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Research article

Leaf metal concentrations, nutrient status and growth of Fraxinus uhdei (Wenz.) Lingelsh. in urban forests

Concentración de metales en hojas, nutrición y crecimiento de Fraxinus uhdei (Wenz.) Lingelsh. en bosques urbanos

Anayetzi Luz Amelia Sánchez-Landero[1], Griselda Benítez-Badillo[2], Wendy Sangabriel Conde[1], Julio César Pérez Hernández[3], Gustavo Ortiz Hernández[1], Gerardo Alvarado-Castillo[1], Elio Guarionex Lagunes-Díaz[2]*

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[1]Facultad de Ciencias Agrícolas campus Xalapa, Universidad Veracruzana. México.
[2]Red de Ambiente y Sustentabilidad, Instituto de Ecología, A. C. (Inecol). México.
[3]Centro de Investigaciones Tropicales. México

*Autor para correspondencia; correo-e: elio.lagunes@inecol.mx
*Corresponding author; e-mail: elio.lagunes@inecol.mx

Abstract

Urban air pollution places chronic stress on trees through the deposition of pollutants from human activities, including metals associated with vehicle and industrial emissions, which can disrupt physiological processes and affect plant growth. Although metal accumulation in leaves has been used as a biomonitoring tool, gaps remain in the understanding of its relationship to morphological and growth changes in dominant urban species. Within this context, the present study evaluated the concentration of metals on the leaf surface and the fraction absorbed by the tissue, as well as the nutrient content in the leaves of the ash tree (*Fraxinus uhdei*), a species widely distributed in urban forests in the Mexico City Metropolitan Area (*ZMVM* in Spanish). The analysis was conducted in three urban forests with contrasting environments. The concentrations of surface and absorbed metals and the nutrient content were determined, and their associations with morphological and growth variables were evaluated using multiple linear regression (stepwise method) and nutrient vector analysis. The results showed that copper (both surface and absorbed) was positively associated with increased leaf area, whereas metals of anthropogenic origin, such as lead, cadmium and chromium were negatively associated with increased diameter. The nutritional analysis revealed negative correlations between leaf biomass and nutrient concentrations. These findings suggest that the accumulation of metals in tree foliage may influence the physiology and nutrition of urban trees and provide a basis for their monitoring and management.

Keywords: Metal uptake, leaf biomass, leaf biomonitoring, urban forests, trace metals, plant nutrition.

Resumen

La contaminación atmosférica urbana ejerce presión crónica sobre el arbolado, debido al depósito de contaminantes generados por actividades antropogénicas, entre ellos metales asociados a emisiones vehiculares e industriales que pueden alterar procesos fisiológicos y afectar el crecimiento vegetal. Aunque la acumulación foliar de metales se ha utilizado como herramienta de biomonitoreo, aún existen vacíos en la compresión de su relación con cambios morfológicos y de crecimiento en especies urbanas dominantes. En este contexto, en el presente estudio se evaluó la concentración de metales en la superficie foliar y la fracción absorbida por el tejido, así como el contenido de nutrimentos en hojas de fresno (*Fraxinus uhdei*), especie ampliamente distribuida en bosques urbanos de la Zona Metropolitana del Valle de México (ZMVM). El análisis se realizó en tres bosques urbanos con entornos contrastantes. Se determinaron las concentraciones de metales superficiales y absorbidos, y el contenido de nutrimentos, evaluando su asociación con variables morfológicas y de crecimiento mediante regresión lineal múltiple (método *stepwise*) y análisis vectorial nutrimental. Los resultados mostraron que el cobre (superficial y absorbido) se asoció positivamente con el incremento del área foliar, mientras que metales de origen antrópico como plomo, cadmio y cromo se relacionaron negativamente con el incremento del diámetro. El análisis nutrimental evidenció relaciones negativas entre la biomasa foliar y las concentraciones de nutrimentos. Estos hallazgos indican que la acumulación foliar de metales puede influir en la fisiología y nutrición del arbolado urbano y aportan bases para su monitoreo y manejo.

Palabras claves: Absorción de metales, biomasa foliar, biomonitoreo foliar, bosques urbanos, metales traza, nutrición vegetal.

Introduction

Air pollution is one of the main environmental pressures in megacities, where emissions from vehicle traffic, industrial activity, and other urban sources generate high concentrations of particulate matter and trace metals (Molina & Molina, 2004). Within this context, urban vegetation plays a significant role by intercepting and trapping pollutants on leaf surfaces, which helps reduce airborne particles such as PM_{10}, $PM_{2.5}$, and PM_1, which carry metals; and as a result, air quality is improved (Lindén et al., 2023). However, this function involves continuous exposure to toxic substances that can accumulate and enter plant tissue, disrupting physiological processes such as photosynthesis, nutrient balance, and the growth of urban trees (Kabata-Pendias, 2010; Bierza & Bierza, 2024).

In the Mexico City Metropolitan Area (*ZMVM*, for its acronym in Spanish), vehicle and industrial emissions are major sources of trace metals in the urban atmosphere (Molina & Molina, 2004). In particular, transportation accounts for more than 50 % of total air pollutant emissions (Secretaría de Medio Ambiente de la Ciudad de México [Sedema], 2023). Recent studies have documented the accumulation of trace metals in the foliage of urban trees (Fonseca-Salazar et al., 2023; Sánchez-Landero et al., 2024), providing evidence of the direct exposure of species to these. However, several of these studies have focused on quantifying metal accumulation, while knowledge regarding its implications for leaf morphology, nutrient status, and the growth of urban trees remains limited.

This gap is significant for dominant species used in urban green spaces in the *ZMVM*, such as *Fraxinus* (Benavides-Meza et al., 2002), which has been cited as being relatively tolerant of air pollution (Catinon et al., 2008). Therefore, this study analyzed the surface and absorbed concentrations of metals and nutrients in the leaves of *Fraxinus uhdei* (Wenz.) Lingelsh. in three urban forests within the *ZMVM* that experience varying degrees of urban pressure. Their relationship with leaf morphological variables—leaf area, specific leaf area, and dry leaf weight—, as well as changes in diameter breast height (*DBH*), were also examined in order to provide evidence on the effects of air pollution on the functioning and growth of urban trees.

Materials and Methods

Study area

The study was conducted in three urban forests in the *ZMVM* with varying levels of anthropogenic pressure: (1) *Naucalli* Park (19°29’27.6” N, 99°14’21.2” W) North of the *ZMVM*, characterized by industrial activity; (2) Section 1 of the *Chapultepec* Forest (19°23’40” N, 99°10’40” W), located in the downtown area, with heavy traffic, and (3) the *Tlalpan* Forest (19°17’38.2” N, 99°11’36.3” W), to the South, with greater tree cover and lower urban density (Figure 1). The sites were selected based on the presence of *Fraxinus uhdei* and because they represent a spatial gradient of human pressure in urban green spaces within the *ZMVM*.

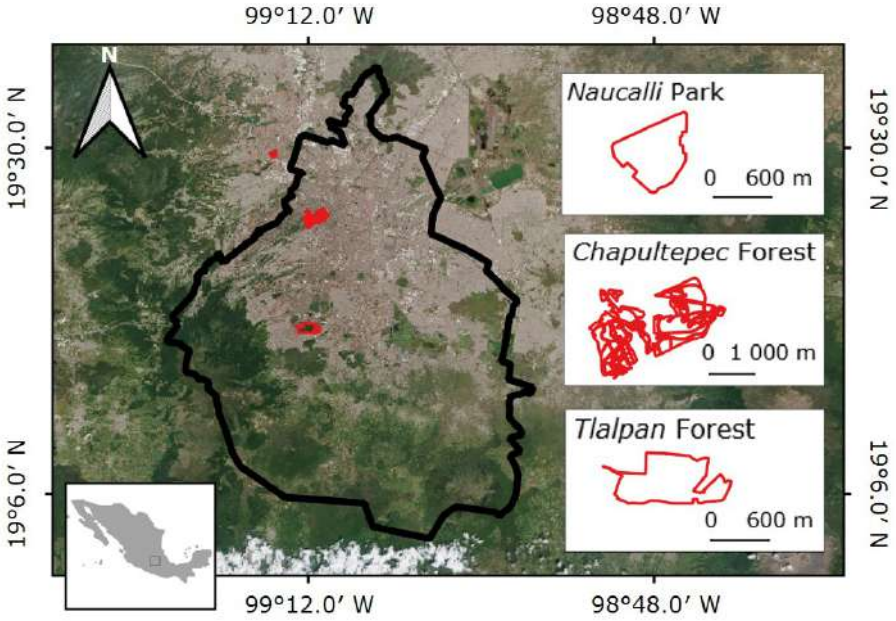


Figure 1. Location of the study areas.

Sampling and collections

A linear transect of approximately 750 m was established for each forest, taking into consideration urban constraints such as infrastructure, sports facilities, and restricted-access areas. A systematic sampling method with a random starting point was utilized, selecting one mature and apparently healthy *F. uhdei* tree every 50 m up to a total of 15 individuals per site (total n=45 trees). When there were multiple eligible individuals at a sampling point (±8 m, GPS accuracy), one was selected by simple randomization (drawing lots); in inaccessible areas, the nearest tree was chosen while maintaining the spatial interval.

Leaves were collected from the canopy at a height of 7 m throughout the four seasons to determine surface and absorbed concentrations of metals and nutrients. Growth was estimated based on the increase in diameter at breast height (*DBH*) measured over three consecutive years using a 320-cm Forestry Suppliers Tape® (accuracy ±1 mm). The soil *pH* was assessed for each tree at 30 cm deep in April, June and September, using a model 210 Hanna® pH potentiometer, according to AS-02 method of the Mexican Official Standard NOM-021-RECNAT-2000 (Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 2002), in view of its influence on the availability and mobility of metals and nutrients in the soil-plant system.

Determination of the leaf area and the specific leaf area

The leaf area (*LA*) was determined for 100 leaves per tree using a model Li-3100C Li-cor® leaf area meter, with the same method applied consistently across all individuals and sites. The leaves were collected from the middle third of the canopy; they were mature leaves with no visible damage, in order to standardize their physiological condition and minimize effects associated with age or position within the canopy. They were then dried at 75 °C until they reached a constant weight (model FE-291 Felisa® drying oven), and the specific leaf area (*SLA*) was calculated using the method suggested by Pérez-Harguindeguy et al. (2013).

$$SLA = \frac{LA}{DW}$$

Where:

SLA= Specific leaf area ($cm^2\ g^{-1}$)

LA = Leaf area calculated for 100 leaves (cm^2)

DW = Dry weight of 100 leaves (g)

Determination of metals and nutrients in leaves

The concentrations of metals (*Cu*, *Zn*, *Pb*, *Ni*, *Cr*, *Co*, and *Cd*) were determined using 20 g of leaves per tree; each tree constituted a sample unit. The surface fraction of metals was obtained by washing with a disodium EDTA desorbing solution (disodium ethylenediaminetetraacetic acid; Na_2EDTA J. T. Baker®, USA; lead-EDTA molar ratio=0.12) (Olguín et al., 2005). The leaves were then rinsed with deionized water, and the resulting solutions were analyzed using a model 3000 PerkinElmer® inductively coupled plasma (ICP) spectrometer. To determine the absorbed concentration, the washed leaves were dried at 75 °C to constant weight (model FE-291 Felisa® drying oven), ground in a GI® mill, and sieved to 2 mm. Next, 0.25 g of the sample was digested with 6 mL of nitric acid (HNO_3) in a microwave digestion system, diluted in 25 mL of deionized water, filtered through Whatman® No. 45 ash-free filter paper, and analyzed by ICP.

The concentrations of phosphorus (*P*) and potassium (*K*) were determined in the leaf material used for metal analysis; the same digestion and ICP analysis procedures were used. Nitrogen (*N*) was quantified in this plant material using the micro-Kjeldahl method, in accordance with the Association of Official Analytical Chemists International (Wendt-Thiex, 2023).

Statistical analysis

Differences among forests in *LA*, *SLA*, dry weight of the leaves (*DW*), and *DBH* growth were assessed using the Kruskal-Wallis and Mood-Median tests at a 95 % confidence level. The sampling unit was one tree (n=15 per site). First, the assumptions of normality (Shapiro-Wilk) and homogeneity of variances (Levene) were tested; since these assumptions were not met, nonparametric tests were applied.

The effect of metals (surface and absorbed), nutrients, and soil *pH* on leaf morphological variables and *DBH* growth was evaluated using multiple linear regression. The dependent variables considered were *LA*, *SLA*, *DW*, and increase in *DBH*, and the predictors were concentrations of metals, nutrients (*N*, *P*, and *K*), and soil *pH*. The analyses were conducted taking into account the location and the four seasons. Variables were selected using the stepwise procedure with forward selection and backward elimination to identify the predictors with the greatest explanatory power. The final models were selected based on the highest Coefficient of determination (adjusted R^2) and significance (α=0.05), following an assessment of multicollinearity using the variance inflation factor (*VIF*). The analyses were performed using MINITAB® version 14 (Minitab Inc., 2004). Finally, the nutrient balance of *N*, *P* and *K* was evaluated using vector nomograms, according to López-López and Alvarado-López (2010).

Results and Discussion

Morphometric variables: differences between sites

The Kruskal-Wallis test revealed significant differences among sites in *SLA* and in the increase in *DBH* (Table 1). The *SLA* recorded the highest median value in *Tlalpan* Forest, which could be attributed to its location in a less disturbed area. In environments with fewer disturbances, the availability of resources like water, light, and nutrients increases; this promotes higher *SLA* values and, consequently, higher tree growth rates (Poorter et al., 2009). The largest increase in *DBH* was found in the *Naucalli* Park, indicating variations in tree growth rates across sites. The literature indicates that local factors such as soil characteristics, site management, or the history of tree establishment can influence tree growth in urban environments (Pretzsch et al., 2017). However, these variables were not assessed in this study; therefore, the differences should be interpreted solely as inter-site variation.

Table 1. Comparison of medians for the *LA*, *SLA*, *DW* and *DBH* variables.

Variable	*Naucalli* M_e	*Chapultepec* M_e	*Tlalpan* M_e	*P* value
LA	2 065	2 595	2 539	0.140
SLA	56.1[b]	66.6[b]	78.7[a]	0.001
DW	34.90	33.67	29.19	0.105
DBH	1.20[a]	0.50[b]	0.50[b]	0.002

LA = Leaf area; *SLA* = Specific leaf area; *DW* = Dry weight; *DBH* = Increase in *DBH*; M_e = Median. Identical letters indicate no significant differences between sites according to the Kruskal-Wallis test.

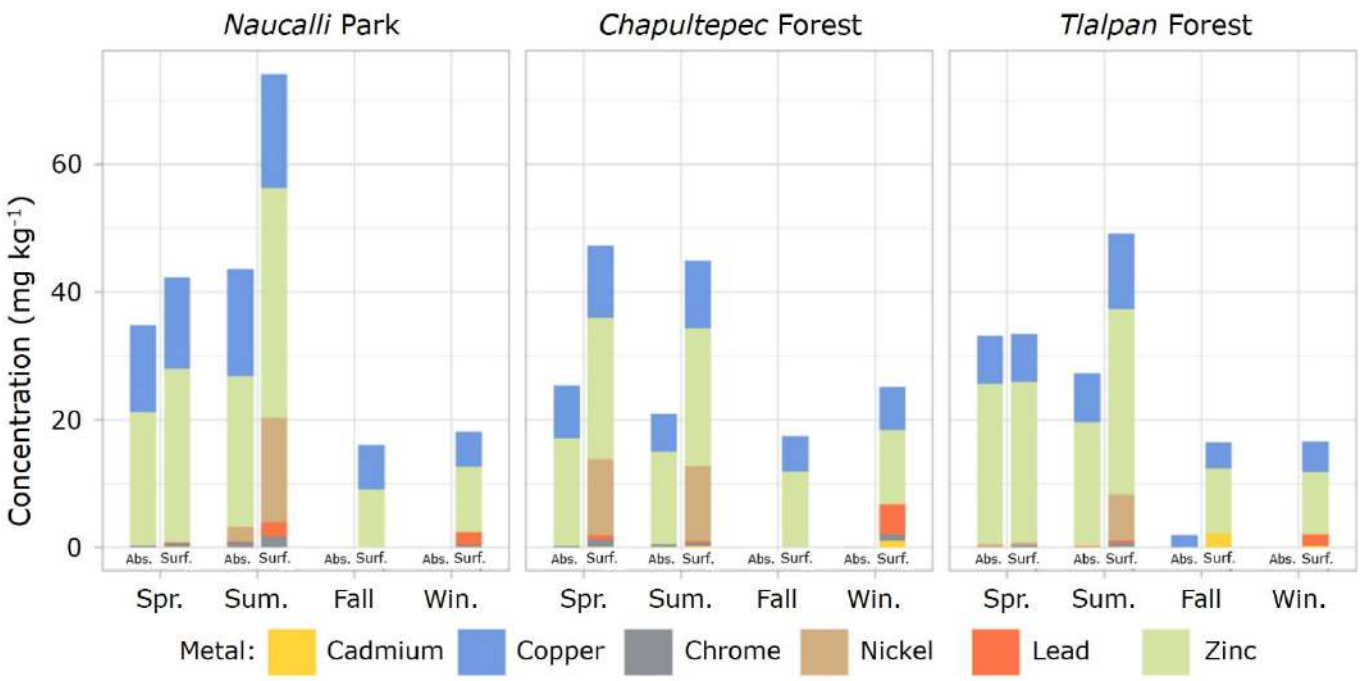
Cu, *Zn*, *Pb*, *Ni*, *Cr* and *Cd* concentrations

Table 2 shows the average surface and leaf tissue concentrations of *Cu*, *Zn*, *Pb*, *Ni*, *Cr*, and *Cd* in *Fraxinus uhdei* leaves, by site and season. At all three sites, *Cu* and *Zn* had the highest concentrations in both the surface and the absorbed fractions, while *Ni* had the lowest values. *Cr*, *Cd*, and *Pb* were detected in lower concentrations, although consistently, in the foliage of *F. uhdei* (Figure 2). The highest concentrations were observed in the spring and summer, suggesting greater accumulation during the growing season, when leaf growth promotes the interception of atmospheric particles over urban vegetation (Lindén et al., 2023).

Table 2. Average surface and absorbed concentrations of *Cu*, *Zn*, *Pb*, *Ni*, *Cr*, and *Cd* in *Fraxinus uhdei* (Wenz.) Lingelsh. leaves by site and season.

Forest	Metal	Spring		Summer		Fall		Winter	
		Surf.	Abs.	Surf.	Abs.	Surf.	Abs.	Surf.	Abs.
NP	*Cu*	14.3±6.1	13.6±5.8	17.90±7.7	16.7±7.3	7.1±3.6	0.004±0.001	5.5±2.0	0.01±0.01
	Zn	27.1±9.4	20.9±6.1	36.0±14.7	23.6±8.1	8.98±2.35	0.01±0.01	10.30±2.8	0.02±0.01
	Pb	0.2±0.16	Ud	2.23±2.25	0.04±0.01	0.05±0.01	0.001±0.001	1.98±2.5	0.01±0.001
	Ni	Ud	Ud	16.4±11.3	2.3±0.6	0.01±0.01	0.002±0.001	0.002±0.001	0.01±0.001
	Cr	0.52±0.23	0.2±0.17	1.66±1.21	0.84±0.57	0.001±0.001	0.001±0.00	0.28±0.61	0.01±0.001
	Cd	0.1±0.04	0.1±0.26	0.05±0.05	0.02±0.02	0.006±0.002	0.001±0.001	0.07±0.02	0.001±0.001
CF	*Cu*	11.37±6.5	8.32±6.01	10.6±5.07	5.96±1.91	5.52±3.03	0.01±0.01	6.79±3.26	0.02±0.02
	Zn	22.1±10.1	16.82±8.6	21.5±7.83	14.5±2.56	11.85±3.30	0.02±0.01	11.66±4.49	0.04±0.03
	Pb	0.58±0.53	Ud	0.26±0.27	Ud	0.01±0.01	0.01±0.01	4.69±4.34	0.01±0.01
	Ni	102.0±1.6	Ud	11.8±10.2	Ud	0.01±0.01	0.001±0.001	0.01±0.01	0.01±0.001
	Cr	1.17±1.07	0.19±0.19	0.53±0.27	0.34±0.02	0.01±0.01	0.01±0.001	1.0±0.6	0.001±0.001
	Cd	0.15±0.08	0.05±0.02	0.21±0.03	0.12±0.13	0.01±0.01	0.001±0.001	1.1±0.2	0.01±0.01
TF	*Cu*	7.59±3.79	7.59±3.79	11.8±6.76	7.8±4.0	4.17±1.05	0.02±0.01	4.77±1.96	0.01±0.001
	Zn	25.1±7.4	25.1±7.4	29.1±6.74	19.4±5.3	10.19±2.66	0.01±0.01	9.74±4.10	0.02±0.01
	Pb	Ud	Ud	0.42±0.42	0.10±0.01	0.001±0.01	0.001±0.001	1.8±2.7	0.01±0.001
	Ni	0.45±0.01	0.5±0.02	7.1±3.7	Ud	0.01±0.01	0.01±0.001	0.001±0.01	0.001±0.001
	Cr	0.32±0.01	Ud	0.57±0.52	Ud	0.001±0.001	0.001±0.001	0.07±0.10	0.01±0.001
	Cd	0.06±0.03	0.06±0.03	0.14±0.05	0.09±0.04	2.18±0.50	0.01±0.01	0.18±0.01	0.01±0.001

NP = *Naucalli* Park; CF = *Chapultepec* Forest; TF = *Tlalpan* Forest. Surf. = Surface; Abs. = Absorbed. *Cu* = Copper; *Zn* = Zinc; *Pb* = Lead; *Ni* = Nickel; *Cr* = Chrome; *Cd* = Cadmium; Ud = Undetermined; ± is the standard deviation. Concentrations are expressed in mg kg^{-1}.



Abs. = Absorbed; Surf. = Surface. Spr. = Spring; Sum. = Summer; Win. = Winter.

Figure 2. Average surface and absorbed concentrations of *Cd*, *Cu*, *Cr*, *Ni*, *Pb*, and *Zn* in *Fraxinus uhdei* (Wenz.) Lingelsh. leaves by season.

The surface fraction is associated with the deposition of atmospheric pollutants on leaves, while the absorbed fraction reflects the uptake and translocation of these elements into plant tissues. This pattern has been documented in urban trees used as bioindicators of pollution, where *Cu* and *Zn* typically reach relatively high concentrations (3-14 mg kg^{-1} and 20-90 mg kg^{-1}, respectively) due to their association with vehicle emissions, brake dust, and other urban sources (Rai, 2016; Youssef, 2020). The differences between fractions suggest that *F. uhdei* can accumulate metals both through surface deposition and through incorporation into leaf tissues. However, the extent of these processes varies by location and season, depending on factors such as traffic intensity, environmental conditions, and the physiological characteristics of the trees (Soba et al., 2022).

Relationships between metals, nutrients, and leaf and growth variables

Multiple regression models identified associations between metal concentrations in foliage (surface and absorbed), soil nutrients, and soil *pH* with growth variables of *Fraxinus uhdei* (*LA*, *SLA*, *DW* and increase in *DBH*) (Table 3). These relationships varied across sites and seasons. In the *Chapultepec* and *Tlalpan* forests, associations were observed primarily for *LA* and *DW* in spring, fall, and winter, and for *DBH* in summer and winter. This pattern aligns with the seasonal dynamics of tree growth, as leaf expansion occurs in the spring and activity related to radial growth increases in the summer (Varela et al., 2023), whereas in the fall and winter, urban atmospheric conditions promote the accumulation of pollutants due to temperature inversions and lower precipitation, which results in increased deposition of metals on the leaves (Molina & Molina, 2004).

Table 3. Response variables for leaf area (*LA*), specific leaf area (*SLA*), diameter at breast height (*DBH*) and dry leaf weight (*DW*) by site and season, with significance values (*p*) and correlation coefficients (Adjusted R^2).

Response variable	Site	Season	Positive predictors	Negative predictores	p-value	*Adjusted* R^2 (%)
LA	CF	Spring	Absorbed *Cu* and *Cd*, surface *Zn*, and soil *pH*	Surface *Cu* and absorbed *Zn*	0.013	72.7
		Fall	Soil *pH*	Absorbed *Cd* and surface *Zn*	0.002	66.9
	TF		Surface *Ni*, Surface and absorbed *Cu*, and surface *K*	Surface *Cr* and *P* and absorbed *Cd*	0.011	79.2
SLA	NP	Spring	-------	Absorbed and surface *Cr* and *N*	0.003	62.6
		Winter	-------	Surface and absorbed *P*	0.001	67.1
DBH	CF	Summer	-------	Soil *pH* and absorbed and surface *Cd*	0.005	58
		Winter	Absorbed *Cr*	Absorbed *K* and *Ni*; surface *Cd*	0.001	85.3
	TF	Winter	Absorbed *Cr* and surface *Cu*	Surface *Cd* and *Pb*; absorbed *Cu*; surface *Ni* and *N*	0.001	99.6
	NP	Spring	-------	Absorbed *Cr*	0.001	65.5
DW	CF	Spring	Surface *Zn*	Surface *Cu* and *Cr*	0.001	83.8

LA = Leaf area; *SLA* = Specific leaf area; *DW* = Dry leaf weight; *DBH* = Increase in *DBH*. CF = *Chapultepec* Forest; TF = *Tlalpan* Forest; NP = *Naucalli* Park.

In the *Naucalli* Park, these relationships were primarily observed for *SLA* and increases in *DBH* in spring and winter, suggesting a seasonal pattern related to resource availability and environmental stress. Within this context, urban trees can serve as a sensitive indicator of the pressures resulting from urban activities (Patel et al., 2023). Overall, the results indicate that the interaction among metals, nutrients, and soil *pH* helps explain some of the leaf traits and growth of *F. uhdei*; although its effect depends on environmental conditions and the degree of urban pressure at each site (Omidi et al., 2025).

Relationship with the leaf area

The leaf area (*LA*) showed correlations with metal concentrations and soil *pH* in the *Chapultepec* and *Tlalpan* forests (Table 3), with seasonal variations but consistent patterns. In *Chapultepec* Forest, during the spring, the *LA* was positively correlated with absorbed copper, surface zinc, and soil *pH* (indicating that these variables increase the *LA*) and negatively correlated with surface copper and absorbed zinc (which affect foliage production). In *Tlalpan* Forest, the *LA* showed positive correlations with soil *pH* in fall, and with copper, nickel, and potassium in winter, while chromium, phosphorus and cadmium showed negative correlations. Overall, soil *pH* and elements such as *Cu*, *Zn*, and *Ni* (which are plant nutrients) showed consistent positive effects, whereas anthropogenic metals such as *Cd* and *Cr* were associated with reduced *LA*. On the other hand, the positive effect of absorbed copper is consistent with its role as an essential nutrient, and surface copper levels may reflect its accumulation, affecting foliar processes (Alcántar-González et al., 2016; Rai, 2016). Furthermore, the positive effect of *pH* at the study sites suggested that it plays an important role in regulating the availability of nutrients and metals in the soil-plant system (Kabata-Pendias, 2010).

Relationship with the specific leaf area

The specific leaf area (*SLA*) was associated with various elements in the *Naucalli* Park; in spring, a negative relationship was observed with surface and absorbed chromium and with foliar nitrogen; in winter, surface and absorbed phosphorus showed a negative association. The average chromium concentrations recorded (0.52 mg kg^{-1}

on the leaf surface and 0.21 mg kg^{-1} in the leaf tissue) were lower than those reported in other studies of urban vegetation and are below the levels considered toxic to plants (Kabata-Pendias, 2010; Ramírez-Méndez et al., 2021). However, the negative association between chromium and the *SLA* suggests that low concentrations of this metal may alter leaf characteristics.

As for nitrogen, the average concentration observed (0.97 %) was below the minimum level generally required for plant growth (≈1.5 %) (Alcántar-González et al., 2016). This condition could lead to an imbalance in the *N*:*P* ratio, reducing the capacity for leaf tissue formation and potentially contributing to the decrease in *SLA* observed in spring and winter. The results indicate that both the presence of metals and the availability of nutrients influence variations in *SLA* in urban environments, and once again highlight the effects of elements such as chromium, which can affect the structure and function of the leaves.

Relationship with the increase in *DBH*

The diameter at breast height (*DBH*) was associated with various metals and soil *pH* at all three sites and across seasons. In *Chapultepec* Forest, during both summer and winter, both surface and absorbed cadmium were negatively associated with an increase in *DBH*. In winter, the *DBH* in *Tlalpan* Forest was negatively correlated with surface cadmium and lead. For the *Naucalli* Park in the spring, a negative correlation was observed between the *DBH* and chromium uptake.

These results suggest that the presence of potentially toxic metals of anthropogenic origin is associated with a lower radial growth rate in *F. uhdei*, particularly during the winter months when rainfall is reduced. Although the cadmium concentrations recorded in this study remained below the levels considered toxic to plants (3-5 mg kg^{-1}) (Kabata-Pendias, 2010), this metal can accumulate in plant tissues and affect

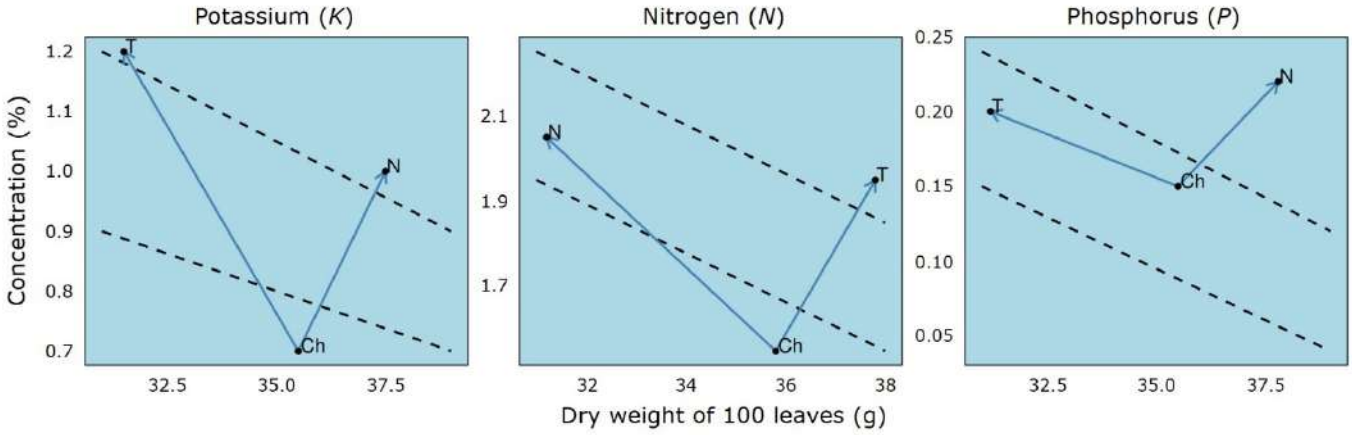
physiological processes such as transpiration and photosynthesis (Bierza & Bierza, 2024), which may account for its negative association with increased *DBH*.

Relationship with the dry weight of the leaves

The dry weight of leaves (*DW*) in *Chapultepec* Forest during the spring was positively correlated with surface zinc and negatively correlated with surface copper and chromium. The beneficial effect of zinc is consistent with its role as an essential nutrient involved in protein stability and plant metabolic processes (Alcántar-González et al., 2016). In contrast, the negative correlation between copper and chromium suggests that their deposition is associated with lower accumulation of leaf biomass.

Concentrations of nitrogen, phosphorus, and potassium

Vector analyses (Figure 3A-C) revealed negative correlations between the dry weight of 100 leaves and the foliar concentrations of *N*, *P* and *K* suggesting a possible nutrient dilution effect associated with increased leaf biomass. This trend was most evident in *K*, while *N* and *P* showed more moderate changes. The results are consistent with those reported for functional leaf traits, as increases in biomass or changes in leaf structure alter the relative concentration of nutrients without causing nutritional limitations (Binkley et al., 2025). Similarly, the morphological and physiological characteristics of leaves can influence the uptake, retention and accumulation of elements present in the atmosphere.



N = *Naucalli* Park; Ch = *Chapultepec* Forest; T = *Tlalpan* Forest.

Figure 3. Vector analysis nomograms for the nutritional diagnosis.

Conclusions

The results reveal differences among urban sites in the leaf and growth characteristics of *Fraxinus uhdei*, particularly in the growth of the specific leaf area (*SLA*) and diameter at breast height (*DBH*), reflecting variability in the trees' response under different urban conditions. Both surface and absorbed metals were detected in the foliage, with higher concentrations of *Cu* and *Zn* and lower concentrations of *Ni*, *Cr*, *Cd* and *Pb*; this indicates that the leaves are involved in processes of atmospheric deposition and absorption of elements present in the urban environment.

The regression models revealed associations between metals, nutrients, and soil *pH* with foliar growth variables (*LA*, *SLA*, *DW* and *DBH*) —an indication that the interaction among these factors accounts partly for the variation in tree performance. Overall, the results show that the leaf characteristics and growth of *F. uhdei* in urban environments are associated with the interaction of metals present in the environment, nutrient availability and soil *pH* conditions. These findings provide

insights into the factors that affect the health and growth of ash trees in urban environments; therefore, they can guide future research and management actions aimed at improving the quality of the urban environment and the resilience of urban vegetation in the face of environmental pressures.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Luz Amelia Sánchez-Landero: experimental and statistical design, drafting of the manuscript and handling of peer reviews; Griselda Benítez-Badillo: data curation; Wendy Sangabriel Conde: formal analysis, revision of the draft; Julio César Pérez Hernández: statistical design, graphs, and review coordination; Gustavo Ortiz Hernández: drafting, statistical analysis; Gerardo Alvarado-Castillo: methodology design; Elio Guarionex Lagunes-Diaz: objectives, methodology design, drafting, and handling of reviews.

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