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Tracking Particulate Matter Accumulation on Green Roofs: A Study at Warsaw University Library

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Abstract: Particulate matter (PM) is a critical component of urban air pollution, with severe implications for human health and environmental ecosystems. This study investigates the capacity of green roofs at the Warsaw University Library to mitigate air pollution by analyzing the retention of PM and associated trace elements (TEs) across eight perennial plant species during spring, summer, and autumn. The results highlight significant interspecies variability and seasonal trends in PM retention, with peak levels observed in summer due to increased foliage density and ambient pollution. *Sedum spectabile* and *Spiraea japonica* emerged as the most effective species for PM capture, owing to their wax-rich surfaces and dense foliage, while *Betula pendula* demonstrated a high retention of TEs like manganese and zinc. Seasonal shifts from surface-bound PM ($_S$PM) to wax-bound PM ($_W$PM) in autumn underline the importance of adaptive plant traits for sustained pollutant capture. These findings underscore the critical role of green roofs in urban air quality management, emphasizing the need for species-specific strategies to maximize year-round phytoremediation efficacy. Expanding the implementation of diverse vegetation on green roofs can significantly enhance their environmental and public health benefits.

Keywords: phytoremediation; particulate matter; green infrastructure; trace elements contamination; seasonal variation

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1. Introduction

The rapid increase in urban populations and the expansion of large urban agglomerations have accelerated the implementation of urban greening strategies, particularly through the integration of green roofs [1]. As cities continue to grow and the impacts of climate change become more pronounced, the practice of incorporating vegetation into architectural surfaces has garnered significant attention from individuals, corporations, and public institutions due to its environmental and ecological benefits for urban ecosystems. Green roofs play a pivotal role in mitigating the adverse effects of urbanization, including air pollution, the urban heat island effect, and biodiversity loss, while simultaneously enhancing the aesthetic and functional appeal of city landscapes [2,3].

Urbanization in developing countries is projected to reach approximately 80% by 2030, exacerbating environmental challenges due to rapid economic growth and unsustainable development practices [4]. The expansion of urban areas frequently results in the degradation of green spaces, leading to poorer air quality, increased temperatures, and a decline in environmental health [5]. In response to these challenges, green roofs present a practical and scalable solution, especially in high-density urban areas where traditional green spaces are limited [6,7]. These structures offer a variety of ecological benefits, including improved thermal insulation, stormwater management, and the capture of pollutants, all of which are essential for urban adaptation to climate change [8–10].

A pressing environmental issue closely linked to urbanization is the decline in air quality, with particulate matter (PM) being a significant contributor [11]. PM consists of a mixture of solid and liquid particles suspended in the atmosphere, varying in size, composition, and origin [12,13]. While natural sources of PM include fires, dust storms, and volcanic eruptions [14,15], human activities, such as fuel combustion, industrial production, and construction, contribute a substantial share [16,17]. PM is typically classified by size: PM_{10} (particles smaller than 10 μm), $PM_{2.5}$ (particles smaller than 2.5 μm), and $PM_{0.1}$ (ultra-fine particles smaller than 0.1 μm) [18,19]. Smaller particles, particularly $PM_{2.5}$ and $PM_{0.1}$, pose greater health risks as they can penetrate deeply into the respiratory system [20,21]. The European Environment Agency has identified fine particles as some of the most toxic pollutants due to their potential to cause serious health problems [22]. Sources of PM_{10} include soil, agriculture, road dust, and mechanical processes like grinding and abrasion [23]. In contrast, $PM_{2.5}$ particles are generated by power plants, fuel combustion, and forest fires [15,18]. The chemical composition of PM in urban environments often includes sulfates, nitrates, polycyclic aromatic hydrocarbons, and heavy metals [24,25]. Factors such as season, local topography, and meteorological conditions can further influence PM concentrations and compositions [26,27].

Plants play a vital role in mitigating air pollution through mechanisms that include the absorption of gaseous pollutants via stomata, the capture of PM on leaf surfaces, and the breakdown of harmful compounds [28,29]. This process, known as phytoremediation, is an eco-friendly and cost-effective approach that uses plants to detoxify the environment [30,31]. The effectiveness of PM accumulation varies among plant species and depends on leaf morphology, surface area, and wax composition [14,32]. PM captured by plants can be categorized as surface PM (${}_{S}PM$) or PM embedded within wax layers (${}_{W}PM$) [33].

Given the urgent need to address air pollution in urban areas, green roofs are hypothesized to be effective tools for enhancing air quality by filtering and capturing PM. Despite their potential, research on the specific air-purifying capabilities of green roofs remains limited, highlighting the importance of further studies to fully understand their effectiveness. Expanding this body of research will help optimize urban greening strategies and improve environmental outcomes in densely populated cities.

2. Materials and Methods

2.1. Study Area and Plant Material

This research was conducted in 2023 in Warsaw, the capital of Poland, located centrally within the country. Warsaw experiences a humid continental climate (Dfb according to the Köppen climate classification), characterized by warm summers and cold, snowy winters. The region undergoes distinct seasonal changes, with an average annual precipitation of approximately 565.2 mm. In 2023, spring recorded an average monthly precipitation of 64.9 mm and an average wind speed of 12.7 km/h, while summer experienced an average monthly precipitation of 72.3 mm and a reduced wind speed of 9.4 km/h. Autumn 2023 was comparatively dry, with an average monthly precipitation of 30.0 mm and higher wind speeds ranging from 14.4 km/h to 17.5 km/h. These climatic conditions are integral to understanding the seasonal dynamics of particulate matter accumulation and the performance of green roofs in mitigating air pollution.

Home to around 1.8 million residents, Warsaw serves as an essential cultural, political, and economic hub. Over the past decades, significant urban expansion and industrial development have contributed to increased air pollution, largely driven by vehicle emissions, industrial activities, and residential heating, which is particularly prevalent during the winter. As a result, maintaining air quality remains a persistent challenge.

The plant samples for these studies were collected from the Green Roof Garden at the Warsaw University Library, a significant green infrastructure project located in the city center (Figure 1). Spanning over one hectare, this green roof is one of the largest in Poland and serves as a vital component of urban greening efforts aimed at mitigating air pollution and enhancing the ecological landscape. The site was selected for its strategic location, representative of Warsaw's typical urban air pollution levels, and its ecological importance in contributing to air quality improvement in a heavily urbanized area. As such, the green roof provided an ideal setting for studying the effectiveness of plants in capturing PM and assessing the broader ecological benefits of urban greenery.

Figure 1. Aerial view of the green roof of the Warsaw University Library (Google Earth).

The studies were conducted on a wide range of species: *Betula pendula* Roth., *Cornus sericea* L., *Cotoneaster dammeri* C.K. Schneid., *Hemerocallis xhybrida* Hort., *Rosa rugosa* Thunb., *Salix alba* L., *Sedum spectabile* Boreau, and *Spiraea japonica* L. These selected species were chosen based on their recognized potential for phytoremediation and adaptability to urban environments. Additionally, these species exhibit diverse leaf morphologies that influence *PM* retention (Table 1). All plants were cultivated within a uniform green roof area specifically designed to ensure consistent growing conditions, including a substrate of uniform composition and depth. The substrate was carefully selected and tested prior to installation to confirm its origin and to ensure that it did not originate from post-industrial sources or contain elevated concentrations of *TEs*. To further minimize the potential variability in trace element concentrations that could arise from substrate properties or plant placement, individual plant replicates were chosen from different areas of the green roof. This ensured that any local heterogeneity within the garden was accounted for, improving the reliability of the study results. Gardening activities on the green roof followed standard horticultural practices, ensuring that plants were maintained without the use of chemical treatments. The green roof employs a drip irrigation system, providing efficient and localized water delivery to plants without significantly affecting the retention of PM on leaf surfaces. To ensure the collected *PM* accurately reflected typical environmental conditions, only naturally exposed leaves from untreated plants were sampled. This approach minimized external influences on *PM* accumulation, preserving the reliability of the results obtained from the collected samples.

Table 1. Key morphological traits of the plant species' leaves.

Species	**Surface Roughness**	**Trichome Density**	**Foliage Density**	**Additional Traits**
Betula pendula	High	Sparse	Medium	High wax content
Cornus sericea	Low	Sparse	Dense	Flexible leaves
Cotoneaster dammeri	Low	Absent	Dense	Small leaf area
Hemerocallis xhybrida	Low	Sparse	Medium	Long, narrow leaves
Rosa rugosa	Medium	Dense	Medium	Thorns leaves
Salix alba	Low	Sparse	Medium	Long, linear leaves
Sedum spectabile	Very low	Absent	Dense	Succulent leaves
Spiraea japonica	Medium	Sparse	Dense	High foliage density

Sampling occurred on three distinct dates: at the beginning of the growing season in July, during the peak of vegetation in August, and at the end of the vegetation period in October. For each species, 20–30 mature leaves were collected and placed into paper envelopes. The leaves were selected from healthy plants, free from any signs of disease or pest infestation, to ensure the integrity of the samples. The leaves collected were fully developed and of similar age, ensuring uniformity in their maturity at the time of sampling. While some minor loss of PM, especially in smaller fractions, may occur during handling, the collection process was conducted with great care to minimize such disturbances. After harvesting, the plant material was stored under controlled conditions until laboratory analyses were conducted.

2.2. Methodology

This study employed a robust methodology to assess the accumulation of particulate matter (PM) and trace elements (TEs) on plant leaf surfaces. Particulate matter was classified into three size fractions: 10–100 µm ($PM_{10–100}$), 2.5–10 µm ($PM_{2.5–10}$), and 0.2–2.5 µm ($PM_{0.2–2.5}$), following a protocol adapted from Dzierżanowski et al. [20]. TE concentrations, including manganese (Mn), iron (Fe), copper (Cu), and zinc (Zn), were determined using X-ray fluorescence (XRF) spectrometry.

2.2.1. Filter Preparation Protocol

To ensure precise PM measurements, paper filters with pore sizes of 10 µm (Whatman, UK, type 91) and 2.5 µm (Whatman, Maidstone, UK, type 42) were used in this study, along with PTFE (polytetrafluoroethylene) membrane filters with a 0.2 µm pore size, reinforced with a polypropylene mesh, and nylon filters (PALL Corp., Port Washington, WI, USA). Based on the pore sizes, the particulate matter was classified into three fractions: diameters of 10–100 µm, 2.5–10 µm, and 0.2–2.5 µm. The filters were initially subjected to a drying phase in a controlled drying chamber (SANYO Laboratory Convention Oven MOV-112F, Osaka, Japan) set to 60 °C for a duration of 30 min. This drying step was implemented to remove any residual moisture, which could otherwise interfere with accurate mass measurements. Subsequently, the filters were acclimated to ambient conditions in a weighing room with a stable temperature and humidity for 60 min before initial weighing. Th filters were passed through an electrostatic gate (Antistatik Kit Universal, Mettler-Toledo International Inc., Greifensee, Switzerland) to remove any static charge and weighed on an analytical balance (XS105DU, Mettler-Toledo International Inc., Greifensee, Switzerland) with a precision of 0.01 mg, establishing a controlled initial mass critical for subsequent PM quantification.

2.2.2. Extraction of Surface Particulate Matter ($_S$PM)

Surface particulate matter ($_S$PM) was extracted from the leaf surfaces through a systematic rinsing protocol designed to minimize leaf damage while ensuring complete particle dislodgement. Each leaf sample was submerged in 200 mL of distilled water and gently agitated for precisely 60 s. This procedure facilitated the dislodgement of particulate matter from the leaf surfaces without affecting the underlying wax layers. The prepared samples were filtered through a metal sieve and transferred into beakers. The resulting wash solution was then filtered sequentially using a pressurized filtration setup, passing through paper filters with pore sizes of 10 μm and 2.5 μm, followed by PTFE membrane filters with a pore size of 0.2 μm. The rinse water, now containing the detached particulate matter, was subsequently passed through the pre-weighed filters to capture $_S$PM. Post-filtration, the filters underwent the same drying process as described previously (60 °C for 30 min), followed by a 60 min acclimation period before passing through an electrostatic gate and reweighing. The difference in filter mass before and after filtration provided a direct measurement of the $_S$PM collected from each sample.

2.2.3. Determination of Particulate Matter Embedded in Epicuticular Waxes ($_W$PM)

Quantification of the particulate matter embedded within the epicuticular wax layer ($_W$PM) involved a selective dissolution protocol using chloroform. Each leaf sample was rinsed in 100 mL of chloroform for a controlled duration of 45 s to dissolve the epicuticular wax layer and release embedded particulate matter. The resultant solution, containing both dissolved waxes and embedded PM, was filtered through a pre-weighed membrane filter, adhering to the same drying and weighing protocol used for $_S$PM extraction. Following filtration, the chloroform solution was transferred to pre-weighed glass beakers and placed under an extractor hood to allow complete evaporation of the solvent, ensuring no residual solvent remained. Upon solvent evaporation, the beakers were reweighed to determine the combined mass of the epicuticular waxes and the particulate matter embedded within them. This method provided a precise quantification of $_W$PM, distinguishing it from surface-deposited PM.

2.2.4. Leaf Surface Area Measurement

Quantification of the leaf surface area was essential to standardize the PM accumulation and epicuticular wax mass data, allowing for the results to be expressed on a per-unit-area basis and enabling cross-sample and cross-species comparability. Leaf area measurements were conducted using the SkyeLeaf 1.2.4. software in conjunction with the Leaf Area & Root Length Analysis System (Skye Instruments Ltd., Llandrindod Wells, UK). Each leaf sample was placed flat on the measurement device with sufficient spacing to avoid contact with adjacent samples. A high-resolution image of each leaf was captured and processed by the SkyeLeaf 1.2.4. software, which calculated the surface area of each sample and provided the results in cm^2. The calculated surface area was subsequently used to normalize the mass of each PM fraction and the epicuticular wax mass, ensuring that these values were expressed in terms of μg/cm^2 for accurate interspecies comparisons.

2.2.5. Determination of Trace Elements Content in Leaves

To determine the concentration of trace elements in plant leaves, harvested samples were first air-dried and ground to a fine, uniform powder using a mechanical grinder, ensuring sample homogeneity. The powdered material was transferred into containers lined with chemically inert polyethylene film to prevent contamination during analysis.

A handheld X-ray fluorescence (XRF) spectrometer (Olympus Vanta Element S, Olympus, Tokyo, Japan) was employed to measure the trace element content in the plant material. The spectrometer, calibrated with certified reference materials, emitted two radiation beams over intervals of 60 and 120 s, optimizing detection across a range of elements, including Mn, Fe, Cu, and Zn. The measurements were performed in triplicate for each sample across three collection dates to ensure statistical reliability and account for any temporal variation in element accumulation. Concentrations were calculated in mg/kg, providing a precise measure of the trace element levels within plant tissues.

2.2.6. Statistical Analysis

Data analysis was conducted using one-way analysis of variance (ANOVA) in StatGraphics 4.1 (Statpoint Technologies Inc., Warrenton, VA, USA) to examine the differences in PM accumulation and epicuticular wax content across plant species and between sampling years. This statistical approach assessed whether the observed differences were statistically significant, accounting for variances within each group. Following the ANOVA, the Newman–Keuls post hoc test was applied to explore specific pairwise comparisons between plant species and sampling years. The Newman–Keuls test was selected for its sensitivity in identifying significant differences while controlling for type I errors, with a significance threshold of $\alpha = 0.05$, ensuring the reliability of statistical inferences. Before performing ANOVA, data normality was verified, and transformation techniques were applied as needed to satisfy the ANOVA assumptions. The homogeneity of variances across groups was tested with Levene's test. Where variances were unequal, Welch's ANOVA provided a robust alternative to ensure an accurate interpretation.

3. Results

This study investigated the seasonal accumulation of PM and TEs across a selection of plant species, with a focus on understanding how different plant characteristics influence their capacity to capture airborne pollutants on the green roof. This analysis allows for a comparative understanding of how each species performs under varying environmental conditions, highlighting those with the greatest potential for urban air pollution mitigation. Below is a detailed description of the PM and TE accumulation patterns observed for each species.

3.1. Total PM ($PM_{0.2–100}$) Accumulation

The results of this study reveal substantial variability in total PM (${}_{S}PM$ + ${}_{W}PM$) accumulation among species and across seasons, with the highest PM retention generally observed during the summer months. Among the species analyzed, *S. spectabile* and *S. japonica* exhibited the highest PM retention values in summer, reaching 274.3 µg/cm^2 and 259.6 µg/cm^2, respectively. These values were significantly higher than those recorded for the lowest accumulating species, *H. xhybrida*, in spring (15.1 µg/cm^2) (Figure 2).

Seasonal differences in PM retention were also pronounced. Across species, PM retention was generally lower in spring compared to summer. For example, *B. pendula* accumulated 24.8 µg/cm^2 in spring, which increased to 131.7 µg/cm^2 in summer, marking a 430% rise in retention. Similar patterns were observed in other species, likely reflecting the interplay between atmospheric PM levels and plant activity. In Warsaw, spring PM concentrations (20–40 µg/m^3 for PM_{10}) are often comparable to or higher than summer levels (15–30 µg/m^3 for PM_{10}) due to lingering emissions from the heating season and reduced atmospheric mixing. Despite this, increased physiological activity and the fully developed leaf area in summer appear to significantly enhance PM capture, resulting in peak retention during this season.

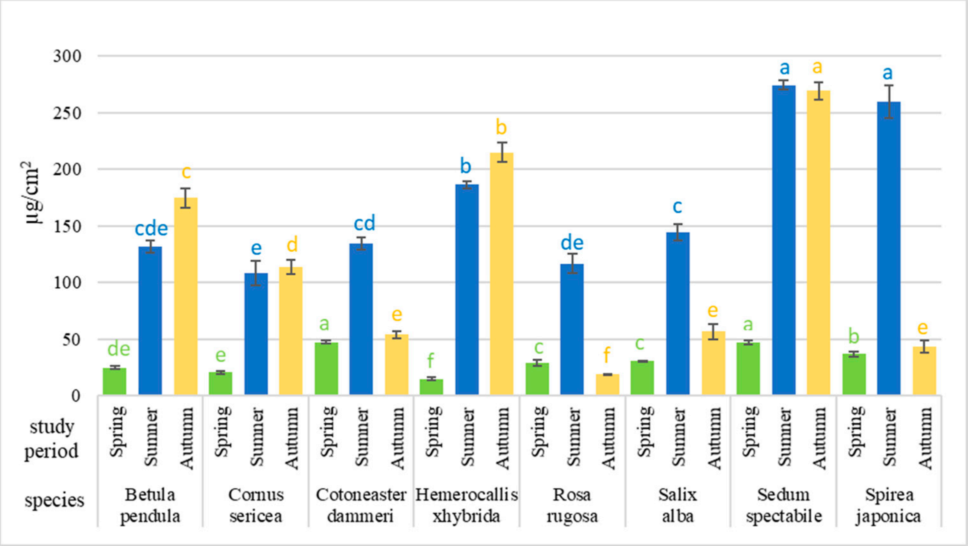

Figure 2. $PM_{0.2–100}$ accumulation on the leaves of the studied plant species. Data are presented as means ± SE. Lowercase letters in matching colors within each species represent statistically significant differences within a single growing season at $p \leq 0.05$.

The autumn PM retention showed considerable variations among species. Atmospheric PM levels in autumn (30–50 $\mu g/m^3$ for PM_{10}) tend to rise as heating activities begin, and meteorological conditions like lower wind speeds and temperature inversions contribute to pollution accumulation. For example, *S. spectabile* demonstrated a sustained retention capacity late into the growing season, with PM accumulation in autumn (269.1 $\mu g/cm^2$) nearly matching the summer levels (274.3 $\mu g/cm^2$), showing only a 2% decrease. In contrast, *S. alba* exhibited a marked reduction, with the PM levels in autumn (56.6 $\mu g/cm^2$) representing a 60% decrease from the summer peak (144.2 $\mu g/cm^2$).

3.2. PM Accumulation of Three Particle Sizes Fractions

This study demonstrates notable seasonal and interspecies variability in PM retention across specific fractions, $PM_{10–100}$, $PM_{2.5–10}$, and $PM_{0.2–2.5}$, indicating that different plant species and seasonal conditions substantially influence the capture and retention of airborne particulates (Figure 3A–C). Retention was consistently higher in the $PM_{10–100}$ and $PM_{2.5–10}$ fractions across most species, with these fractions showing peak values, particularly in the summer (Figure 3A,B). *S. spectabile* exhibited the highest retention among the species studied, with values reaching 130.2 $\mu g/cm^2$ and 122.4 $\mu g/cm^2$ in the $PM_{10–100}$ and $PM_{2.5–10}$ fractions during summer. Similarly, *S. japonica* also demonstrated high PM retention in these fractions, with notable accumulations of 118.2 $\mu g/cm^2$ and 124.5 $\mu g/cm^2$, respectively.

The seasonal variation in PM retention was particularly pronounced, with most species exhibiting substantially lower PM capture in spring and autumn compared to summer. *B. pendula* showed a marked increase in the $PM_{10–100}$ fraction from spring (10.1 $\mu g/cm^2$) to summer (61.5 $\mu g/cm^2$), a 510% increase, underscoring the effect of seasonal growth on PM accumulation (Figure 3A). However, some species, such as *S. spectabile*, retained high PM values even in autumn. In contrast, *R. rugosa* and *S. alba* demonstrated significant reductions in PM retention in autumn, particularly in the $PM_{10–100}$ and $PM_{0.2–2.5}$ fractions (Figure 3A,C).

Across all species and seasons, the $PM_{10–100}$ and $PM_{2.5–10}$ fractions showed consistently higher retention levels compared to the $PM_{0.2–2.5}$ fraction (Figure 3A–C). This trend underscores the importance of leaf surface properties, such as the thickness of the wax layer and trichome density, in retaining specific PM fractions. In contrast, the lower retention observed in *R. rugosa* and *S. alba* for certain fractions, particularly during the less favorable seasons, suggests that these species may be less effective for long-term PM capture.

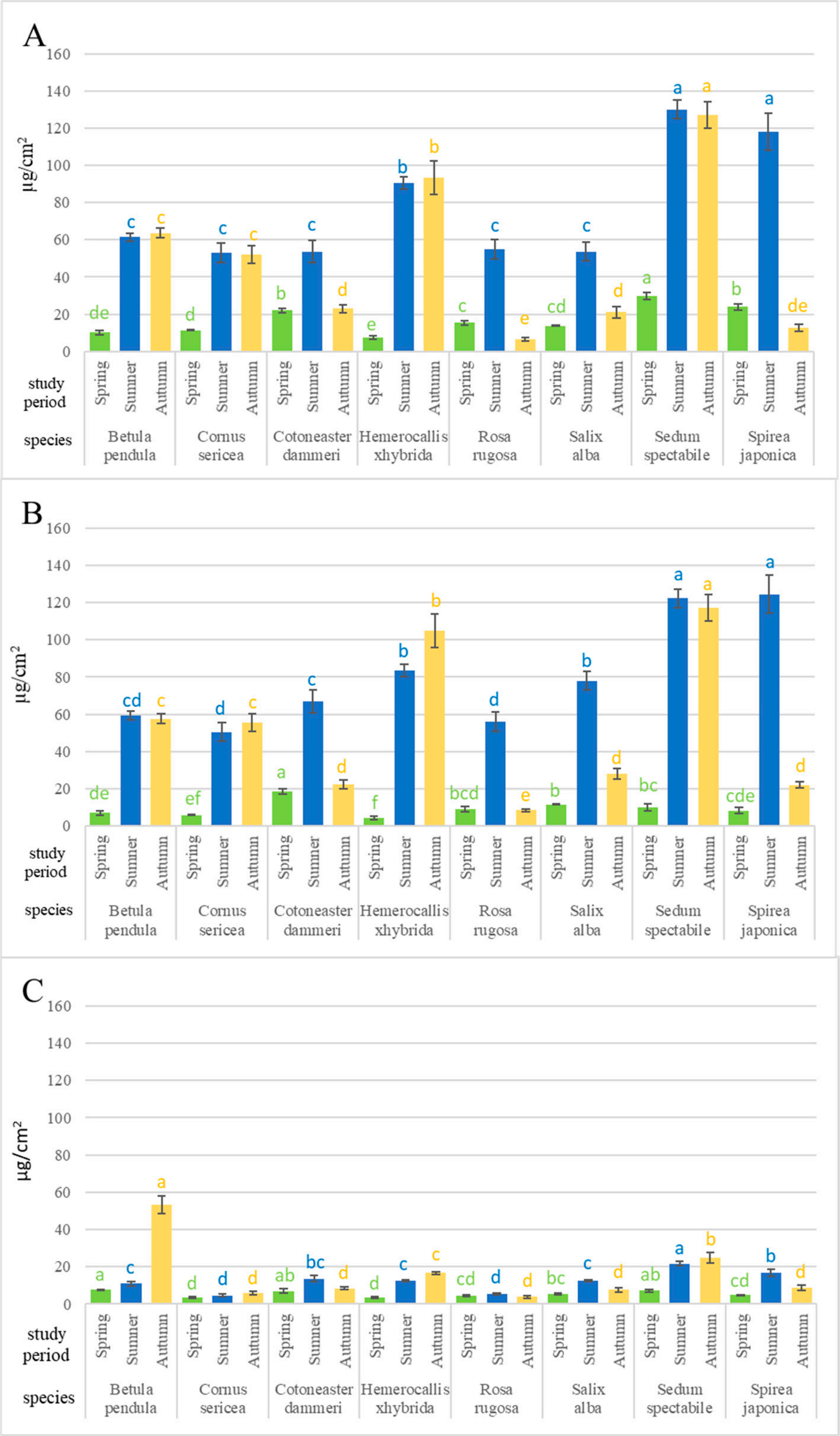

Figure 3. Fraction $PM_{10–100}$ (**A**), $PM_{2.5–10}$ (**B**), and $PM_{0.2–2.5}$ (**C**) accumulation on the leaves of the studied plant species. Data are presented as means ± SE. Lowercase letters in matching colors within each species represent statistically significant differences within a single growing season at $p \leq 0.05$.

3.3. Comparison of $_S$PM and $_W$PM Accumulation

The analyses of the $_S$PM and $_W$PM retention revealed key differences in the way PM is captured and stored on plant leaf surfaces across species and seasons (Figure 4). In general, $_S$PM constitutes the majority of PM retention, particularly in spring and summer. During these seasons, over 70% of the total PM was typically retained as $_S$PM across most species, suggesting that the particulate matter largely adheres directly to the leaf surface. However, in autumn, a notable shift toward a higher proportion of $_W$PM was observed in certain species. Species such as *S. spectabile* and *S. japonica* showed a substantial increase in $_W$PM proportion in late summer and autumn.

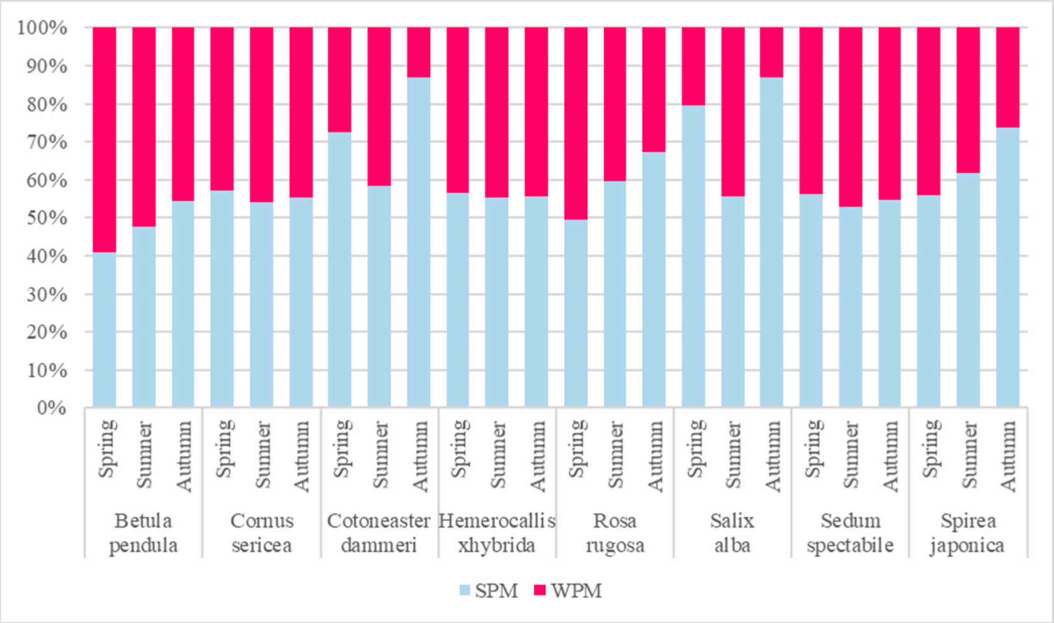

Figure 4. Comparison of $_S$PM and $_W$PM accumulation on the leaves of the studied plant species.

3.4. Amount of Waxes

The analysis of wax content highlights significant differences among species, with *B. pendula* showing the highest wax levels overall, particularly in spring, where it reached 581.7 µg/cm^2 (Figure 5). Despite a seasonal decrease, *B. pendula* maintained a relatively high wax content across the year, indicating its strong initial capacity for particulate retention. Other species with high wax levels include *C. dammeri* and *S. japonica*, both of which exhibited consistently high wax contents across the seasons. *S. japonica*, in particular, showed an increasing trend, with its wax levels rising from 275.1 µg/cm^2 in spring to 347.0 µg/cm^2 in autumn, marking a 26% increase, which could enhance its particulate retention capacity later in the year.

In contrast, *C. sericea* consistently displayed the lowest wax content, with a peak of only 79.5 µg/cm^2 in spring, decreasing by 44% to 44.8 µg/cm^2 in autumn (Figure 5). *H. xhybrida* and *R. rugosa* also showed relatively low wax contents across the seasons, though they were slightly higher than *C. sericea*. For instance, *H. xhybrida* had a maximum wax content of 107.0 µg/cm^2 in spring, which decreased by about 47% to 56.1 µg/cm^2 in summer.

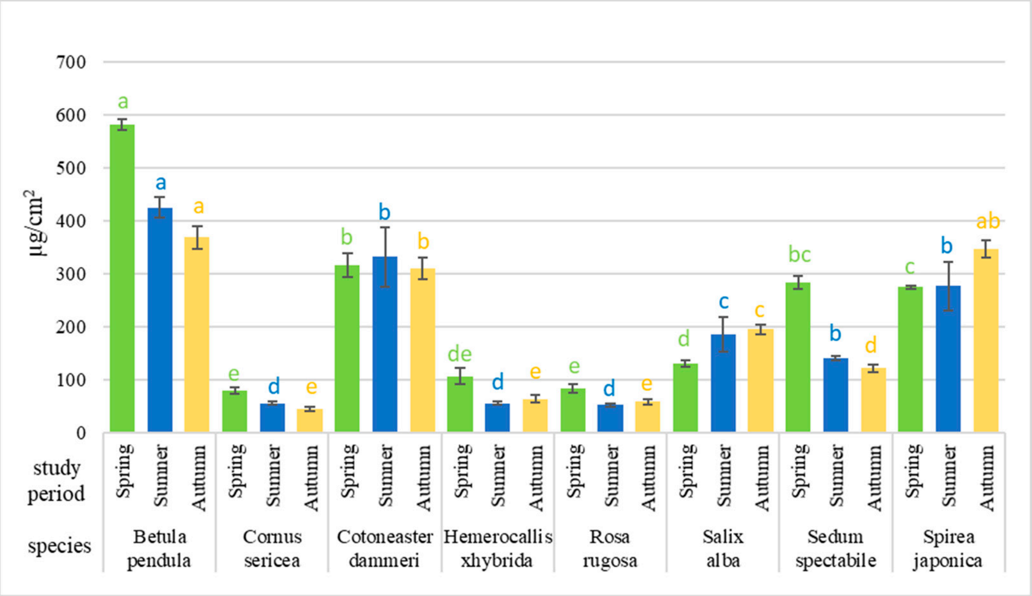

Figure 5. Amount of waxes on the leaves of the studied plant species. Data are presented as means ± SE. Lowercase letters in matching colors within each species represent statistically significant differences within a single growing season at $p \leq 0.05$.

3.5. Concentration of Trace Elements on Leaves

The analysis of trace element accumulation across species and seasons reveals significant variability in the retention of Mn, Fe, Cu, and Zn. This variability was influenced by species-specific characteristics and seasonal environmental conditions, which impact each species' capacity to capture and store these elements.

Manganese accumulation varied notably among species and seasons (Table 2). *S. japonica* consistently showed high Mn levels, particularly in spring and summer, with values of 84.0 μg/g. *B. pendula* also accumulated substantial amounts of Mn, with levels peaking at 99.3 μg/g in summer before declining to 87.0 μg/g in autumn. Other species, such as *S. spectabile*, showed a marked seasonal decline, with Mn levels decreasing from 52.0 μg/g in spring to 29.3 μg/g in autumn, indicating a reduced retention of Mn as the season progressed.

Iron retention showed substantial interspecies variability, with *S. alba* exhibiting the highest Fe levels, peaking in spring at 746.3 μg/g and gradually decreasing to 432.0 μg/g in autumn. *H. xhybrida* also showed significant Fe accumulation, with the highest value recorded in autumn (586.0 μg/g), suggesting increased retention in later seasons. In contrast, *R. rugosa* consistently displayed lower Fe levels, with the highest value in autumn at 264.3 μg/g, which is comparatively low relative to other species, indicating a limited capacity for Fe accumulation.

Copper retention was generally lower across the species compared to Mn and Fe but still showed notable seasonal trends. *H. xhybrida* accumulated the highest Cu levels, especially in summer (40.5 μg/g), indicating a peak in Cu retention during this season. Other species, such as *B. pendula* and *C. dammeri*, showed more stable Cu levels across the seasons, with *B. pendula* retaining around 20 μg/g in spring and 14.3 μg/g in autumn. *R. rugosa* consistently exhibited the lowest Cu levels, with values peaking in spring at 9.3 μg/g and decreasing to 7.5 μg/g in autumn, indicating minimal seasonal fluctuations in Cu accumulation.

Table 2. Concentrations of Mn, Fe, Cu, and Zn on the leaves of the studied plant species. The different lowercase letters for each species within the trace element category indicate differences between the seasons.

Species	Term	Trace Elements (mg/kg)							
		Mn	±SE	Fe	±SE	Cu	±SE	Zn	±SE
Betula pendula	Spring	58.0 c	2.0	375.0 a	22.9	20.0 a	2.1	473.1 c	18.7
	Summer	99.3 a	5.4	342.7 b	9.7	18.3 a	1.5	721.7 a	52.7
	Autumn	87.0 b	6.8	324.3 c	14.6	14.3 b	0.9	581.2 b	57.3
Cornus sericea	Spring	65.2 a	2.4	184.7 c	8.8	15.3 b	0.7	34.7 c	0.7
	Summer	43.3 b	7.4	167.0 b	18.9	16.7 b	3.2	56.3 a	10.1
	Autumn	41.7 b	3.8	251.0 a	18.3	19.7 a	2.3	44.7 b	1.8
Cotoneaster dammeri	Spring	45.3 a	6.2	255.0 a	2.1	17.7 a	0.3	62.7 a	0.7
	Summer	40.2 a	7.5	215.7 b	26.4	12.3 b	3.3	48.5 b	7.8
	Autumn	28.1 b	4.4	259.7 a	25.3	16.3 a	1.3	41.3 b	3.8
Hemerocallis xhybrida	Spring	60.4 a	3.0	466.7 b	40.8	24.0 b	3.5	54.0 b	4.0
	Summer	63.0 a	9.1	433.7 b	23.6	40.5 a	2.0	63.7 a	4.9
	Autumn	63.0 a	8.7	586.0 a	45.7	20.0 b	5.6	51.7 b	6.4
Rosa rugosa	Spring	57.7 a	1.0	203.7 b	10.5	9.3 a	0.3	28.5 b	0.3
	Summer	38.7 c	2.0	135.0 c	9.1	6.2 b	0.7	40.5 a	5.4
	Autumn	51.3 b	4.3	264.3 a	26.3	7.5 b	0.3	25.7 b	1.9
Salix alba	Spring	58.7 a	5.4	746.3 a	57.6	24.7 a	0.9	56.3 a	2.2
	Summer	54.7 ab	7.8	596.7 b	72.2	23.1 a	3.2	54.0 a	5.0
	Autumn	48.3 b	4.4	432.0 c	90.1	17.2 b	4.6	43.6 b	4.0
Sedum spectabile	Spring	52.0 a	5.0	213.0 a	23.5	15.9 a	2.3	304.2 a	61.7
	Summer	40.4 b	2.7	209.7 a	30.7	12.7 b	0.6	225.7 b	13.8
	Autumn	29.3 c	4.6	196.3 a	54.1	10.1 c	2.3	122.3 c	21.2
Spirea japonica	Spring	84.0 a	7.4	237.0 a	21.0	22.3 a	1.8	66.7 a	4.1
	Summer	84.0 a	1.2	245.7 a	6.5	21.0 a	1.2	57.0 b	0.9
	Autumn	78.7 a	3.2	239.3 a	19.6	19.7 a	0.6	43.5 c	0.7

Zinc levels displayed both interspecies and seasonal variability, with *B. pendula* and *S. spectabile* demonstrating high Zn accumulation. *B. pendula* showed peak Zn retention in summer at 721.7 µg/g, while *S. spectabile* accumulated its highest Zn levels in spring (304.2 µg/g) before declining to 122.3 µg/g in autumn, a reduction of approximately 60%. Other species, such as *C. sericea*, showed consistently low Zn levels across the seasons, with a peak of only 56.3 µg/g in summer.

3.6. Correlation Coefficients

The correlation analysis between PM size fractions, wax contents, and TEs reveals key patterns in particulate and element retention on plant surfaces (Table 3). The strongest relationship was observed between the wax content and Zn, with a significant positive correlation (r = 0.63). Additionally, there was a moderate positive correlation between the wax content and manganese (Mn, r = 0.34) (Table 3). For PM size fractions, $PM_{0.2–2.5}$ showed a positive correlation with the wax content (r = 0.23) (Table 2). $PM_{0.2–2.5}$ also correlated positively with Zn (r = 0.42). Conversely, larger PM fractions ($PM_{10–100}$ and $PM_{2.5–10}$) displayed weak and mostly negative correlations with the waxes and TEs (Table 3).

Table 3. Correlation coefficients between PM size fractions, wax contents, and TEs accumulated on plant foliar surfaces. Statistically significant correlations at the α = 0.05 level are bolded to highlight the relationships with strong statistical relevance.

Parameters	Waxes	Mn	Fe	Cu	Zn
$PM_{0.2–100}$	−0.12	−0.09	−0.09	−0.02	0.04
$PM_{10–100}$	−0.16	−0.11	−0.13	0.00	0.02
$PM_{2.5–10}$	−0.16	−0.11	−0.07	−0.01	−0.04
$PM_{0.2–2.5}$	**0.23**	**0.20**	−0.01	−0.10	**0.42**
sPM	−0.11	−0.12	−0.07	−0.03	−0.03
wPM	−0.13	−0.05	−0.11	0.00	0.13
Waxes	1.00	**0.34**	−0.02	−0.03	**0.63**

4. Discussion

This study provides valuable insights into the retention of total particulate matter ($PM_{0.2–100}$) across eight plant species grown on a green roof, uncovering significant interspecies variability and emphasizing the critical role of species-specific traits in PM capture. The role of leaf surface characteristics, such as surface roughness and trichome density, in particulate matter retention, is inferred from established literature and the observed differences in PM accumulation across species in this study [34–36]. Air pollution also contributes to the variations in PM retention, underscoring the dynamic interplay between plant morphology and external conditions [37,38].

Notably, species such as *S. spectabile* and *S. japonica* exhibited significantly higher PM retention compared to others, with *S. spectabile* retaining up to 274.3 $\mu g/cm^2$ in summer. This reinforces their potential suitability for green roof systems aimed at mitigating urban air pollution. The dense foliage of *S. spectabile* likely plays a pivotal role in its effectiveness, providing a larger surface area for PM deposition and contributing to its high retention capacity. These findings align with previous studies [39], which emphasized the efficacy of succulent species like *Sedum* on green roofs due to their distinct leaf morphology. Similarly, the dense foliage of *S. japonica* enhances its total surface area, optimizing it for PM adhesion. This observation is consistent with earlier work [20], which highlighted the influence of dense canopies on PM accumulation. These results collectively reaffirm the importance of selecting plant species with specific structural adaptations for urban green infrastructure aimed at air pollution mitigation [40,41].

Seasonal variations in PM retention on the green roof were pronounced, with the highest PM levels observed during summer across most species. This pattern likely reflects fully developed foliage and environmental conditions typical of the season, including potentially elevated ambient PM concentrations and increased industrial and vehicular activity, as suggested by related studies [42]. Additional seasonal influences, such as rainfall in spring, may reduce PM retention by washing particles off leaf surfaces, while gardening activities like irrigation and soil disturbance during summer could contribute to higher PM levels and increased capture. In autumn, leaf senescence and shedding likely decrease the available surface area for PM retention. Species such as *S. spectabile* and *S. japonica* exhibited peak PM retention during summer, likely due to structural adaptations, including waxy surfaces and dense foliage, coupled with greater particulate availability in the environment. Also, the role of environmental factors, particularly rainfall and wind dynamics, cannot be overlooked at that period of time, as rainfall can act as a natural cleansing agent, washing away surface-bound PM, while the wind may redistribute particles, further influencing PM retention patterns [43].

Interestingly, *B. pendula*, *C. sericea*, *H. xhybrida*, and *S. spectabile* did not follow the expected seasonal patterns. This deviation suggests that species-specific traits, such as wax composition, leaf roughness, or surface microstructures, may play a more significant role than external factors like rainfall, gardening activities, or leaf loss. Further investigation is needed to understand these underlying mechanisms. The large interspecies variability observed underscores that certain plants, when incorporated into green roofs, are significantly more effective at capturing airborne particulate matter than others. These findings have important implications for urban phytoremediation strategies, highlighting the need for species selection based on both structural traits and environmental resilience [44,45].

The present research also highlights the critical role of particle size in PM retention, revealing that larger fractions ($PM_{10–100}$ and $PM_{2.5–10}$) consistently exhibit higher accumulation than finer fractions ($PM_{0.2–2.5}$) across most plant species. Larger PM fractions are more susceptible to gravitational settling, allowing them to be intercepted and retained more effectively by plant leaves [46]. In contrast, finer particulates remain airborne for extended periods due to their low settling velocity, making their deposition on leaf surfaces less frequent and resulting in lower accumulation rates [47]. This size-dependent behavior has profound implications for species selection in urban phytoremediation, as plants that excel in capturing larger PM fractions may deliver immediate reductions in coarse particulate pollution.

Leaf morphology emerges as a pivotal factor influencing the retention of larger PM fractions. Structural traits such as a high trichome density, surface roughness, and non-smooth textures provide greater adhesion points and surface area, significantly enhancing the interception and capture of larger particulates [48]. Species like *S. spectabile* and *S. japonica* consistently demonstrated superior retention of $PM_{10–100}$ and $PM_{2.5–10}$, likely due to their waxy coatings, dense foliage, and microstructural adaptations [49]. These features promote the adherence of coarse particles, aligning with studies that highlight the role of surface microstructures in improving PM capture efficiency [20,39].

Seasonal trends in PM retention further highlight the interplay between plant phenology and particulate capture. During the growing season, plants undergo physiological and morphological changes, such as maximal leaf expansion and increased metabolic activity, which enhance particulate retention. In this study, *B. pendula* exhibited a remarkable 510% increase in $PM_{10–100}$ accumulation from spring to summer, driven by an expanded leaf surface area and increased interaction with airborne particulates. These findings align with the observations by Popek et al. [43], emphasizing the influence of seasonal growth dynamics on phytoremediation efficacy.

Conversely, some species, including *R. rugosa* and *S. alba*, displayed significant declines in PM retention across all size fractions during autumn, reflecting reduced phytoremediation capacity as they transitioned toward dormancy. Reduced leaf area, decreased metabolic activity, and senescence likely contribute to this seasonal decline. In contrast, resilient species such as *S. spectabile* maintained high PM retention levels into autumn, making them particularly well-suited for environments with prolonged pollution exposure. This resilience may be attributed to sustained physiological activity, evergreen characteristics, or adaptive traits that support year-round PM capture [41]. These findings support earlier research indicating that evergreen or late-season species play an essential role in extending the temporal effectiveness of urban vegetation [45].

The variability in PM retention across particle sizes and seasons underscores the need for a nuanced approach to plant selection for green roofs, ensuring optimized year-round air purification in urban environments. Species with consistently high retention across multiple PM fractions, particularly in $PM_{10–100}$ and $PM_{2.5–10}$, offer substantial air purification benefits, especially during peak pollution periods in summer. On the other hand, species with significant seasonal declines in PM retention, such as deciduous plants with early dormancy, may be less effective for year-round applications. Selecting complementary species that account for size-specific PM retention and seasonal dynamics could enhance the overall performance of urban green infrastructure. For example, combining deciduous species with high summer efficacy and evergreens capable of capturing fine particulates during colder months may provide balanced and continuous air purification. It is also essential to consider the potential influence of gardening activities, such as fertilization, irrigation, and soil conditioning, on PM and TE accumulation on green roofs. These activities can serve as sources of pollutants, complicating the assessment of the extent to which green roofs mitigate air pollution.

The distinction between $_{\mathrm{S}}$PM and $_{\mathrm{W}}$PM retention provides critical insights into the mechanisms by which plants capture and store particulates across species and seasons. Current findings demonstrate that $_{\mathrm{S}}$PM constitutes the majority of total PM retention during spring and summer on green roofs, coinciding with periods of maximal leaf expansion and metabolic activity. During these active growth phases, over 70% of retained PM adhered to the leaf surfaces, highlighting the primary role of direct particle adhesion facilitated by increased foliage density and surface area availability [14,20,40]. This high proportion of $_{\mathrm{S}}$PM retention reflects the dynamic interaction between particle deposition and plant growth, particularly in species with dense canopies and rough surfaces, which promote adhesion.

A notable seasonal shift was observed in $_{\mathrm{W}}$PM retention, particularly in late summer and autumn. This trend is likely attributable to the physiological changes in leaf surface characteristics, such as the development or thickening of epicuticular waxes. Epicuticular waxes provide a hydrophobic, viscous medium that not only embeds particulate matter but also enhances its resistance to displacement by environmental forces [50]. *S. japonica* exhibited a notable increase in wax particulate matter (wPM) retention during autumn, suggesting that enhanced wax deposition may contribute to PM stabilization in specific species. However, this trend was not consistent across all species, with some, like *B. pendula*, showing reduced wax levels during the same period. Additionally, surface-bound particulate matter (sPM) retention remained the dominant mechanism in autumn, even for *S. japonica*, underscoring the importance of surface adhesion in PM capture during periods of reduced growth. This aligns with the findings by Chen et al. [51], who emphasized the critical role of epicuticular waxes in particulate retention, particularly in urban environments with high pollution loads.

$_{\mathrm{W}}$PM retention offers additional advantages over $_{\mathrm{S}}$PM, including its reduced susceptibility to removal by wind and rain. This stability contributes to long-term phytoremediation efficacy by minimizing the resuspension of particulates into the atmosphere [40,52,53]. These properties are particularly valuable in urban contexts where fluctuating environmental conditions and persistent air pollution require robust mechanisms for particulate capture and storage. The ability of waxes to embed PM reinforces their role as a durable and efficient medium for particulate retention, extending the phytoremediation potential of species with high wax production.

Species-level variabilities in wax contents further underscore the importance of epicuticular waxes as a determinant of PM retention capacity. For instance, species such as *B. pendula*, *C. dammeri*, and *Spiraea japonica* were observed to maintain high and stable levels of PM retention, supported by their substantial wax production throughout the year. Notably, *S. japonica* exhibited a marked increase in wax deposition during autumn, enhancing its efficacy in PM stabilization under conditions of declining foliage density. Conversely, species with low wax contents, including *C. sericea*, *H. xhybrida*, and *R. rugosa*, consistently demonstrated lower PM retention efficiency [14,20]. This suggests that such species may be less effective for urban phytoremediation, particularly during seasons when $_{\mathrm{S}}$PM retention is naturally diminished.

The accumulation of TEs, including Mn, Fe, Cu, and Zn, demonstrated significant interspecies and seasonal variability, reflecting differences in plant surface characteristics and environmental conditions. These findings are consistent with studies emphasizing that airborne particulate deposition is a key pathway for trace element accumulation on leaves, with retention driven by leaf morphology, surface chemistry, and environmental deposition dynamics [35].

Mn retention was consistently high in *S. japonica*, particularly during spring and summer. Mn is commonly associated with industrial emissions, such as steel manufacturing, and is often present in coarse particulate fractions prone to gravitational settling and deposition on plant surfaces. The high Mn accumulation in *S. japonica* likely reflects its dense foliage and rough leaf surface, which enhance particulate adhesion during peak deposition periods. The decline in Mn retention in *S. spectabile* during autumn suggests that seasonal shedding of surface particulates or decreased atmospheric Mn availability may reduce its accumulation. This seasonal trend is consistent with Burkhardt [50], who reported reduced metal retention on leaf surfaces as plants transition to dormancy. Given that Mn is deposited directly from the air and retained on leaves, the findings highlight the importance of surface-bound interactions, particularly in species with waxy or textured leaf surfaces that facilitate particulate adherence.

Copper accumulation peaked in *H. xhybrida* during summer, with a subsequent decline in autumn. Cu is a trace element often associated with vehicular brake wear, industrial emissions, and airborne particulate matter in urban settings. Its accumulation during summer may be linked to increased dry deposition rates that are facilitated by elevated temperatures and reduced rainfall. The observed decline in Cu retention during autumn may result from natural surface-cleansing processes such as precipitation and the detachment of leaf cuticles, which have been noted as a mechanism for removing particulate deposits [54]. The temporal variability in Cu accumulation underscores the dynamic interaction between deposition rates and leaf surface stability over the growing season.

Zinc retention was highest in *B. pendula* during summer, which can be attributed to the greater availability of atmospheric Zn from tire wear and industrial sources during this period. The increased surface area provided by expanded foliage during peak growth likely contributed to the enhanced Zn retention observed in this species. Conversely, the decline in Zn retention in *S. spectabile* from spring to autumn aligns with the findings [55], suggesting that surface-bound Zn on leaves is more effectively captured during the early stages of the growing season when deposition rates and leaf surface properties are optimized. Additionally, Zn's association with fine particulate fractions, which are more susceptible to resuspension or wash-off, may explain the observed seasonal declines.

The exclusive attribution of trace element accumulation to airborne deposition emphasizes the critical role of leaf surface traits in particulate retention. Species with rough, waxy, or dense foliage, such as *S. japonica* and *B. pendula*, were particularly effective at retaining metals like Mn and Zn, even under variable environmental conditions. In contrast, species with smoother leaf surfaces or lower wax content, such as *S. spectabile*, exhibited more variable retention patterns, particularly during seasons with increased precipitation or declining metabolic activity. These differences highlight the need to consider both species-specific morphological traits and seasonal environmental factors when selecting plants for urban phytoremediation.

The relationship between PM size fractions and wax contents was most pronounced for fine particulates ($PM_{0.2–2.5}$), which displayed a strong positive correlation with wax levels. This correlation reflects the properties of fine PM, which include prolonged atmospheric residence time and a higher surface area-to-mass ratio, enabling more effective adhesion to waxy surfaces [56]. The observed positive correlation between $PM_{0.2–2.5}$ and Zn further suggests that Zn retention is closely linked to the capture of fine particulates, which often contain trace metals derived from vehicular emissions, industrial sources, and other anthropogenic activities.

In contrast, larger PM fractions ($PM_{10–100}$ and $PM_{2.5–10}$) exhibited weak or negative correlations with the wax content and trace element retention. This disparity likely reflects the deposition dynamics of larger particles, which are primarily influenced by gravitational settling rather than chemical interactions with waxes. Larger PM fractions are more effectively captured by rough, hairy, or highly structured leaf surfaces, which provide physical barriers and adhesion points for particle deposition. These findings align with the work of Dzierżanowski et al. [20], who demonstrated that non-smooth leaf surfaces are better suited for retaining larger PM fractions compared to wax-dominated surfaces.

A moderate correlation between wax content and Mn retention further underscores the role of waxes in enhancing trace element capture. This relationship may be influenced by the catalytic role of Mn^{2+} ions in promoting sulfur dioxide (SO_2) oxidation on leaf surfaces, as suggested by Burkhardt and Drechsel [57]. The resulting formation of hygroscopic sulfate particles on the leaf surface indicates that wax layers not only retain Mn directly but may also create favorable conditions for its chemical stabilization, thereby enhancing an overall Mn accumulation in wax-rich species.

5. Conclusions

This study indicates that green roofs may play a role in supporting urban air quality improvement through PM retention on plant surfaces. By analyzing the retention of PM and TEs across eight plant species, this study highlights the critical role of species-specific traits, such as wax-rich surfaces and dense foliage, in pollutant capture. Species like *S. spectabile* and *S. japonica* demonstrated exceptional retention capacities, making them ideal candidates for green roof vegetation.

Seasonal variations in PM retention are influenced not only by adaptive plant traits but also by external factors such as rainfall, gardening activities, and leaf shedding. The deviations observed in species like *B. pendula* and *S. spectabile* highlight the need for further research into plant-specific adaptations that contribute to sustained PM retention despite these seasonal challenges. Green roofs populated with both evergreen and deciduous species can complement seasonal dynamics, ensuring consistent mitigation of pollutants. The ability of wax-rich plants to retain fine particulates further strengthens the role of green roofs in addressing urban air quality challenges, particularly in areas with high levels of vehicular and industrial emissions.

Green roofs serve as multifunctional systems, contributing not only to air pollution mitigation but also to urban heat island reduction, stormwater management, and biodiversity support. Future research should explore the long-term performance of diverse plant species under varying environmental conditions, focusing on optimizing species combinations for maximum efficiency. Expanding the implementation of green roofs with selected vegetation can provide substantial environmental and public health benefits, reinforcing their importance as a cornerstone of sustainable urban planning.

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