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Phytobarriers reduce the dispersion of particulate matter associated with potentially toxic elements

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Abstract

Particulate matter (PM) poses risks to human health and the environment because wind can disperse it and carry it far from its emission source. This study evaluated the capacity of plant species to retain PM associated with potentially toxic elements (PTEs). Twenty-six sampling sites were selected along the Peñon–Texcoco and Anillo Periférico Roads to collect soil and leaf samples. In soil, pH, electrical conductivity (EC), and pseudototal PTEs concentrations after aqua regia digestion. In plant tissues, PTEs were quantified after sulfuric and perchloric acid digestion. The phytobarrier index (PI) was calculated based on PTE concentrations in washed and unwashed leaves. Species with the highest PI values were characterized using environmental scanning electron microscopy, and particles were analyzed using ImageJ software. The soil had slightly alkaline pH, with EC values ranging from 0.58 to 29.51 dS m^{-1}. The mean concentrations of Pb, Cd, Zn, and Mn were 27.8, 1.3, 140, and 278 mg kg^{-1}, respectively. PTE concentrations in plant tissue were consistently higher in unwashed leaves than in washed leaves, indicating atmospheric PM deposition. Micrographs confirmed the presence of particles, predominantly smaller than 10 µm. *Tamarix* sp. and *Eucalyptus* sp. showed the highest particle retention; however, site conditions favor *Tamarix* sp. establishment. The results indicate that vegetation in is a viable alternative for mitigating PM dispersion associated with PTEs.

Keywords: Airborne particulates; foliar retention; heavy metals; air pollution mitigation

Introduction

Air pollution is one of the most significant environmental challenges worldwide because chemical substances and particles accumulate, degrading air quality. Particulate matter (PM) is one of the most dangerous air pollutants for human health and the environment (Agibayeva et al., 2022). It is a complex mixture with solid particles, liquid droplets, and substances of varying size and chemical compositions (Kim et al., 2015). The morphological characteristics (size and shape) and chemical composition of PM determine its potential risk to health and ecosystems (Ali et al., 2019). The PM composition depends largely on its origin, which can be natural or anthropogenic. The time of year, prevailing winds, and geographic location influence its dispersion (Guevara,

2016). Natural sources of PM include soil dust, primarily from arid and sparsely vegetated areas (Guevara-Macías et al., 2023). Among anthropogenic sources, road dust is a major contributor to atmospheric PM levels (Ali et al., 2019). This type of PM can act as a carrier of potentially toxic elements (PTEs), such as lead (Pb), cadmium (Cd), zinc (Zn), and manganese (Mn) (Guevara, 2016), facilitating their transport and subsequent deposition on soil, vegetation, roads, houses, etc.

High PM levels are associated with respiratory and cardiovascular diseases in humans (Kim et al., 2015). In this context, PM exposure is estimated to cause about 4.3 million deaths annually worldwide (Izzotti et al., 2022). Beyond its health implications, PM can disrupt ecosystem stability and shifts meteorological and climate patterns (Agibayeva et al., 2022). Consequently, various countries have established maximum permissible limits for PM mass concentrations in the air. Given this problem, it is necessary to find alternatives that help mitigate PM dispersion, regardless of its source. Plants represent one such alternative, as they reduce soil erosion and also act as sinks by capturing and retaining atmospheric particles (López-Sánchez et al., 2015; González-Chávez et al., 2023; Chauhan et al., 2025). PM capture efficiency depends on foliage complexity and the leaf morphology of each plant species. This suggests that not all plants have the same capacity to retain PM and act as phytobarriers—physical obstacles that prevent particle dispersion (López-Sánchez et al., 2015).

In this context, the study was conducted at the periphery of the former Lake Texcoco Protected Natural Area (PNA), a lacustrine-origin zone. Alkaline soils and high electrical conductivity (EC) characterize this site. It also has sparse vegetation cover and a temperate, semiarid climate. These conditions favor the resuspension and dispersion of PM. Furthermore, nearby highways with heavy vehicular traffic may promote the association of PTEs with PM. Additionally, the area is located adjacent to densely populated zones, thereby increasing the likelihood of human exposure to PM. These characteristics make the area a relevant setting for evaluating vegetation´s role as a phytobarrier under restrictive edaphic conditions and environmental pressure. Therefore, this study aimed to evaluate the capacity of different plant species to retain PM associated with PTEs.

Materials and methods

Study site and sample collection

This research was conducted in the municipality of Texcoco, State of Mexico, located between parallels 19° 24′ and 19° 33′ N latitude and meridians 98° 38′ and 99° 02′ W longitude, with an elevation ranging from 2,200 to 4,200 m above sea level (Instituto Nacional de Estadística y Geografía [INEGI], 2010). Twenty-six sampling sites were selected along the transect of the Peñón–Texcoco and Anillo Periférico highways (Figure 1). These roads border Mexico City and the municipality Nezahualcóyotl and run along the periphery of former Lake Texcoco PNA. Soil and leaf samples were collected from established plants at each site (Table S1). Soil samples were placed in polyethylene bags, whereas plant samples were collected in paper bags. All samples were labeled with the site number and its geographic coordinates. For plant samples, the scientific names of the species were also included.



Fig. 1 Location of sampling sites along the transect of the Peñón–Texcoco and Anillo Periférico highways in the former Lake Texcoco, Mexico

Sample analysis

In the laboratory, soil samples were shade-dried and sieved through a 2-mm mesh. pH and EC were determined according to Rowell (1994). Ten grams of soil were weighed into 50 mL Falcon tubes and 20 mL of distilled water was added. The mixture was shaken for 30 min, after which the pH was determined using an Orion 701A potentiometer. In the same samples, 24 h later, EC was determined using a Conductronic model CL 35 conductivity bridge. The pseudototal PTE concentrations were determined after aqua regia digestion of soil samples following the International Organization for Standardization (ISO, 1995). One gram of soil was weighed into digestion tubes and 6 mL of a bi-acid mixture of HCl and HNO_3 at a 3:1 (v/v) ratio was added. The samples were ensured to be completely wet and placed in a digestion oven at 120 °C for 6 h. After cooling, the samples were brought to 25 mL with deionized water and filtered. PTE quantification was performed using a PerkinElmer model 3110 atomic absorption spectrophotometer (Oliveira et al., 2010).

Plant samples were processed into two groups: washed and unwashed. The washing procedure was performed according to the methodology described by Sánchez-López et al. (2015). For PTE determination, wet digestion was carried out according to Jones and Case (1990). Plant material (0.25 g) was weighed into digestion tubes, to which 1 mL of 30% hydrogen peroxide and 4 mL of an H_2SO_4–$HClO_4$ bi-acid mixture at a 4:1 (v/v) ratio were added. The tubes were then placed in a digestion oven at 240 °C until the samples became transparent. Finally, the samples were brought to 25 mL and filtered using Whatman No. 42 filter paper. Zn and Mn were quantified using a PerkinElmer model 3110 atomic absorption spectrometer. Pb and Cd were determined using an Agilent 725-ES inductively coupled plasma optical emission spectrometer (ICP-OES). No Cd concentrations were detected in the samples; the ICP-OES detection limit was 10 ppb.

The phytobarrier index (PI) was determined according to the equation reported by González Chávez et al. (2023)

$$PI = \frac{UC - WC}{WC} \times 100$$

Where: UC is the PTE concentration in unwashed samples, and WC is the PTE concentration in washed samples.

For morphological analysis and elemental characterization, six plant species were selected based on the highest PI, representing the greatest PTE retention capacity. Washed and unwashed leaves were analyzed for each species. In species with well-defined dorsiventral leaves, the adaxial and abaxial surfaces were analyzed separately. In species with unifacial leaves (*Tamarix* sp. and *Casuarina* sp.), the analysis was performed on the observable surface. For this purpose, three 1 cm^2 segments were used per species, yielding 36 samples. The analysis was conducted using an environmental scanning electron microscope (Carl Zeiss, Evo LS10) operated at 20 kilovolts (kV), coupled with an energy-dispersive X-ray spectrometer (Bruker, model: QUANTAX 200, ESPRIT 1.9 software). Samples were mounted on an aluminum stub using conductive carbon tape. One micrograph and its corresponding X-ray spectrum (EDS) were acquired per sample, both at 150x magnification. The size and number of particles present in the micrographs were estimated using ImageJ software (V. 1.6r for Windows). To do this, three squares of known area were randomly selected within each micrograph to count particles and estimate their diameter. Subsequently, the average number of particles per unit area was calculated, and the number of particles per square centimeter of leaf surface was estimated using a proportional relationship.

Statistical analysis

Of the 26 samples, the nine most common species were collected. However, only three had at least three independent replicates; therefore, statistical analysis was performed exclusively on these species. Because the analyzed variables did not meet the assumptions of normality and homogeneity of variance, the non-parametric Kruskal-Wallis test was used. For significant differences, Dunn's post-hoc test with Holm's adjustment was applied for multiple comparisons. The Mann-Whitney U test was used to compare washed and unwashed plants. Statistical analyses were performed using R statistical software version 4.1.1 for Windows. The remaining species were reported descriptively because of insufficient number of replicates.

Results and discussion

Soil analysis

The average soil pH at the periphery of the former Lake Texcoco PNA is moderately alkaline (pH > 7.3), according to the Official Mexican Standard NOM-021-SEMARNAT-2000. Sites 12, 17, 18, and 20 had a neutral pH; however, the values were close to 7 (Figure 2). Overall, 84% of the sites had a moderately alkaline pH due to lacustrine sediments accumulated in the former Lake Texcoco. These sediments contain high concentrations of carbonates and bicarbonates (Valenzuela-Encinas, 2009). The hydrolysis of these compounds produced OH^- ions, which generate alkalinity. The average pH across the 26 sites was 7.7, lower than 8.3

reported by Barragán-Maravilla et al. (2025) for the former Lake Texcoco area, which included sites with and without vegetation cover. The lower pH at the present study sites can be attributed to vegetation. According to Ortiz-Torres et al. (2023), soils in the former lake with vegetation cover have a lower pH than bare soils because organic acids produced by organic matter decomposition lower pH.

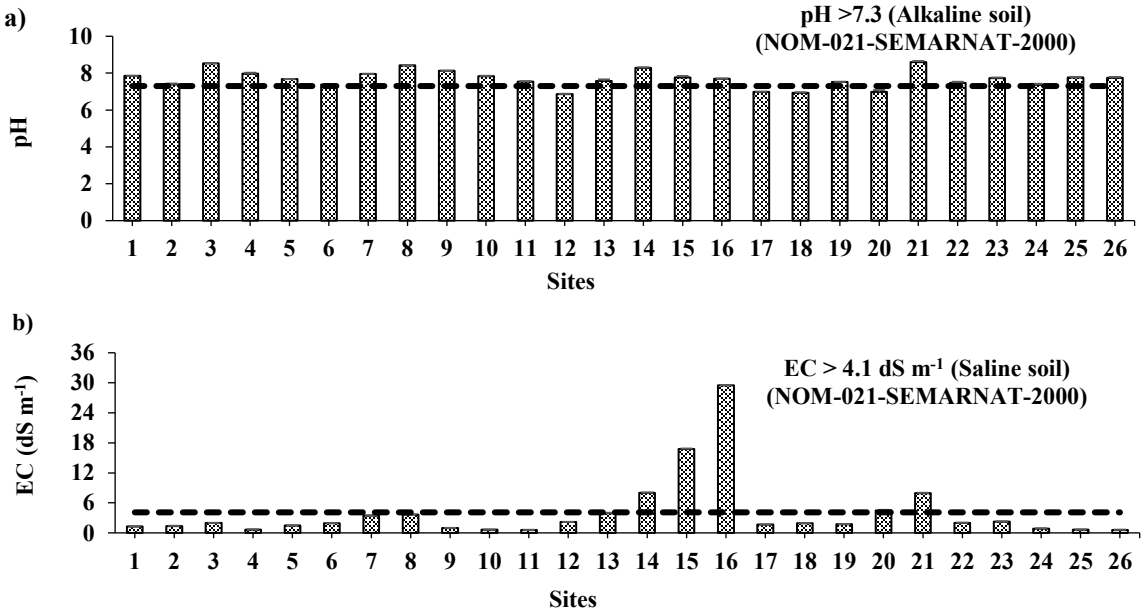


Fig. 2 Soil pH and electrical conductivity along the transect in the former Lake Texcoco, Mexico. The dashed lines indicate the thresholds for a) alkaline soil (pH > 7.3) and b) saline soil (EC > 4.1 dS m^{-1}) according to the Official Mexican Standard NOM-021-SEMARNAT-2000

EC at varied across the 26 sites, ranging from 0.58 to 29.51 dS m^{-1}. This EC wide range reflects processes such as evaporation, drainage, microtopographic variation, and vegetation cover (Zhang et al., 2023). These conditions in the study area can create zones with varying salinity, from non-saline to highly saline soils. Similarly, Valenzuela-Encinas et al. (2009) reported a wide range of EC in the soils of the former Lake Texcoco (0.69 to 159 dS m^{-1}).

In addition to alkalinity and salinity, PTEs are another limiting factor for vegetation establishment. The average concentrations of Pb, Cd, Zn, and Mn across the 26 sites were 27.8, 1.3, 140, and 278 mg kg^{-1}, respectively (Figure 3). Because sample collection sites lack an official land-use classification, the Cd, Pb, and Zn concentrations were compared with national and Canadian standards for residential land use. For Mn,

background values reported by Kabata-Pendias (2010) were used, as this element is not included in national or international standards.

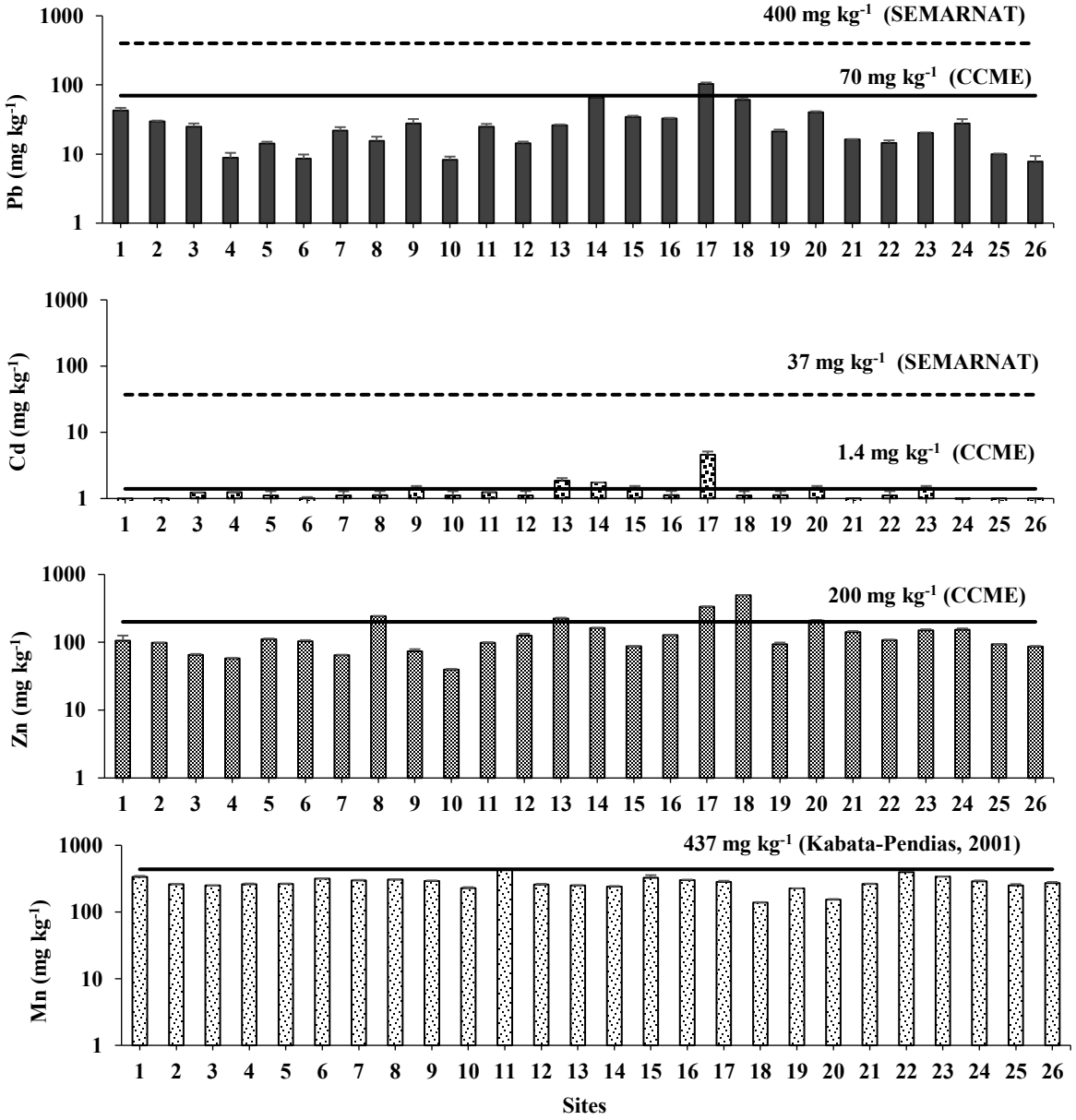


Fig. 3 Concentrations of potentially toxic elements (PTEs) in soil samples along the transect in the former Lake Texcoco, Mexico. Solid horizontal lines represent reference thresholds established by the Canadian Council of Ministers of the Environment (CCME) and world soil background values (Kabata-Pendias 2001), whereas dashed horizontal lines indicate thresholds according to Official Mexican Standard NOM-147-SEMARNAT/SSA1-2004

Based on national standards, the soils show no contamination problems. However, interpret these results with caution, as these standards are considerably lax. Compared with international standards, some sites exceeded the maximum limits. For Pb, site 17 had a concentration 1.5 times higher than the maximum permissible value

(70 mg kg^{-1}). For Cd, sites 13, 14, and 17 recorded concentrations at least 1.2 times higher than 1.4 mg kg^{-1} value established by the Canadian Council of Ministers of the Environment (CCME, 2007). For Zn, sites 8, 17, 18, and 20 exceeded regulatory limits (greater than 200 mg kg^{-1}; CCME, 2007). Although concentrations at most sites did not exceed the limits established by Canadian standards, the average values approached the maximum permissible levels. Pb reached 40% of the limit, Cd 93%, and Zn 70%.

The 26 sites were located along heavily trafficked roads; therefore, the high concentrations of these elements may be linked to this activity. The wear and tear of automotive parts, such as tires and brakes, is a source of particles associated with Pb, Cd, and Zn (Aguilera et al., 2021). Finally, Mn concentrations were close to the background value (437 mg kg^{-1}) reported by Kabata-Pendias (2010). Taken together, alkalinity, salinity, and the presence of PTEs represent limiting edaphic conditions for plant establishment. Likewise, they constitute a source of particulate matter that can accumulate, be suspended, and disperse across the studied sites. Consequently, the vegetation at the periphery of the former Lake Texcoco PNA—already adapted to site conditions— represents a viable alternative for use as phytobarriers.

PTE analysis in plant tissue

In the statistical comparison of washed and unwashed leaves, only *Tamarix* sp. showed significantly higher average Pb and Zn Concentrations in unwashed leaves ($\alpha = 0.05$; Table 1). For Pb, average concentrations were 8.8 and 13.7 mg kg^{-1} in washed and unwashed leaves, respectively; for Zn, they were 56.5 and 67.1 mg kg^{-1}, respectively.

No significant differences were detected in the other plant species when evaluating the effect of washing on PTE concentrations. In species with two or fewer replicates, unwashed leaves showed higher concentrations of Pb, Zn, and Mn. For example, *B. scoparia*, *Eucalyptus* sp., *N. glauca*, and *S. molle* showed up to twice the Pb concentration in unwashed leaves compared to washed ones. For Zn, these same species showed concentrations at least 1.3 times higher in unwashed leaves. Regarding Mn, *R. communis* had a 1.4-fold higher concentration in unwashed leaves. These data suggest surface retention of PTEs on leaves because, according to González-Chávez et al. (2023), plants accumulate PTE-associated dust on unwashed leaves, which acts as a physical barrier that reduces PTE dispersion.

The lack of statistical differences in some plant species may reflect variability in dust retention among leaves and the fact that the quantified PTEs are present not only in PM but also as structural components of plant tissues. Sánchez-López et al. (2015) reported similar results, observing higher average PTE concentrations in unwashed leaves, although they found no statistical differences across all plant species. Likewise, Barrios-Arlanzón et al. (2019) reported that Cd concentration in *Dalea bicolor* leaves decreased after washing, but showed no statistical difference compared with unwashed leaves.

Table 1 Concentrations of PTEs in washed and unwashed plant tissues from the periphery of the former Texcoco Lake.

Scientific name	Washed Pb	Unwashed Pb	Washed Zn	Unwashed Zn	Washed Mn	Unwashed Mn
	---------- mg kg^{-1} ----------					
Dichondra argentea	10.3 ± 6.5 a	17.7 ± 6.6 A	59.8 ± 24.6 ab	77.7 ± 44.0 AB	42.2 ± 2.4 a	53.8 ± 8.7 A
Casuarina sp.	7.7 ± 4.1 a	17.0 ± 5.2 A	39.6 ± 3.6 b	42.8 ± 3.3 B	35.6 ± 9.8 ab	40.2 ± 10.7 AB
Tamarix sp.	8.8 ± 5.3 a	13.7 ± 6.2 A *	56.5 ± 9.9 a	67.1 ± 12.3 A *	25.6 ± 7.3 b	36.8 ± 19.8 B
Barkleyanthus salicifolius	16.5	27.4	54.7	56.2	14.9	17.9
Bassia scoparia	8.5	19.4	60.3	78.7	26.5	31.7
Eucalyptus sp.	7.9 ± 0.6	14.8 ± 3.3	39.9 ± 7.6	56.7 ± 22.3	33.7 ± 9.6	42.3 ± 7.1
Nicotiana glauca	10.7 ± 11.2	22.3 ± 15.9	81.6 ± 27.0	103.9 ± 46.7	31.5 ± 4.5	38.1 ± 4.9
Ricinus communis	10.1	13.1	43.4	44.4	59.6	85.5
Schinus molle	10.8	25.8	39.4	41.8	20.9	24.9
			Reference values^{+}			
Pb (10 mg kg^{-1})	Zn (150 mg kg^{-1})	Mn (400 mg kg^{-1})				

Lowercase letters indicate differences in PTE concentration among washed plants, while uppercase letters indicate differences among unwashed plants, based on the Kruskal–Wallis test. Asterisks denote significant differences in PTE concentration between washed and unwashed plants according to the Wilcoxon test (α = 0.05). For *Eucalyptus* sp. and *Nicotiana glauca*, statistical analyses were not performed because of the limited number of replicates (n = 2). For *Barkleyanthus salicifolius*, *Bassia scoparia*, *Ricinus communis*, and *Schinus molle*, standard deviation is not reported because only a single sample was available. $^{+}$ Indicates the maximum value found in plants according to Kabata-Pendias (2001).

However, when comparing Pb concentrations among the analyzed plant species, no statistically significant differences were observed. *Tamarix* sp. had higher foliar Zn concentrations than *Casuarina* sp. ($\alpha = 0.05$) in both washed and unwashed leaves. *D. argentea* showed higher Mn concentrations than *Tamarix sp*. in both cases (washed and unwashed). Descriptively, some species had concentrations higher than the average of the other evaluated species. *B. salicifolius* leaves showed the highest Pb concentration in both washed and unwashed leaves, with values of 16.5 and 27.4 mg kg^{-1}, respectively. These values were 1.7 and 1.4 times higher than the average Pb concentration recorded in the other five evaluated species (9.6 and 19.1 mg kg^{-1}, respectively). *N. glauca* exhibited the highest Zn concentration among all plant species, with 81.6 and 103.9 mg kg^{-1} in washed and unwashed leaves, respectively. This exceeded the average recorded in the other five species (47.5 and 55.6 mg kg^{-1}) by 1.7 and 2.1 times. Likewise, the highest Mn concentrations were recorded in *R. communis*, with values of 59.6 and 85.5 mg kg^{-1} in washed and unwashed leaves, respectively. These values were 2.3 and 2.7 times higher than the averages for the other species (25.5 and 30.9 mg kg^{-1}, respectively). These results suggest that PTE retention or accumulation capacity may differ and depend on leaf morphology and physiology, which vary by plant taxon (Sánchez-López et al., 2015; Muthusaravanan et al., 2018). Similarly, González-Chávez et al. (2023) reported species-level variation. For example, these authors observed 2.7- and 5.8-fold higher concentrations of Cd and Pb, respectively, in unwashed leaves of *Zaluzania triloba* and *Plantago lanceolata* than in other species they evaluated. This supports the premise that PTE accumulation depends on species-specific attributes and PM composition.

No regulations set maximum permissible values for PTEs derived from PM in plant species; however, normal concentrations of different elements in plant tissue can serve as a reference (Kabata-Pendias, 2010). For Pb, Zn, and Mn, this author established concentration ranges of 5-10, 27-150, and 30-300 mg kg^{-1}, respectively. In the present study, no plant species (washed or unwashed) exhibited Mn or Zn concentrations exceeding these ranges. In contrast, the average Pb concentration in the leaves of *D. argentea*, *B. salicifolius*, *N. glauca*, *R. communis*, and *S. molle* was 11.7 mg kg^{-1} in washed leaves and 21.3 mg kg^{-1} in unwashed ones. These values were 1.2 times and 2.1 times higher, respectively, than the maximum normal concentration reported by Kabata-Pendias (2020). This behavior may be attributed to these species´capacity to accumulate Pb. Barba-Brioso et al. (2023) reported Pb concentrations of up to 11.5 mg kg^{-1} in *N. glauca* leaves collected from an area influenced by agricultural and industrial activities. Doganlar et al. (2012) reported Pb concentrations of up to 17.9 mg kg^{-1} in *S. molle* leaves exposed to urban pollution conditions. Similarly, *Senecio salignus*, now recognized as *B. salicifolius*, showed Pb concentrations up to 1000 mg kg^{-1} in plant tissues (Cortés-Jiménez et al., 2013). Furthermore, González-Chávez et al. (2023) found that even in washed *D. argentea* leaves, Pb concentrations can exceed 60 mg kg^{-1}. The presence of Pb in these species suggests they may contribute not only to PM retention on the leaf surface but also to incorporating PTEs into their tissues, potentially reducing the risk of Pb dispersion in the environment.

Phytobarrier index

The phytobarrier index showed no significant differences among the species evaluated statistically, nor a consistent trend in the descriptive analysis (Figure 4).

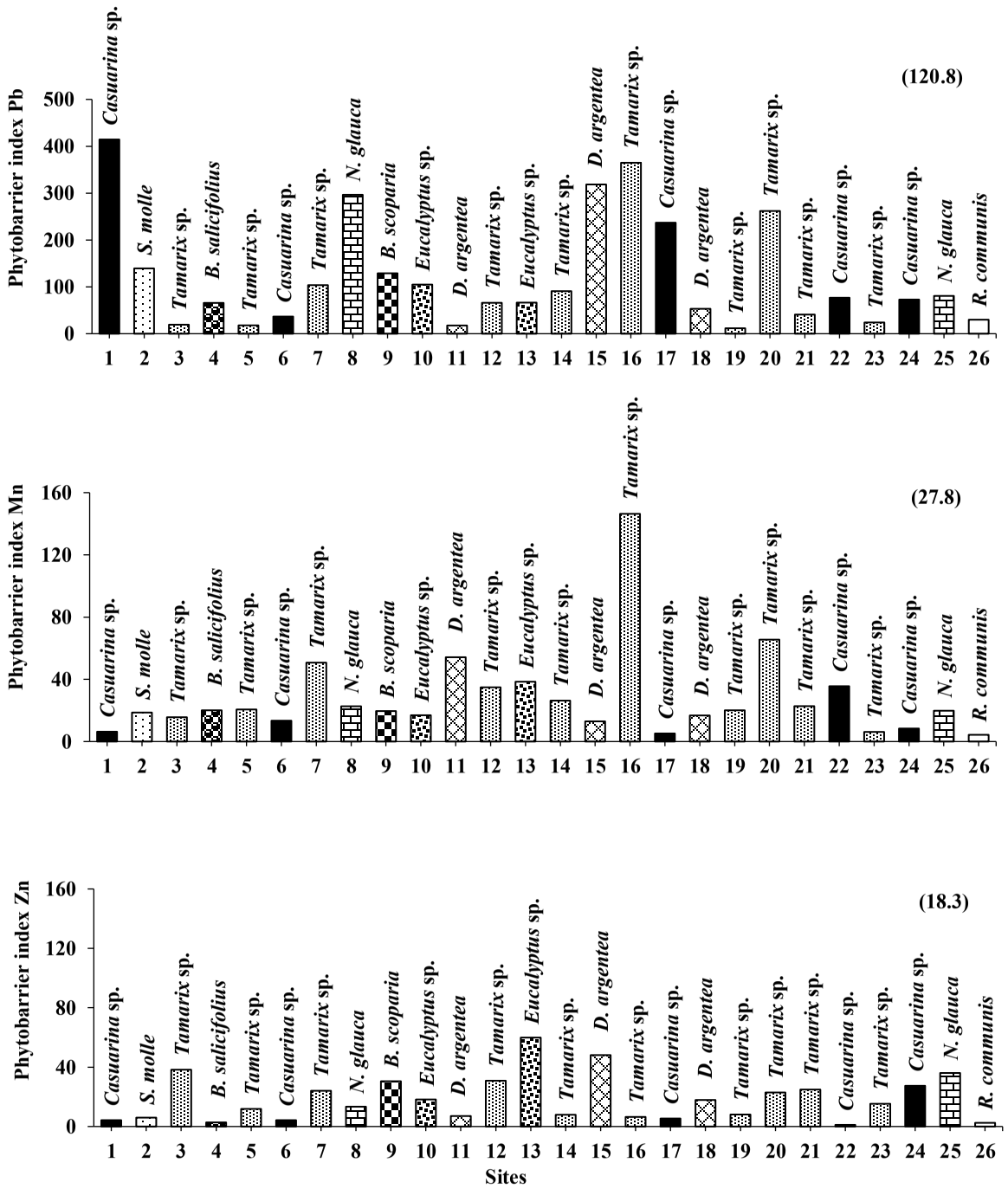


Fig. 4 Phytobarrier index of Pb, Mn, and Zn for plant species collected across sampling sites in the former Lake Texcoco, Mexico. Values in parentheses indicate the mean phytobarrier index for each element. Species abbreviations: *S. molle = Schinus molle*; *B. salicifolius = Barkleyanthus salicifolius*; *N. glauca = Nicotiana glauca*; *B. scoparia = Bassia scoparia*; *D. argentea = Dichondra argentea*; *R. communis = Ricinus communis*

For Pb, index values ranged from 12 to 414; for Mn, from 4 to 146; and for Zn, from 1 to 60. This variability can be explained by the fact that, although all species were collected in areas adjacent to roads, they were not all located at the same distance from the roadside. Furthermore, surrounding vegetation density and differences in plant size or age could have influenced the amount of PM retained on the surface and, consequently, the concentration of PTEs retained or accumulated in their leaves. Gupta and Yadav (2025) noted that pollutant deposition on plants depends on species and leaf anatomy, distance from emission sources, and fluctuating meteorological and seasonal patterns. In addition, Wei et al. (2026) noted that PM composition varies widely because it can originate from different sources, such as vehicle exhaust and dust resuspension. In a mining-influenced area, González-Chávez et al. (2023) also observed variability in the phytobarrier index. They noted that plants can serve different roles as a phytobarrier depending on the site.

Although no significant differences were observed between species, the average phytobarrier index was considerably higher for Pb (120.8) than for Mn (27.8) and Zn (18.3), suggesting a greater relative retention of Pb in the leaves. This higher retention may relate to the reported atmospheric contribution of Pb on roadsides, where it is typically associated with PM (Hu et al. 2025), which may favor deposition on leaf surface. Furthermore, Pb has low internal mobility in plants (Chauhan et al. 2025); thus, much of the Pb detected in leaves reflects surface deposition and particle retention.

Morphology and EDS analysis

Micrographs showed that unwashed leaves accumulated more PM on their surfaces than washed ones (Figure 5). This confirms that plant surfaces act as PM sinks, in agreement with Popek et al. (2013) and Sánchez-López et al. (2015).

On the unwashed leaves of the dorsiventral species, *Eucalyptus* sp. exhibited the highest PM density, with 1,260,417 and 1,252,015 particles cm^{-2} on the adaxial and abaxial surfaces, respectively (Figure 6). The adaxial surface of *Eucalyptus* sp. leaves retained 3.7, 5.2, and 2.7 times more particles than that of *D. argentea*, *B. scoparia*, and *N. glauca*, respectively. On the abaxial surface, the differences were even greater, with values of 74.5, 6.0, and 3.8 times, respectively. This may be associated with the presence of papillae, which give the leaves a rough surface and facilitate particle retention. Additionally, surface exudates were observed during sampling of these leaves, which may have contributed to PM retention. According to Guzmán et al. (2014), these exudates in *Eucalyptus* sp. form an epicuticular wax layer.

The lower PM density recorded in *D. argentea* (336,111 and 16,806 particulates cm^{-2} on the adaxial and abaxial surfaces, respectively), *B. scoparia* (243,681 and 210,070 particulates cm^{-2}), and *N. glauca* (462,153 and 327,709 particulates cm^{-2}) suggests that leaf roughness is not the sole factor determining PM retention. Other attributes, such as plant height, leaf area, and the presence of exudates, may also influence retention (Sánchez-López et al., 2015). No consensus exists on which morphological characteristics determine greater efficiency in particle retention.

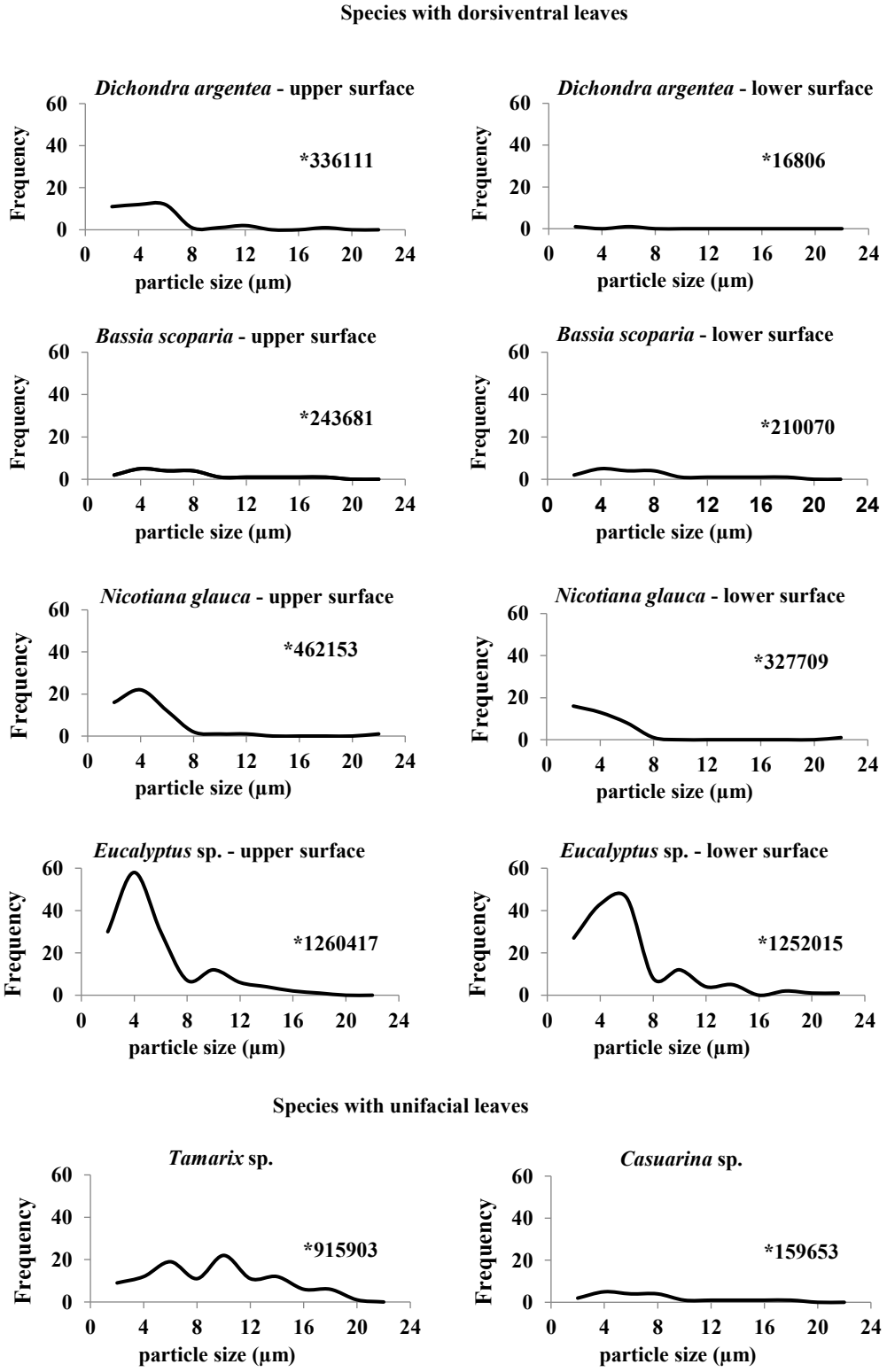
On unwashed leaves of unifacial species, *Tamarix* sp. showed the highest PM density (915,903 particles cm^{-2}), 5.7 times higher than in *Casuarina* sp. (159,653 particles cm^{-2}). PM retention in *Tamarix* sp. could be associated with the scale-like morphology of its leaves, which creates microstructures that trap particles. Wafa'a (2009) defines *Tamarix* sp. as an effective vegetation filter for retaining PM. Conversely, the lower particle retention in *Casuarina* sp. may be linked to the cylindrical, relatively smooth morphology of its photosynthetic structures, which limits PM deposition and anchorage sites.

EDS spectra revealed Cd, Pb, Zn, and Mn in the PM retained by the six plant species (Figure 5). These results show that PM is associated with PTEs. Weerakkody et al. (2018) reported similar results, using EDS to identify elements such as Zn and Mn in particles retained on the leaves of plants exposed to urban environments.

Particle size distribution analysis showed that most of the particles retained on dorsiventral leaves fell within the 2-8 µm size range (Figure 6). This trend was consistent across most species, though the most frequent size classes varied. In *D. argentea* and *B. scoparia*, the 3-8 µm particle size range predominated on both the adaxial and abaxial surfaces. In *N. glauca*, the predominant particle size on the adaxial surface was 4-5 µm, while on the abaxial surface it was 2-3 µm. *Eucalyptus* sp. exhibited the highest particle frequency in the 3-5 µm and 4-6 µm ranges for the adaxial and abaxial surfaces, respectively. In plants with unifacial leaves, particle size distribution differed. In *Tamarix* sp., the particle size distribution was broader, ranging from 4 to 16 µm, with the highest frequencies in the 5 to 6 and 9 to 11 µm ranges. In *Casuarina* sp., the highest frequency was in the 4-8 µm range.

Tamarix sp. and *Eucalyptus* sp. were the most efficient species at retaining foliar PM. The former is a candidate plant for reforesting the transect under study as a phytobarrier. This is because the species is resistant to high EC (Wei et al., 2020) and appears adapted to alkaline soil conditions, as shown by its higher dominance. Conversely, *Eucalyptus* sp. shows variable EC tolerance (Adams et al., 2005).

The predominance of particles in the 2-8 µm range on the leaves of the plants in this study is similar to that observed by Yan et al. (2016). These authors found a higher frequency of 2 - 10 µm particles retained by *Broussonetia papyrifera* on the streets of Beijing, China. This matters from a public health perspective, as particles ≤10 µm are inhalable and can cause adverse health effects (Kurth et al., 2014; Urbanowicz et al., 2024). Because the evaluated species retain particles in this inhalable fraction (≤10 µm), and because these particles are associated with PTEs, their establishment on the periphery of the former Lake Texcoco could reduce the population's exposure. This would minimize contact with both PM and PTEs. The latter can enter the body through inhalation and induce oxidative stress, inflammation, and other toxic effects linked to respiratory illnesses (Jomova et al., 2025).



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313 **Fig. 6** Particle size distribution retained on the foliar surface of six plant species. For dorsiventral species,
314 measurements are presented separately for adaxial and abaxial leaf surfaces. Asterisks indicate the estimated
315 mean number of particles per cm^2 of foliar area determined using ImageJ software

Furthermore, this PM retention capacity is highly relevant on the periphery of the former Lake Texcoco, because, according to Soto-Coloballes (2020), extensive soil areas in the former lake generate dust storms during the dry season that blow toward Mexico City and the municipality of Nezahualcóyotl. The PM from these dust storms can cause sneezing, coughing, conjunctivitis, and other ailments (Mack et al., 2020). PM exposure not only has negative health effects but is also associated with economic losses. For example, Trejo-González et al. (2019), in a study conducted in metropolitan areas and Mexico City, analyzed the impact of reducing PM concentration to an annual average of 10 μg m^{-3} in 2015. The authors noted that this reduction would have prevented 14,666 deaths, at an estimated cost of US$64,164. Therefore, using plants as phytobarriers is an innovative strategy with favorable implications for health and for reducing air pollution-related costs.

Conclusion

The soils evaluated at the periphery of the former Lake Texcoco PNA had slightly alkaline pH; however, values were lower at sites with vegetation cover, suggesting that organic matter decomposition influences edaphic conditions. PTEs were detected in soil, plant tissue, and PM retained on leaves, primarily associated with road dust. PTE concentrations in leaves were consistently higher in unwashed samples than in washed ones, although the differences were not always statistically significant. This suggests atmospheric deposition of PTE-associated PM on the leaves of plants growing in this area. The phytobarrier index showed no significant differences between species, but it did reveal significant differences between elements, with Pb exhibiting the highest average concentration. This may be relate to atmospheric Pb inputs in roadside environments, where road dust is often associated with this element. Micrographs confirmed that PM adhered to the leaf surface, predominantly <10 μm in size, which can be easily inhaled and cause adverse health effects. *Tamarix* sp. and *Eucalyptus* sp. showed the highest capacity to retain PM; however, site conditions (pH and EC) favor *Tamarix* sp. establishment. Overall, the results show that vegetation established at PNA periphery can help retain PTE-associated PM, offering a viable, cost-effective, and environmentally friendly strategy to reduce PM dispersion and exposure in surrounding areas.

Declarations

Ethical Approval

All authors have read, understood, and have complied as applicable with the statement on "Ethical Responsibilities of Authors" as found in the Instructions for Authors.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contributions

MCAGC conceptualized the study, managed and coordinated the study from planning to execution; MCAGC, RCG, and JECS designed the methodology and followed soil and plant sampling; JECS performed the chemical analysis, interpreted the data, and wrote the first draft; DTM analyzed the micrographs; RCG and MCAGC provided financial support and laboratory facilities for the study, supervised the study, reviewed the data, and critically revised the different manuscript versions.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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