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ATMOSPHERIC PARTICULATE MATTER DEPOSITION IN HERBACEOUS SPECIES ON A UNIVERSITY CAMPUS IN COLOMBIA

Partículas atmosféricas depositadas en especies herbáceas de un campus universitario en Colombia

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Key words: Leaf area, inhalable particles, morphological traits, ornamental species, urban greening.

ABSTRACT

Atmospheric particulate matter (PM) is one of the most harmful atmospheric pollutants with implications for human health. Plants have been used as an alternative for the removal of atmospheric PM in urban environments. The removal of PM depends on different plant morphological traits, including trichomes and epicuticles evaluated on trees. However, leaf traits for herbaceous plants commonly used in urban gardens have not been fully explored. This study used filtering to quantify the PM deposition and to describe leaf morphological traits throughout optical devices on 20 leaves from six herbaceous species –*Calathea rufibarba, Calathea zebrina, Heliconia psittacorum, Heliconia rostrata, Philodendron* sp. and *Dieffenbachia* sp. Our results suggest that structures such as trichomes –*C. rufibarba*– and epicuticle –*H. psittacorum*– play a role in PM deposition. On the other hand, large leaf size did not influence the deposition of PM per leaf unit area. Therefore, for improving city air quality, our study suggests selecting species with epidermal traits independent of leaf area. This is the first study focusing on ornamental herbaceous species ability for PM deposition in urban environments in Medellín, Colombia.

Palabras clave: área foliar, partículas inhalables, rasgos morfológicos, especies ornamentales, enverdecimiento urbano.

RESUMEN

Las partículas atmosféricas (PA) son uno de los contaminantes atmosféricos más dañinos con implicaciones para la salud humana. Las plantas se han utilizado como una alternativa para la eliminación de PA en entornos urbanos. Este mecanismo de eliminación depende de diferentes rasgos morfológicos, incluidos los tricomas y epicutículas evaluados en los árboles. Sin embargo, las características de las hojas de las plantas herbáceas comúnmente utilizadas en los jardines urbanos no se han explorado completamente. Este estudio cuantifica cómo se depositan las PA por filtración y describe los rasgos morfológicos de las hojas a través de dispositivos ópticos en 20 hojas de seis especies herbáceas –*Calathea rufibarba, Calathea zebrina, Heliconia psittacorum, Heliconia rostrata, Philodendron* sp. y *Dieffenbachia* sp–. Nuestros resultados sugieren que estructuras como los tricomas –*C. rufibarba*– y la epicutícula –*H. psittacorum*– juegan un papel en cómo se depositan las PA. Por otro lado, las hojas de gran tamaño no influyeron en las PA depositadas por unidad de área foliar. Por lo tanto, para mejorar la calidad del aire en las ciudades nuestro estudio sugiere seleccionar especies con rasgos epidermales independientemente del área foliar. Este es el primer estudio que se enfoca en las capacidades de las especies herbáceas ornamentales, utilizadas en ambientes urbanos en Medellín, Colombia, para retener las PA que se depositan en su superficie.

INTRODUCTION

Atmospheric particulate matter (PM) is one of the most harmful atmospheric pollutants for human health, especially in urban areas. Exposure to high concentrations of atmospheric PM has been associated with adverse respiratory and cardiovascular health effects (El-Fadel and Massoud 2000, Voutsa and Samara 2002, Andersson-Sköld et al. 2015, Mukherjee and Agrawal 2017, Wang et al. 2017). The toxicity of atmospheric PM depends on its components and their chemical and physical features (Kelly and Fussell 2012). Coarse inhalable particles –$PM_{2.5\text{-}10}$; diameters between 2.5 - 10 µm– are deposited preferentially in the upper respiratory tract; whereas fine particles –$PM_{2.5}$; diameters below or equal 2.5 µm– travel deeper into the lungs and can reach the alveolar region (Voutsa and Samara 2002). In addition, these noxious effects can be more severe in cities where the air circulation is limited by topography (Rendón et al. 2020). Such is the case of Medellín, Colombia, wherein topographic characteristics limit air circulation, and daily PM exposure peaks can reach concentrations up to 114.5 $\mu g/m^3$ of PM_{10} and 74.8 $\mu g/m^3$ of $PM_{2.5}$ (EAFIT 2020), more than double the admissible values dictated by the World Health Organization (OMS 2006).

Plants play a determining role in the welfare of citizens in highly urbanized areas providing benefits such as temperature and noise regulation, social wellness, and air purification (Nowak and Heisler 2010, Sæbø et al. 2012, Klingberg et al. 2017). Based on a simulation carried out by Fallmann and Renate-Forkel (2016), urban greening can decrease the average concentration of secondary pollutants generated by photochemical reactions, such as ozone by 5–8 %. In addition, direct measurements at urban sites where vegetation is present, especially trees, have shown significant reductions in NOx, ozone, and volatile organic compounds (Bonn et al. 2016, Klingberg et al. 2017). It is also known that, due to the evapotranspiration process and shading effects, vegetation in urban sites reduces surface and local air temperatures. In indoor spaces, vegetation indirectly reduces the energy required to maintain cool temperatures –e.g., via air conditioning. These indoor and outdoor effects reduce the heat-island effect (Nowak and Heisler 2010, Escobedo et al. 2011, Kleerekoper et al. 2012, Gunawardena et al. 2017). Plants also serve as surfaces where atmospheric PM is deposited (Grote et al. 2016). Few studies have focused on PM deposition in plants in Medellin. Duran-Rivera and Alzate-Guarin (2009) evaluated PM deposition on five tree species surfaces –*Syzygium malaccense*, *Psidium guajava, Zygia longifolia, Mangifera indica*, and *Lagerstroemia speciosa*– and found that although all species have the potential to intercept atmospheric PM, *S. malaccense* and *L. speciosa* captured the highest amount of PM. In addition, Buitrago-Posada et al. (2023) evaluated the magnetic particle retention capacities of two *Tillandsia* species and concluded that there were no differences in their retention capacities, and both species were appropriate for biomonitoring.

Plant morphological traits influence the capacity to retain air pollutants (Duran-Rivera and Alzate-Guarin 2009, Janhäll 2015). For instance, PM capture depends on both leaf micromorphology –e.g., trichomes, epicuticles, and stomata (Barima et al. 2016, Zhang et al. 2018)– and plant macromorphological traits –e.g., growth form, leaf shape, and branch density (Chen et al. 2017)–. Micromorphological traits that confer roughness on leaf surfaces, such as trichomes and epicuticular waxes, have been reported to be relevant traits for atmospheric PM deposition through particle trapping or air microcurrent modification (Sæbø et al. 2012, Muhammad et al. 2019, Corada et al. 2020). Stomatal density also modifies leaf roughness, thereby affecting deposition capacity. Likewise, macromorphological traits, such as leaf shape –e.g., lanceolate, acicular, and obovate– and leaf size have been reported as determinant traits for PM deposition (Corada et al. 2020, Sgrigna et al. 2020). Li et al. (2019) indicated that, in addition to the traits mentioned above, leaf longevity also influences PM deposition and evergreen species tend to deposit more atmospheric PM when compared to deciduous ones.

PM retention has been widely evaluated in trees and shrubs, which are conspicuous elements of the urban flora. Only a few studies have focused on the PM deposition capacity of herbaceous species, such as Weber et al. (2014), who showed that these plants play an important role in PM deposition and highlighted the importance of these species in cities. Considering the importance of the herbaceous species as relevant elements of the urban flora and the limited studies regarding plant material retention, we evaluated PM_{10} and $PM_{2.5}$ deposition in six herbaceous species to understand their effectiveness in the removal and deposition of atmospheric PM, and therefore their relevance in urban greening. In addition, we determined which morphological leaf traits and which plant species maximize atmospheric PM retention, which can serve as guidance for plant selection to improve air quality in urban environments. Considering that leaf traits of herbaceous plants have not been fully explored despite the common use of these plants in gardens, the aims of this research were: i) determine the deposition of atmospheric PM in different species of herbaceous plants commonly used in the gardens of a university campus in Medellín, Colombia, and ii) determine which macro- and micromorphology leaf traits enhances the atmospheric PM retention.

METHODS AND MATERIALS

Sampling site

This study was carried out at EAFIT University (**Fig. 1**), located in the south of Medellín, Colombia, which is the second-most populous city in the country. This city is the nucleus of the Aburra valley, an elongated depression with a total length of 60 km. It ranges in width between 3 to 10 km and is surrounded by mountains with elevation between 1300 and 1750 m asl (Hermelin 2007). The main sources of atmospheric PM are industrial activities and high vehicle density. Air quality conditions diminish severely around March-April and October-November, the time of arrival of the intertropical convergence zone (Lopez-Restrepo et al. 2020).

EAFIT University covers an area of 148 339 m^2 (EAFIT 2023) and it is located between two main avenues characterized for heavy traffic. The area has an annual mean temperature of 22 ºC and annual mean rainfall of 1750 mm (Baca-Cabrera 2016).

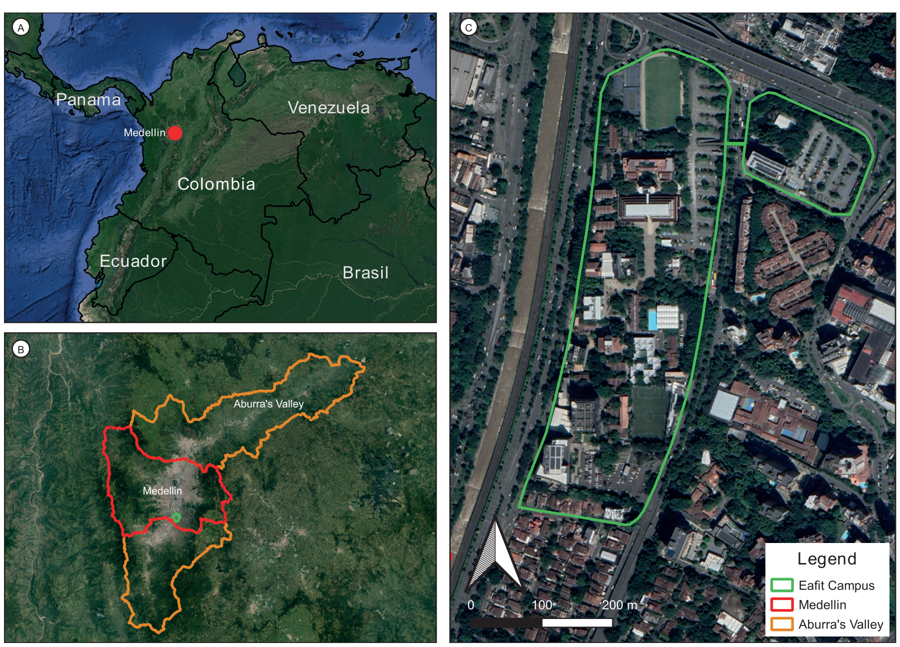

Fig. 1. Sample site. A) Medellín city B) Aburra's Valley C) EAFIT university campus N 6º 11' 57.77'', W -75º 34' 41.59''.

Species selection and collection

A total of 120 leaves were collected from six herbaceous plant species, belonging to three families, namely Marantaceae –*Calathea rufibarba* Fenzl and *Calathea zebrina* (Sims) Lindl, small herbs with bushy growth– Heliconiaceae –*Heliconia psittacorum* L.f., a medium size herb, and *Heliconia rostrata* Ruiz & Pav., a large herb– and Araceae –*Philodendron* sp. Schott and *Dieffenbachia* sp. Schott, both are large herbs. These 120 leaves correspond to 20 leaves collected from each species in two different periods, collecting 10 different individuals per species in each period. To guarantee that all leaves were in similar ontogenetic stages, and thus similar air-exposure time, the third leaf from the apex to the base was collected from each specimen. Furthermore, a photo from each plant was taken to assess the angle formed between the petiole and the main axis, measured using the ImageJ software (Schneider et al. 2012). Immediately after collection, leaves were placed in hermetic plastic bags, such that PM loss was minimized during manipulation.

Samples were collected in two periods, March-April and October-December of 2017 that initially corresponded to rainy and dry seasons, respectively. However, due to climate abnormalities, it was not possible to obtain samples exposed to the dry season. Therefore, from now on, the "rainy and dry period" will be referred to as the "first and second period." In the first period, *C. rufibarba* and *C. zebrina* were collected on March 18th, *Dieffenbachia* sp. and *H. psittacorum* on April 10th, and *H. rostrata* and *Philodendron* sp. on April 11th. The previous day before each of the three collection periods, it rained (Table SI). In the second period, *C. rufibarba* and *C. zebrina* were collected on October 24th, while *H. psittacorum* and *H. rostrata* on November 11th. The previous day before these two dates it rained. *Philodendron* sp. was collected on November 27th with three days of no-rain before sampling. Finally, *Dieffenbachia* sp. was collected on December 12th for which we do not have precipitation data (**Table SI**). The average monthly precipitation is reported in **table SI**. Climatic data were obtained from the Olaya Herrera climatic station, which is the closest station to EAFIT University (IDEAM 2018).

Leaf-wash, PM weight, and trait measure

To determine PM_{10} and $PM_{2.5}$ accumulated in leaves, we adapted the method described in Dzierżanowski et al. (2011). The leaf surface was washed with distilled water and passed through a 10 µm mesh filter and then through a 2.5 µm mesh filter –both filters by Whatman. These filters were previously weighted on a TX323L analytical balance (Shimadzu, resolution 0.001g). After all the water dripped out, the filters were dried in an oven at 23 ºC until a constant weight was obtained. The filter final weight minus the filter weight before the leaves were washed was used to calculate the mass of PM_{10} and $PM_{2.5}$. Leaf fresh mass weight and leaf dry mass weight were measured using an analytical balance –Shimadzu, resolution 0.001g–. To obtain leaf dry mass weight, the leaves were dried in an oven at 60 ºC until a constant weight was obtained. Further, leaf contours were scanned at 400 ppp resolution and analyzed using ImageJ software (Schneider et al. 2012) to calculate leaf area in cm^2. Using fresh leaf area and dry weight, the specific leaf area (SLA) was also calculated (Perez-Harguindeguy et al. 2016). To express PM deposition in $\mu g/m^2$, leaf area was transformed to m^2.

We also determined the presence of trichomes, epicuticles, and epidermal thickness. All of these procedures were performed with cross-section cuts observed under an optical microscope and measured using ImageJ software (Schneider et al. 2012). The adaxial leaf surfaces of each species were photographed under an environmental scanning electron microscope (SEM) –Phenon G2Pro– operating in low-vacuum mode –8 kV–, to determine the relationships between dermal tissue, morphological traits, and PM deposition.

Statistical analysis

To evaluate differences in the deposition of PM10 and PM2.5 among species, we analyzed variance (ANOVA) using species as the main factor. We transformed the data using log10+1 to meet the normality criteria for these variables. Subsequently, we made pairwise comparisons using Tukey criteria. ANOVA was performed only with the data from the first sampling period because species were measured under different dates in the second sampling period due to logistic problems. Therefore, comparisons among species for this period were not possible. However, we performed a t-test to evaluate differences in the PM deposited between each species' first and second sampling periods. With the aim to understand how leaf traits were associated with PM deposition we performed Pearson correlations. A Kruskal Wallis test was performed to find significant differences among species traits. All statistical analyses were performed using the R statistical package 3.6.2 (RCT 2022) using command aov, lsmeans, t.test, and cor.test.

TABLE I. MEAN ± s.d PM_{10} AND $PM_{2.5}$ DEPOSITED BY LEAF AREA FOR SIX HERBACEOUS SPECIES DURING THE FIRST SAMPLE PERIOD (MARCH-APRIL) AND SECOND SAMPLE PERIOD (OCTOBER-DECEMBER).

Sample period	Species	$PM_{2.5}$ (μg/m^2)	PM_{10} (μg/m^2)
1	*Calathea rufibarba*	0.027 ± 0.015 ns	0.037 ± 0.019 **
	Calathea zebrina	0.008 ± 0.005 **	0.018 ± 0.007 **
	Heliconia psittacorum	0.0046 ± 0.004 *	0.040 ± 0.026 *
	Heliconia rostrata	0.0016 ± 0.0015 ns	0.014 ± 0.009 ns
	Philodendron sp.	0.002 ± 0.001 ns	0.025 ± 0.010 ns
	Dieffenbachia sp.	0.0012 ± 0.0013 *	0.007 ± 0.005 ns
2	*Calathea rufibarba*	0.037 ± 0.022	0.168 ± 0.057
	Calathea zebrina	0.036 ± 0.010	0.087 ± 0.017
	Heliconia psittacorum	0.039 ± 0.030	0.158 ± 0.096
	Heliconia rostrata	0.004 ± 0.004	0.018 ± 0.018
	Philodendron sp.	0.003 ± 0.002	0.022 ± 0.007
	Dieffenbachia sp.	0.0003 ± 0.0008$^+$	0.010 ± 0.009

n = 10. Asterisks represent significant differences between sampling periods. **p-values < 0.001, *p-value < 0.05, ns: Nonsignificant. $^+$Among 10 individuals only 1 registered pm deposition, the other individuals reported 0 depositions.

RESULTS

PM deposition in different species

We observed that species showed differences in $PM_{2.5}$ and PM_{10} deposition in both sampled periods (**Table I**). In the first period, there were significant differences between species in PM_{10} and $PM_{2.5}$ deposition –$F = 7.301$, p-value < 0.005 and $F = 19.47$, p-value < 0.005, respectively– (**Fig. 2**). *H. psittacorum, C. rufibarba* and *C. zebrina* showed significantly high deposition of PM_{10} and $PM_{2.5}$, while *Dieffenbachia* sp. and *H. rostrata* showed low deposition of PM_{10}. In the case of $PM_{2.5}$, *H. psittacorum* and *C. zebrina* showed significantly higher deposition than the other species. In the second period, although higher quantities of PM were deposited on the species compared with the first period, those differences were not statistically significant, as shown in **table I**. The variability in the results of both periods shows that deposition of PM in herbaceous plants is a complex phenomenon that requires constant monitoring to make better predictions.

Leaf traits associated with PM deposition

Leaf traits that could be associated with PM deposition significantly differed between species (**Table II**). In terms of leaf area, *C. rufibarba, C. zebrina*, and *H. psittacorum* had small leaf area compared with *H. rostrata, Dieffenbachia* sp., and *Philodendron* sp.

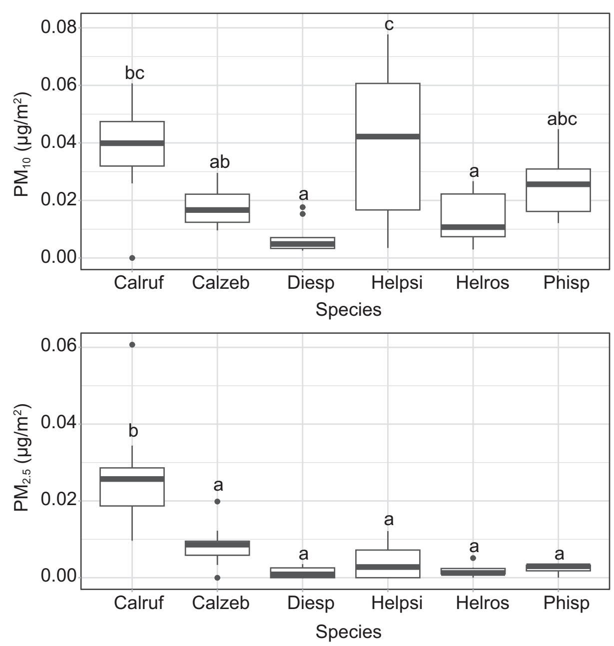

Fig. 2. Results of PM_{10} (top) and $PM_{2.5}$ (bottom) deposited for six herbaceous species in the first sample period. Calruf: *Calathea rufibarba*, Calzeb: *Calathea zebrina*, Helpsi: *Heliconia psittacorum*, Helros: *Heliconia rostrata*, Phisp: *Philodendron* sp. and Diesp: *Dieffenbachia* sp. measured in 2017-2018. Different letters represent significant differences between species. The error bars indicate the 95% confidence interval, the lower and upper ends of the box represent the 25th and 75th percentiles respectively, the line within the box represents the median, and outliers are represented as dots.

TABLE II. MEAN VALUES AND STANDARD DEVIATION FOR LEAF AREA, SPECIFIC LEAF AREA (SLA), LEAF EPIDERMIS THICKNESS, LEAF FRESH WEIGHT, ANGLE AND EPIDERMAL TRAITS AND LEAF SHAPE FOR ALL SIX SPECIES.

Species	Leaf area (cm^2)*	SLA (cm^2/g)*	Leaf thickness (μm)*	Leaf fresh weight (g)*	Angle*	Epidermal traits	Leaf shape
C. rufibarba	124.28 ± 20.49	222.12 ± 25.91	6.0 ± 1.0	2.518 ± 0.523	55.26 ± 14.51	Trichomes and epicuticle	Lanceolate leaves, elongated and slightly wavy at the edges
C. zebrina	284.26 ± 63.85	191.47 ± 28.52	9.0 ± 2.0	7.486 ± 2.176	42.943 ± 21.22	Concave epidermal cells	Oval leaves
H. psittacorum	251.49 ± 116.95	163.40 ± 39.91	8.0 ± 8.0	6.61 ± 2.84	50.363 ± 17.50	Smooth epidermal cells, irregular epicuticle	Leaves elliptic-lanceolate to oblong-lanceolate with pointed apex
H. rostrata	741.65 ± 250.73	162.66 ± 21.23	4.0 ± 1.0	17.326 ± 6.65	57.083 ± 16.54	Smooth epidermal cells, irregular epicuticle	Oval and elongated leaves
Philodendron sp.	947.57 ± 337.98	99.11 ± 18.29	4.0 ± 2.0	49.373 ± 20.99	69.082 ± 21.70	Smooth epidermal cells	Large cordate leaves
Dieffenbachia sp.	583.75 ± 356.79	191.49 ± 29.68	3.0 ± 1.0	24.84 ± 16.86	58.963 ± 25.07	Smooth epidermal cells	Lanceolate oval leaves

Epidermal traits correspond to leaf surface morphological traits (n = 20). Asterisks represent significant differences among species leaf traits. **p-value < 0.001, *p-value < 0.05.

which had big leaf areas. As expected, lowest fresh weight corresponds with species that had the smallest leaf area. SLA was significantly larger for *C. rufibarba, Dieffenbachia* sp. and *C. zebrina* compared with the other species. Values for leaf epidermis thickness were significantly high for *C. rufibarba, C. zebrina*, and *H. psittacorum*. The angles between leaf petioles and the main axis did not show significant differences among species. Besides, we observed that several species had special features on the leaf surface such as trichomes in *C. rufibarba*, epicuticles in *H. psittacorum, H. rostrata* and *C. rufibarba*, and concave epidermal cells in *C. zebrina* (**Table II** and **Fig. 3**).

Not all traits were correlated with PM deposition. Leaf area –Pearson coefficient: –0.46 and –0.48 to PM_{10} and PM_{25} respectively, **table III**– and SLA –Pearson coefficient: -0.20 and -0.30 to PM_{10} and PM_{25} respectively, **table III**– correlated with PM deposition, whereas leaf epidermis thickness, leaf fresh weight, and leaf angle did not correlate with PM (**Table III**). We found that species with large leaf areas such as *H. rostrata* and *Dieffenbachia* sp., did not retain high amounts of $PM_{2.5}$ and PM_{10}, suggesting that large leaf area is not an important trait in PM deposition (**Fig. 4**). Conversely, we observed that species with small leaf areas such as *C. rufibarba, H. psittacorum* and *C. zebrina* retain higher amounts of $PM_{2.5}$ and PM_{10} (**Fig. 4**). We also found a weak but significant –p-value = 0.001– positive correlation between the deposition of $PM_{2.5}$ and SLA.

DISCUSSION

Leaf traits associated with PM deposition

According to our results, there were three species that had high amounts of PM deposition. *H. psittacorum* was one of the species that showed the highest PM_{10} deposition in the first sample period –PM_{10} = 0.040 ± 0.026 μg/m^2 – and in the second sampling period –PM_{10} = 0.158 ± 0.096 μg/m^2, $PM_{2.5}$ = 0.039 ± 0.030 μg/m^2. – (**Table I** and **Fig. 2**). It was followed by *C. rufibarba* in the first and second sample period –PM_{10} = 0.037 ± 0.019 μg/m^2, $PM_{2.5}$ = 0.027 ± 0.015 μg/m^2 and PM_{10}, = 0.168 ± 0.057 and $PM_{2.5}$= 0.037 ± 0.022 μg/m^2, respectively. Finally, *C. zebrina* also deposited high PM_{10} and $PM_{2.5}$ concentrations –PM_{10} = 0.018 ± 0.007 μg/m^2 and $PM_{2.5}$= 0.008 ± 0.005 μg/m^2– during the first period (**Table I**). Interestingly, *H. psittacorum, C. rufibarba,* and *C. zebrina* presented epidermal traits such as epicuticle deposition, trichomes, and concave epidermal cells

Fig. 3. Scanning electron microscope micrographs of leaf epidermal surfaces of A) *Calathea zebrina*: arrangement of epidermal concave cells. B) *Calathea rufibarba*: trichomes and epicuticle. C) *Heliconia psittacorum:* smooth epidermal cells with irregular epicuticle deposition.

TABLE III. PEARSON CORRELATION COEFFICIENT BETWEEN PM_{10} AND $PM_{2.5}$ AND MEASURED LEAF TRAITS WITH SIGNIFICANCE LEVEL.

Leaf traits	PM_{10}	$PM_{2.5}$
Leaf area (cm^2)	–0.46**	–0.48**
SLA (cm^2/g)	0.25*	0.30**
Leaf epidermis thickness (μm)	0.15	0.17
Fresh weight (g)	–0.35	–0.39
Angle	–0.08	–0.12

**p-values < 0.001 *p-value < 0.05.

(**Fig. 3**). These differences compared with the other three species –*Heliconia rostrata, Philodendron* sp., *Dieffenbachia* sp.– suggest that leaf surfaces vary among herbaceous species and that these variations are important in their role in the PM deposition.

We found that some epidermal traits, such as epicuticle deposition, trichomes, and concave epidermal cells, were associated with PM deposition. The above is supported by the study of Sæbø et al. (2012), which showed that the amount of epicuticle in the leaves is directly proportional to the capacity to accumulate PM. El-Khatib et al. (2011) also found that species having wax rings retain the highest amounts of PM10 among the species studied. However, authors such as Dzierżanowski et al. (2011) state that the potential for particle accumulation lies in the chemical composition of the epicuticle rather than the amount of the epicuticle and the structure of the epicuticular layer. Additional studies are required to determine whether PM accumulation in *H. psittacorum* and *C. rufibarba* is due to the amount of epicuticle, chemical composition, and arrangement because this was beyond our scope.

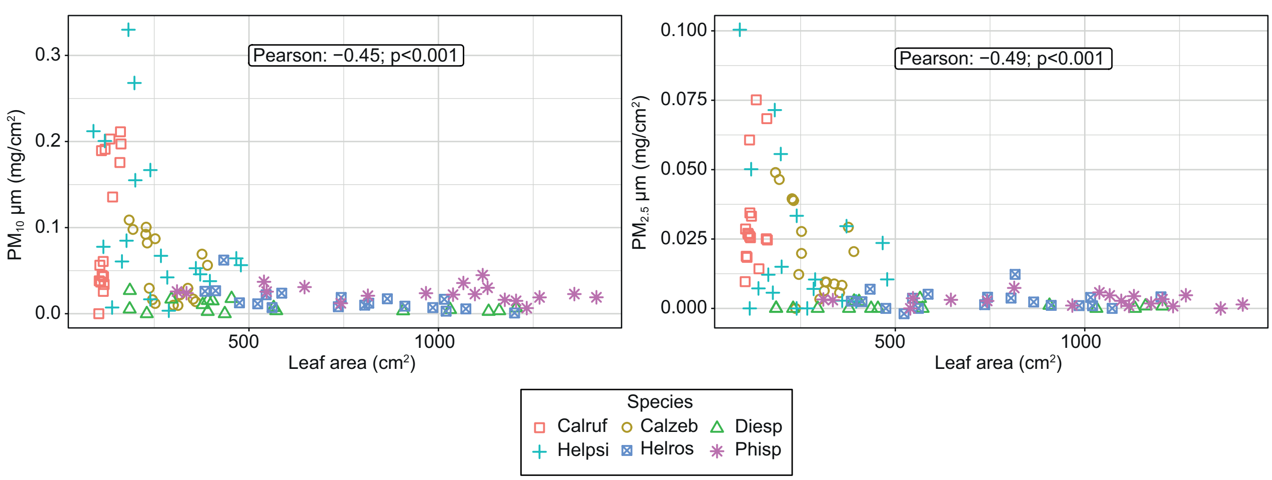

Fig. 4. Correlation between PM_{10} (left) and $PM_{2.5}$ (right) and leaf areas. Calruf: *Calathea rufibarba*, Calzeb: *Calathea zebrina*, Helpsi: *Heliconia psittacorum*, Helros: *Heliconia rostrata*, Phisp: *Philodendron* sp. and Diesp: *Dieffenbachia* sp.

Our results suggest that trichomes are an important trait that play a role in the deposition of PM. Findings obtained by Kim et al. (2020), who assessed the effects of *Tillandsia usneoides* trichomes on PM deposition, found differences in the performance of the species PM_{10} deposition when trichomes were removed compared to the species with the trichomes present, the latter depositing higher amounts of PM_{10}. Besides, Kwak et al. (2019) support the relevance of trichomes to PM deposition; they demonstrated that leaf surfaces with trichomes had enhanced PM deposition compared to smooth leaf surfaces. Additionally, Shao et al. (2019) showed that PM deposition was improved when trichomes were present and associated with other leaf microstructures, such as epicuticle, presence of small chambers, stomatal and leaf roughness.

Leaf shape seems to be an important trait related with PM deposition. In our study, the three species that retained the most PM had lanceolate- or ovate-shaped leaves (**Table I** and **Table II**). Corada et al. (2020) reported that lanceolate and ovate leaves facilitate PM deposition. In addition, Leonard et al. (2016) showed that species with lanceolate-shaped leaves can accumulate more PM than obovate- and elliptic-shaped leaves, which supports our results. This was also shown by Weerakkody et al. (2018a), who studied PM captured by green wall plants and concluded that plants with needle-shaped leaves and small leaf areas accumulated more PM.

Finally, in our study, species with small leaf areas tend to deposit higher amounts of PM compared to species with large leaf areas –*Dieffenbachia sp., H. rostrata,* and *Philodendron* sp.–. This can be verified in our negative correlation between leaf areas and atmospheric PM deposition (**Table III** and **Fig. 4**). The above was also found by Weerakkody et al. (2018b), who showed a significant negative relationship between leaf size and PM deposition; the smaller the leaf size, the greater the PM deposition. Weerakkody et al. (2018b) explained this by the edge effect generated by the larger leaf perimeter/surface area ratio of small leaves. Moreover, smaller leaves have a thinner resistance boundary layer, allowing more contact between air pollutants and the leaf surface (Murray 1979, Chen et al. 2017). This could explain the low PM deposition of *H. rostrata*, which presented an irregular epicuticle on the leaf surface but had the second-largest leaf area among our species.

PM deposition capacities of ornamental herbaceous plants

Urban greening is an important strategy for the regulation of air pollutants. Herbaceous plants, as shown in this study, promote air pollutant deposition, and therefore offer the possibility of air quality improvement. This is because they can be placed very close to motor vehicle traffic, maximizing the capture of air pollution (Weber et al. 2014, Janhäll 2015). In addition, herbaceous plants can complement trees by depositing resuspended or washed-off particles from their canopy (Weber et al. 2014).

Low vegetation can be easily adapted to complex urban architectural designs by expanding the possibilities of urban design to vertical structures and green walls. The integration of high and low vegetation according to urban street canyons, traffic density, wind flow, and other local meteorological conditions could be an important strategy for air pollution mitigation policies. Nevertheless, to encourage the use of herbaceous vegetation for air quality improvement, more research is needed, such as those related to allergenic and biogenic volatile organic compounds.

In our study, the three herbaceous species that most retained PM –*H. psittacorum, C. rufibarba*, and *C. zebrina*– presented small leaves areas, with lanceolate or oval shapes and micromorphological epidermal traits like trichomes and epicuticle deposition compared to the other species. These characteristics influenced PM depositions. These species are potentially appropriate to be used in gardens, thus improving the air quality in urban environments. To date, this is the first study to focus on the PM deposition capacity of ornamental herbaceous species used in urban environments in Colombia.

CONCLUSIONS

Our results suggest that *Heliconia psittacorum, Calathea rufibarba*, and *Calathea zebrina* are suitable herbaceous plants to improve air quality, due to their high PM deposition capacity among the surveyed plants. Furthermore, this study suggests an apparent association between epidermal leaf traits, such as epicuticle depositions and the presence of trichomes, with the deposition of PM_{10} and $PM_{2.5}$, while large leaf size did not influence the deposition of PM per leaf unit area. These results provide an opportunity to look for ornamental species with traits to be selected in urbanistic projects.

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SUPPLEMENTARY MATERIAL

TABLE SI. SAMPLING DATE, LAST RAINY DAY BEFORE SAMPLING AND MONTHLY AVERAGE PRECIPITATION.

Sample period	Species	Sampling day	Last rainy day before sampling	Monthly average precipitation
1	*Calathea rufibarba*	March 18th	March 17th	25.5 mm
	Calathea zebrina	March 18th	March 17th	
	Heliconia psittacorum	April 10th	April 9th	27.0 mm
	Dieffenbachia sp.	April 10th	April 9th	
	Heliconia rostrata	April 11th	April 10th	
	Philodendron sp.	April 11th	April 10th	
2	*Calathea rufibarba*	October 24th	October 23rd	40.2 mm
	Calathea zebrina	October 24th	October 23rd	
	Heliconia psittacorum	November 11th	November 10th	25.2 mm
	Heliconia rostrata	November 11th	November 10th	
	Philodendron sp.	November 27th	November 24th	
	Dieffenbachia sp.	December 12th	n.d.*	n.d.*

n.d. * refers to no data.