads on *Ligustrum lucidum* leaves were reduced by 28–48% and 27–36%, respectively [34]. Field samples of *Ligustrum lucidum* exhibited high PM deposition, exceeding 50 $\mu g/cm^2$ for particles ranging from 2 to >10 μm [52]. Similarly, *Ligustrum obtusifolium* is noted for its high PM deposition [53]. While several studies highlight the high deposition capacity of these species [53,54], their use in urban plantings is not always recommended, due to their air pollution tolerance as well as biological and socioeconomic characteristics [55]. As these studies focus on different *Ligustrum* species, direct comparisons remain limited. In the present study, *Ligustrum ovalifolium* exhibited comparatively high deposition levels for the $PM_{1–2.5}$ fraction, with 325.2 $10^3/cm^2$. However, the net removal rate for this fraction was only 30.9%, which is similarly low to that of *Hedera helix*. Both species feature smooth leaf surfaces with little number of trichomes in comparison. Despite the lack of specific wind-induced resuspension studies for the genus, the fact that *Ligustrum ovalifolium* remains semi-evergreen in temperate climates suggests that its use in urban greening for year-round PM mitigation can be beneficial.

Only few studies on PM deposition for *Cornus mas* are currently available. One such study investigated the PM load on leaves under field conditions and found that $PM_{2.6}$ tends to become encapsulated within the cuticle, whereas this behavior is negligible for larger particles (>$PM_{10\text{-}6}$ in this case). After 125 days, the amount of PM_{10} retained on the leaf surface was 6.25 $\mu g/m^2$ [56]. Compared to other species in that investigation, *Cornus mas* exhibited the lowest deposition amounts—a finding that is consistent with the results of the present study. This lack of deposition can be attributed to the absence of dense leaf trichomes and a very smooth leaf surface. Regarding particle immobilization, Muhammad et al. (2020) reported an immobilized fraction of 55% after washing [13]. In the present study, *Cornus mas* showed a net removal of 53.2% for $PM_{1–2.5}$ and 21.2% for $PM_{2.5–10}$. This corresponds to a resuspension rate of 46.8% and 78.8%, respectively. No further studies on PM deposition or wind-induced resuspension for *Cornus mas* have been reported to date.

Integrating our findings into a comprehensive conceptual framework allows for a more nuanced interpretation of actual urban decontamination efficiency. For instance, *Parthenocissus quinquefolia* demonstrated the highest efficiency within this cycle; its high initial deposition combined with a low resuspension rate ensures that a substantial fraction of PM is held on the leaf surface long enough to either be permanently sequestered in its abundant wax layer or effectively removed via subsequent wash-off events. Conversely, smooth-leaved species like *Cornus mas* or *Hedera helix*, which exhibit high resuspension rates or low initial capture, fail to transition particles from temporary deposition to permanent removal. This highlights that evaluating green infrastructure solely based on initial capture traps planners in a false sense of mitigation efficiency, as wind dynamics can continuously undo temporary air quality gains depending on species-specific retention traits.

4.3. Evaluation of Resuspension Rates and Methodological Consistency

It is noteworthy that, in contrast to the abundance of deposition studies, research on particle immobilization remains scarce. While a limited number of studies investigate immobilization in relation to artificial or natural precipitation, research focusing specifically on wind-induced resuspension is particularly rare.

The resuspension rates determined in this study range from 1.3 to $2.2 \times 10^{-4} \cdot s^{-1}$. These values are consistent with a comparable study by Zheng et al. (2019) [12], who recorded rates of approximately 1 to 3 × 10^{-4}·s^{-1} after accounting for differences in resuspension duration.

Comparisons with other studies yield similar conclusions, especially regarding the relatively low performance of *Hedera helix* and *Cornus mas*. As shown in Figure 2, both species exhibit a glossy surface, indicating a smooth texture that reflects light with minimal scattering. Such smooth surfaces are known to reduce deposition and promote resuspension [19].

Nevertheless, it must be noted that while comparisons with the existing literature are possible, they are inherently limited. Discrepancies in research designs arise from differing research questions and hypotheses. Most studies collect plant samples in the field [11,12,19], and PM application occurs either under ambient conditions [12,19] or in the laboratory using sieves [12] or the injection of silica particles of 1.85 µm into a test chamber [23]. Furthermore, immobilization studies predominantly focus on water-induced removal [11], whereas wind-induced resuspension is only rarely investigated in field [34] or laboratory settings [11,12,23].

To enhance the robustness of the findings, future research should employ both particle counting and mass-based calculations for comparison. This dual approach would allow for a comprehensive cross-validation of resuspension rates and account for potential particle coagulation, which may affect purely numerical counts.

4.4. Limitations

The authors acknowledge that PM derived from incense sticks differs in chemical composition as well as physical behavior from the heterogenic and polydisperse PM typically found urban environments. However, its application as a standardized aerosol source is supported in the previous literature [40,57–60]. The use of incense smoke ensures a stable and reproducible emission of particulate matter which effectively simulates the physical behavior of combustion-related urban pollutants. Due to the specific particulate matter source used in this study, the results regarding net removal quantities must be interpreted specifically in relation to this aerosol type. To enable more holistic conclusions concerning the air purification potential of various plant species, further investigations employing a broader range of particulate matter types—such as PM from road, industrial, mineral, and combustion sources—are necessary to assess the effects of chemical composition, density and hygroscopicity.

Despite the high precision of SEM, specific limitations arise regarding particulate matter quantification. The two-dimensional representation complicates the detection of particles on complex surfaces. As the analysis is mostly restricted to planar areas, particles located on trichomes are not captured. Particularly in densely pubescent species, this leads to an underestimation of the retention performance and allows for fewer conclusions regarding the net removal quantity. Furthermore, in cases of high loading—as frequently encountered in field samples—2D imaging prevents the detection of overlapping particles [34,46]. However, this aspect does not appear to be a complicating factor in the present study due to the specific loading density. While SEM is predestined for controlled laboratory studies, it reaches its limits with field samples characterized by clogged surfaces, where gravimetric wash-off methods provide more reliable overall data [46,50]. Another factor of uncertainty is the geometric interpretation: the particle diameter is calculated based on the projected area, which causes deviations from the actual volume. As particle density is unknown, the aerodynamic diameter can only be determined by approximation, or demands additional tests. The presented study focuses on particle sizes ranging from 1 to 10 µm, meaning that the significance for smaller or larger fractions remains unaddressed. Furthermore, a limitation of this design is the exclusive reliance on a single wind speed of 3 m/s. In real-world urban environments, resuspension is highly dynamic and non-linear, driven by velocities ranging from light breezes to traffic-induced turbulence. Future studies should, therefore, implement multi-speed or dynamic wind tunnel scenarios to comprehensively map this non-linear behavior under varying meteorological conditions.

Additionally, the kinetic understanding of the resuspension process in this study is bounded by the evaluation of a single 1 h time scale. Due to the nature of the selected methodological approach, conclusions are strictly limited to short-term retention effects. Given that particle detachment rates drop over time due to detachment fatigue [11,41], tracking particle numbers over different intervals would provide a more detailed temporal resolution of the detachment kinetics.

5. Conclusions

Several of the plant species are being described in the literature for the first time regarding their wind-induced resuspension properties, underscoring that this field remains under-researched [12,31,32].

However, because real-world air purification is governed by highly dynamic, non-linear variables, the practical conclusions from this standardized laboratory framework cannot be directly extrapolated to macro-scale urban environments. In real urban street canyons, atmospheric factors such as high wind turbulence variability, shifting diurnal humidity dynamics, and localized precipitation events will constantly alter particle–leaf adhesion thresholds. Furthermore, continuous biological surface transformations—including seasonal aging of foliage, chemical degradation of the epicuticular wax layer, and the deposition of ambient heterogenic polydisperse particles—will significantly affect long-term retention capacities. Therefore, the established species-specific hierarchy should be treated as a valuable baseline for initial botanical screening, rather than a definitive predictor of absolute outdoor mitigation efficiency, meaning that the quantified values reflect the short-term retention after wind exposure rather than permanent atmospheric removal. While this exploratory study provides a baseline using a highly controlled technical replication framework, it represents an initial pilot step that necessitates larger-scale biological sampling to fully map real-world urban vegetation performances.

Among the climbing plants, *Parthenocissus quinquefolia* proved to be the most efficient. Among the shrub species, *Viburnum opulus* showed the highest efficiency, followed to a lesser extent by *Viburnum lantana* and *Ligustrum ovalifolium*. While not explicitly tested in this setup, the semi-evergreen nature of *Ligustrum ovalifolium* suggests a high potential for year-round PM mitigation, which should be verified in long-term studies. However, a long leaf lifespan has a positive effect on seasonal PM deposition [14,61]. Consequently, the annual performance of evergreen or semi-evergreen and foliage-retaining plants, such as *Ligustrum ovalifolium*, might be underestimated in this study.

To advance urban green infrastructure planning in terms of air purification properties, additional efforts must focus on scaling these empirical laboratory results into comprehensive urban modeling frameworks, enabling precise assessments of localized concentration reductions. As a result, future studies should adopt a holistic approach that links deposition, resuspension, and subsequent wash-off or immobilization cycles. Validating these baseline insights under complex, multi-pollutant outdoor conditions requires evaluating how species-specific hierarchies respond to diverse particulate matter typologies (e.g., mineral dust, industrial soot, and non-exhaust traffic emissions). This necessitates the precise quantification of specific leaf traits—such as trichome density, surface roughness, and epicuticular wax mass—to fully resolve the intricate interplay between particle characteristics and micro-surface leaf morphology.

Regarding the methodological comparison with other studies, it should be noted that a unification or standardization of the methodology would be of great advantage. This would facilitate the establishment of a robust knowledge base, allowing for better comparability and standardized data collection. Ultimately, urban planners, greening professionals, and the general public would significantly benefit from such developments, fostering the implementation of targeted green infrastructure as a cornerstone of sustainable urban development.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13060337/s1, Table S1: particle numbers after image processing of REM pictures and explanation.

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Abbreviations

The following abbreviations are used in this manuscript:

PM	Particulate matter
SEM	Scanning electron microscopy
BSE	Backscattered electron

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