Heavy metal accumulation in urban trees and phytoremediation potential

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Abstract

The aim of this study was to evaluate the concentrations of heavy metals (Cd, Cu, Pb, and Zn) in the leaves and bark of two tree species (*Populus alba* and *Melia azedarach*). The study also aimed to assess their metal accumulation capacity and potential use in phytoremediation. Sampling was carried out in the spring of 2025 across thirty stations using a transect method in an urban area with high traffic intensity. Additionally, leaves and barks samples of the same species were collected from a control area distant from any anthropogenic disturbances. Results revealed notable variations in HM concentrations both between species and among different plant organs. In general, unwashed leaves exhibited higher metal contents than washed regardless of the species. For Cd and Cu, *Populus alba* showed higher concentrations in unwashed leaves than in bark, while *Melia azedarach* accumulated more metals in the bark. Pb concentrations were higher in the bark of both species. Regarding Zn, accumulation was greater in unwashed leaves of *Melia azedarach* and in the bark of *Populus alba*. Furthermore, the concentrations of all heavy metals measured in the urban area were higher than those in the control area, regardless of the species or plant part analyzed. The Metal Accumulation Index values varied by species and plant organ. *Melia azedarach* exhibited the highest MAI (14.64), indicating a greater accumulation capacity than *Populus alba* (14.25). The Bioaccumulation Factor values suggest that both species can be used for biomonitoring and phytoextraction of heavy metals. *Melia azedarach* demonstrated a higher accumulation potential, whereas *Populus alba* showed greater efficiency in restricting metal translocation within its tissues.

Keywords : Heavy metals, phytoremediation, *Populus alba*, *Melia azedarach*, leaves, barks.

1. Introduction

The evolution of society and population, combined with industrialization, the expansion of transportation, and intensive agricultural activities, has played a crucial role in worsening environmental problems [1]. For several decades, humans have progressively introduced various pollutants into the biosphere, mainly originating from industrial activities, excessive use of pesticides, urbanization, and road traffic and transportation. All these substances have had a significant impact on air, soil, and water, which subsequently accumulate within the food chain, causing harmful effects on plants, animals, and human health [2].

Over the past decade, increasing attention has been given to heavy metals and their effects on various ecosystems. Heavy metals are substances with a density greater than 5 g cm^{-3} and an atomic number higher than 20 [3]. Sources of heavy metal pollution may be of natural origin (such as volcanic eruptions and rock weathering) or anthropogenic origin (including industrial waste, oil industry discharges, spreading and runoff of chemical fertilizers and pesticides, road traffic, and military industry activities) [4]. The intrinsic nature of these elements prevents them from degrading naturally ; they remain persistent in the environment for very long periods and can be absorbed by plants and living organisms [5].

In Algeria, atmospheric metal pollution has been steadily increasing, particularly in connection with the expansion of major road networks [6,7,8,9]. In Constantine, where the urbanization rate exceeds 94%, this phenomenon represents a major environmental issue. It results from both heavy automobile traffic and local topographic and climatic characteristics that promote the retention of pollutants in the atmosphere. Several studies have confirmed significant metal contamination (Cd, Co, Cr, Cu, Ni, Pb, Zn) affecting the aquatic and terrestrial ecosystems of the region [10,11,12,13,14]. Numerous studies have investigated atmospheric metallic pollution using plants as bioindicators and bioaccumulators. The accumulation of lead by plants was first reported in Finland [15]. Since then, several studies have demonstrated a correlation between the proximity of roadways and the accumulation of heavy metals in both vascular plants and lichens. The latter, due to their exclusive dependence on the atmosphere, are considered the most efficient bioaccumulators of airborne metal deposits. However, in highly degraded environments where anthropogenic pressure limits their presence, certain persistent vascular plants can serve as alternative bioaccumulators [16,17,18,19].

Furthermore, scientific literature suggests that trees are more suitable biomonitors than lichens and mosses, as they integrate heavy metal contamination over long periods of time [20,21]. Nevertheless, the accumulation potential of plants for heavy metals remains insufficiently explored. Some plant species have been assessed for their ability to biomonitor metal pollution, highlighting their specific advantages and limitations [22,23,24]. In Algeria, several studies have focused on the accumulation of heavy metals in different tree species, including *Platanus* and *Cupressus sempervirens* [25], *Casuarina equisetifolia* [8], *Tamarix gallica* [11], as well as *Cupressus sempervirens var. fastigiata* and *Eucalyptus cladocalyx* [13].

The use of trees, particularly their leaves and bark, as bioindicators of air pollution has significantly developed in recent years [22,23]. The leaves of higher plants capture pollutants from both wet and dry deposits and accumulate metals originating from the soil and the atmosphere [20,21]. Metal absorption occurs mainly through the roots, followed by transfer to other plant organs. Atmospheric particles can be retained on foliage, washed off by rainfall, or transferred to the soil, depending on climatic conditions, pollutant properties, leaf morphology, and particle size. Therefore, the accumulation of metals in plants serves as a reliable indicator for tracking the spatial and temporal evolution of air pollution [26,27,7,13].

Phytoremediation is an *in situ* decontamination approach that relies on the use of specific plant species capable of reducing the toxicity of pollutants present in soils, water, and the atmosphere [28]. Unlike conventional engineering methods, this technique offers an eco-friendly, sustainable, and cost-effective alternative for restoring polluted environments without disturbing ecosystem balance [29, 30].

Recent studies, notably those by [30], have demonstrated that long-term phytoremediation promotes an increase in soil organic matter as well as an enhancement of microbial abundance and diversity, thereby contributing to the recovery of functional soils [31]. Furthermore, advances in plant biotechnology and functional genomics have improved plant tolerance to heavy metals. These developments rely on the regulation of specific genes involved in the uptake, transport, and chelation of metals, leading to their transformation into less toxic or more volatile forms, thus enhancing the overall efficiency of the phytoremediation process [32,33]. To highlight the relevance of using trees as bioindicators of atmospheric metal pollution, leaves and barks have long been employed in biomonitoring compared to other parts of the tree, such as flowers and buds [34,35].

In this context, the present study pursues a dual objective. The first is to establish a relationship between road traffic intensity and the accumulation of heavy metals cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) in the leaves and barks of two woody species growing in both a contaminated and an uncontaminated area. The second objective is to evaluate the ability of these two species to contribute to the phytoremediation of urban soils, using the bioconcentration factor (BCF) and the metal accumulation index (MAI) as indicators. The results obtained in this research provide preliminary reference values for heavy metal concentrations in urban areas of the region and complement previous findings on the use of woody trees in phytoremediation processes.

2. Material and methods

2.1.Study area and sampling sites

The present study was conducted in Constantine, a city located in northeastern Algeria at 36°17'00" N, 6°37'00" E, with an elevation of 694 m (Figure 1). Constantine covers an area of 2,197 km² and exhibits a high population density of approximately 428 inhabitants per km². The city experiences a Mediterranean climate, with mean summer temperatures ranging from 25 to 40 °C, winter temperatures between 0 and 12 °C, and annual precipitation levels of 350–700 mm. Within this urban agglomeration, traffic density is particularly high [13]. In 2020, Constantine's vehicle fleet totaled 727,605 units, including 115,868 newly registered vehicles. The fleet is highly heterogeneous, encompassing passenger cars, trucks, buses, motorcycles, and road tractors, with gasoline as the dominant fuel (71.01%) and diesel representing 28.99%. Notably, new vehicles account for only 15.92% of the total fleet, indicating that a substantial proportion of vehicles are older and, consequently, contribute disproportionately to environmental pollution due to higher emission levels [14].

To assess the impact of vehicular traffic and road infrastructure on trees, as well as to evaluate their potential role in phytoremediation, this study focused on two species (*Populus alba* and *Melia* azedarach), established from seeds collected in Algeria.This species was selected because of its high dispersion in the studied area. Around thirty samples of this species were collected along the national road (RN05) linking the center of the city of Constantine to the commune of Ain smara, characterized by intense road traffic (Figure1). Samples of the same species were taken in an uncontaminated control area, far from all sources of anthropogenic disturbance, this is the Draa Naga arboretum (Figure 1).

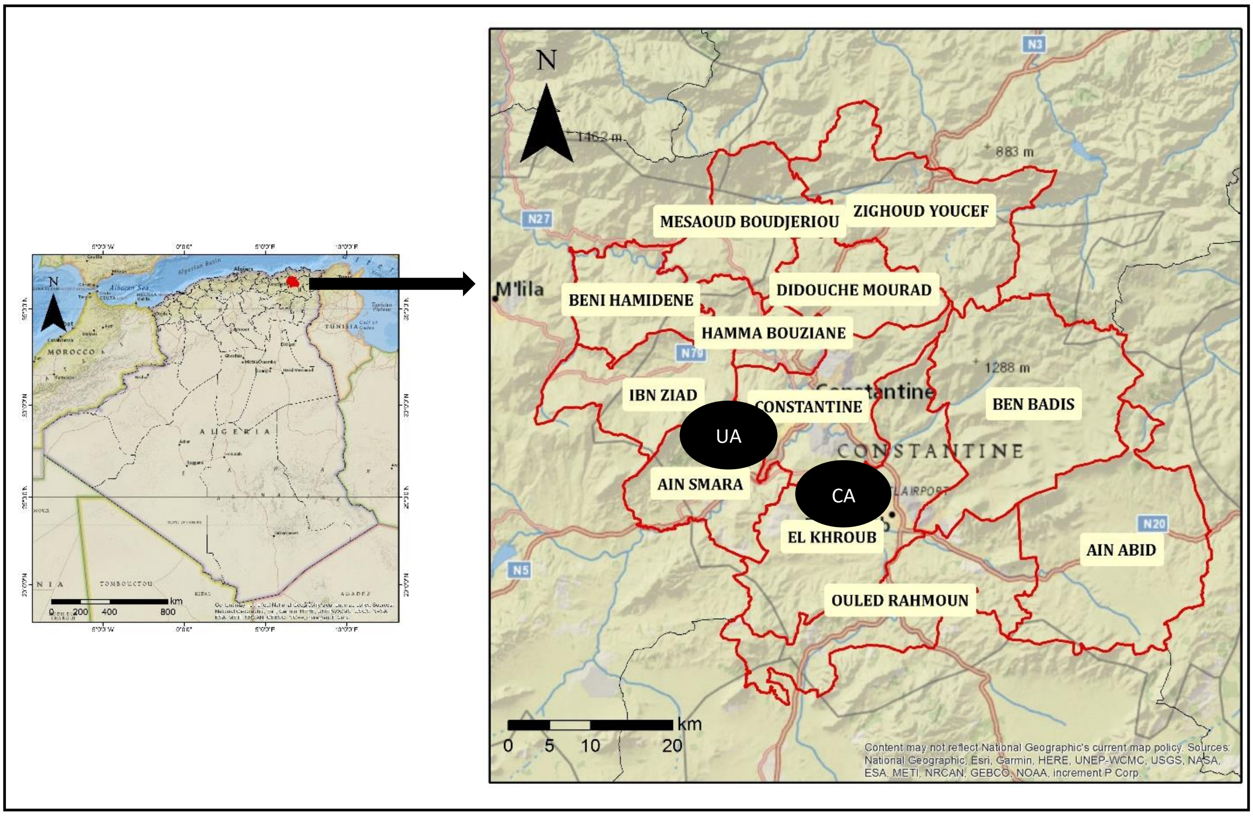

Figure 1. Geographical location of the urban and control areas.

A transect-based sampling approach was adopted to ensure uniform exposure time and comparable levels of metal contamination. Trees of the same age were selected to maintain consistency across samples. Mature leaves and bark from each species were collected at a distance of 3 meters from the roadside. Leaves were cut directly from the branches, approximately 1 cm from their base, and randomly collected from the lower two-thirds of each tree's canopy.

Only leaves of similar size, fully developed, and free from visible anomalies (chlorosis or necrosis) were included. Following the recommendations of [36], trees showing abnormal leaf or bark conditions (yellowed leaves, cracked bark) were excluded. Particular attention was also given to avoiding leaves with external imperfections, such as bird droppings, insect infestations, or traces of pesticide treatment. The bark samples were collected at breast height, approximately 1.30 meters above the ground, from the middle section of the tree trunk. All leaf and bark samples were stored separately in clean bags to prevent cross-contamination and were transported to the laboratory on the same day as sampling.

Leaf samples were divided into two distinct subsamples : the first was thoroughly washed with ultrapure deionized water to remove dust and airborne particles, while the second was kept unwashed for comparative purposes. Subsequently, both bark samples and washed and unwashed leaves were oven-dried at 85 °C and then finely ground in preparation for chemical analysis.

Additionally, soil cores were collected around the tree trunks using an auger at a depth of 0–20 cm. Prior to sampling, twigs and dried leaves were carefully removed. The collected soil samples were then air-dried and passed through a 2-mm stainless-steel sieve to prepare them for heavy metal analysis.

Moreover, leaf, bark, and soil samples were obtained from a reference (control) site located in the Draa Nega arboretum, approximately 10 km away from the contaminated urban area. Sampling of all materials was conducted during the spring of 2025.

2.2. Heavy metals extraction

Heavy metal (HM) extraction was performed following the procedure outlined by [37]. The method involves dry calcination of finely ground samples (1 g) in a muffle furnace for 16 hours, with a gradual increase in temperature up to 450 °C. After cooling, 10 mL of diluted aqua regia (1/3) was added to dissolve the resulting ash. The digested solutions were filtered through Whatman No. 540 filter paper, and the filtrates were subsequently stored in Teflon containers at 4 °C until analysis [13]. The concentrations of cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) were determined using inductively coupled plasma–optical emission spectrometry (ICP-OES, Perkin Elmer Optima 8000).

Analytical quality was assessed through tests of linearity, precision, and reproducibility using external calibration standards (0.1–5 mg/L for Cd and 0.5–10 mg/L for Cu, Pb, and Zn). Reproducibility was verified using a certified reference material (BCR62 – *Olea europaea* leaves), yielding high recovery rates (97–100%), thereby confirming the reliability and robustness of the analytical procedure employed.

For soil analysis, aliquots of 500 mg were digested using 10 mL of aqua regia a 3:1 mixture of hydrochloric acid (HCl, 12 N) and nitric acid (HNO_3, 15 N) in Teflon vessels within a microwave digestion system (Speedwave R-2, BERGHOF B). The concentrations of Cd, Cu, Pb, and Zn were subsequently determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Perkin Elmer Optima 8000).

Analytical accuracy and precision were verified using a certified reference material (BCR CRM 141 R, calcareous loam soil, Community Bureau of Reference, Brussels, Belgium). Recovery rates were satisfactory, ranging from 87% to 96% (92 ± 1.5% for Cd, 87 ± 1.1% for Cu, 87 ± 1.6% for Pb, and 96 ± 2.2% for Zn), confirming the reliability and robustness of the applied analytical method.

2.3.Data analysis

Statistical analyses were performed using Statistica 7.0 software. For each studied species, minimum, maximum, mean values, and standard deviations were calculated for each element and plant organ. A one-way analysis of variance (ANOVA) followed by the Newman–Keuls post-hoc test was conducted to identify significant differences between species and/or plant parts. In addition, an independent-samples t-test was applied to compare data between the urban and control sites. The level of statistical significance was set at $p < 0.05$.

Moreover, two indicators were employed to assess both the origin and the accumulation capacity of heavy metals by tree species occurring in the investigated area : the Bioconcentration Factor (BCF) and the Metal Accumulation Index (MAI).

The Bioconcentration Factor (BCF) represents the ability of a plant to absorb and translocate heavy metals from the soil into its internal tissues [38,39,40,41,20]. It is defined as the ratio between the total concentration of a metal measured in plant tissues (leaves and bark) and that detected in the soil. The BCF is determined using the following formula :

$$BCF = \frac{C_{\substack{harvested \\ tissue}}}{C_{soil}}$$

Where $C_{harvested\ tissue}$ is the metal concentration in harvested tissues (leaves, barks), and C_{soil} is the metal concentration in soil.

The Metal Accumulation Index (MAI), on the other hand, provides an integrated measure of the overall metal accumulation potential of a plant species [42,43]. It allows for the comparison of total metal burdens across different species or environmental conditions. The MAI is calculated as the arithmetic mean of the standardized concentrations of all analyzed metals in plant tissues, according to the following expression :

$$MAI = \frac{1}{n}\sum_{i=1}^{n} Ij$$

Where n is the total number of HMs, and Ij is the sub-index for variable j, obtained by dividing the mean concentration (x) of each HMs by its standard deviation.

3. Results and discussion

The statistical results of heavy metal concentrations for the studied species are presented in Table 1. The table reports the minimum, maximum, and mean ± standard deviation values of cadmium, copper, lead, and zinc contents measured in washed leaves (WL), unwashed leaves (UL), barks (BK), and soil.

Table 1. Heavy metals concentrations (µg/g) organs of studied species (urban area).

Species	Plant part	Cd	Cu	Pb	Zn
Populus alba	**WL**	[019 – 0.57] 0.32 ± 0.16 [a]	[4.19 – 10.23] 7.17 ± 2.03 [a]	[3.33 – 10.00] 6.40 ± 1.92 [a]	[15.31 – 40.89] 28.10 ± 9.58 [a]
	UL	[0.38 – 0.95] 0.67 ± 0.22 [a]	[5.12–10.70] 7.73 ± 2.28 [a]	[6.67 – 20.00] 10.77 ± 4.00 [a]	[22.79 – 66.59] 37.81 ± 13.12 [a]
	BK	[0.19 – 0.95] 0.57 ± 0.22 [a]	[3.26 – 8.84] 5.76 ± 1.81 [b]	[10.00– 26.67] 17.66 ± 4.72 [b]	[14.41 – 138.77] 55.64 ± 43.70 [b]
Soil		[0.38 –1.20] 0.82 ± 0.37	[11.23 –16.55] 13.93 ± 2.58	[78.87–160.24] 121.36 ± 38.37	[61.54 – 70.58] 65.37 ± 4.18
Melia azedarach	**WL**	[0.19 – 0.76] 0.34 ± 0.20 [a]	[6.05 – 19.07] 9.79 ± 3.92 [a]	[3.33 – 13.87] 6.70 ± 3.96 [a]	[18.54 – 47.04] 28.04 ± 8.68 [a]
	UL	[0.38 – 0.95] 0.56 ± 0.17 [a]	[6.51 – 20.00] 11.79 ± 3.69 [b]	[6.67 – 20.00] 10.23 ± 4.29 [a]	[20.00 – 59.66] 35.98 ± 11.83 [b]
	BK	[0.19 – 0.95] 0.69 ± 0.32 [a]	[6.51– 22.79] 17.06 ± 5.29 [b]	[12.55 – 166.67] 79.38 ± 68.70 [b]	[15.31 – 49.61] 33.44 ± 10.99 [b]
Soil		[0.55 – 1.80] 0.94 ± 0.62	[12.24 – 16.45] 13.62 ± 1.93	[79.44 – 148.55] 113.00 ±	[65.47 – 88.78] 72.61 ± 12.62

[a,b]Different letters indicate significant differences (Newman–Keuls test, α = 0.05) between metal contents in plant parts.

In urban areas, the results indicate a relatively high accumulation of heavy metals. The concentrations of the four studied heavy metals (Cd, Cu, Pb, and Zn) vary between species and among different organs within the same species (Table 1).

Cadmium accumulation in the various tree organs follows the following decreasing order : for *Populus alba* : unwashed leaves (UL) > bark (BK) > washed leaves (WL) ; for *Melia azedarach* : bark (BK) > unwashed leaves (UL) > washed leaves (WL). In *Populus alba*, the mean concentrations are approximately 0.67 µg/g in unwashed leaves, 0.57 µg/g in bark, and 0.32 µg/g in washed leaves. In *Melia azedarach*, the highest concentrations are found in bark (0.69 µg/g), followed by unwashed leaves (0.56 µg/g) and washed leaves (0.34 µg/g), with the maximum concentration reaching 0.95 µg/g. These results are similar to those reported by [13] in urban areas of the Constantine region, concerning the leaves and bark of *Cupressus fastigiata* (0.95 and 1.09 µg/g) and *Eucalyptus cladocalyx* (0.57 and 0.50 µg/g), respectively. Very high concentrations were also recorded in a contaminated area of the same region in the leaves of *Ampelodesmos mauritanicus*, reaching maximum values of 1.52 µg/g. Additionally, the concentrations obtained in this study are comparable to those reported by [44], who observed values ranging from 0.1 to 2.73 µg/g in leaves collected near the Tuncbilek thermal power plant in Kütahya, Turkey. For both washed and unwashed leaves, the cadmium levels were lower than those reported by [45] in washed leaves of *Platanus orientalis*, *Robinia pseudoacacia*, and *Fraxinus rotundifolia* collected from the urban area of Karaj, a city in Alborz Province, Iran, characterized by relatively intense vehicular traffic. The concentrations reported by Monfared were 2.4 ± 0.2 µg/g, 2.5 ± 0.1 µg/g, and 2.4 ± 0.2 µg/g for *P. orientalis*, *R. pseudoacacia*, and *F. rotundifolia*, respectively, with corresponding soil concentrations of approximately 3.7 ± 0.3 µg/g. Furthermore, the levels recorded in the present work remain within the same range as those reported by [44] for leaves sampled in the vicinity of the Tuncbilek power plant. However, they are considerably higher than those documented by [46] for *Quercus ilex* leaves collected from urban, roadside, and control environments, where concentrations ranged from 0.01 to 0.09 µg/g in urban areas, 0.007 to 0.21 µg/g along roadsides, and 0.007 to 0.01 µg/g at control sites. Similarly, the cadmium concentrations measured in this study were significantly higher than those reported by [20] in unwashed leaves of *Robinia pseudoacacia* (0.5 ± 0.21 µg/g), *Pinus eldarica* (0.62 ± 0.09 µg/g), *Olea europaea* (0.45 ± 0.17 µg/g), and *Cupressus arizonica* (0.38 ± 0.22 µg/g) collected from the urban area of Yazd, Iran. In the city of Ibadan (Nigeria), [47] reported a cadmium concentration of 0.10 mg/kg in tree bark collected from 65 sites exposed to various anthropogenic activities. Similarly, [48], in a study on the phytoremediation of cadmium-contaminated soils using young Douglas fir trees, observed high Cd concentrations in the wood, particularly in the bark, which exhibited the highest Cd levels among the aerial parts (reaching 6 mg/kg of dry matter in the presence of 68 mg/kg of Cd in the soil).

Regarding copper, its concentrations were higher than those of cadmium. In *Populus alba*, the highest Cu contents were recorded in unwashed and washed leaves, with mean values of 7.73 µg/g and 7.17 µg/g, respectively. For this species, the decreasing order of accumulation was UL > WL > BK. The bark showed concentrations averaging 5.76 µg/g, with a maximum value of 8.84 µg/g. Similar to cadmium, *Melia azedarach* exhibited the same decreasing order of copper accumulation (BK > UL > WL). In this species, bark contained the highest Cu levels, with an average concentration of 17.06 µg/g, followed by unwashed leaves (11.79 µg/g) and washed leaves (8.79 µg/g). These concentrations were notably higher than those measured in *Populus alba* ($Cu_{Melia\ azedarach}$, > $Cu_{Populus\ alba}$). This variation was confirmed by the one-way ANOVA test, which showed statistically significant differences for *Populus alba* ($p < 0.05$) and *Melia azedarach* ($p < 0.01$). [47] reported a copper concentration of 7.29 mg/kg in the bark of trees collected from 65 sites subjected to various anthropogenic activities, whereas [49] recorded Cu concentrations ranging from 1.5 to 82.7 mg/kg in the bark of *Cupressus sempervirens* var. *fastigiata*. Furthermore, [44] reported Cu concentrations ranging from 2.1 to 59 mg/kg in tree leaves. These results are consistent with, and add to, those reported by [9] in the same region, concerning twelve woody tree species (e.g., *Nerium oleander*, *Eucalyptus globulus*, *Acacia cyanophylla*, *Pinus halepensis*, etc.) growing in an urban area characterized by high traffic intensity. Indeed, elevated copper concentrations were recorded in plant tissues, reaching a maximum of 20.00 µg/g in the leaves of *Fraxinus excelsior* and 30.01 µg/g in the bark of *Eucalyptus cladocalyx*. Indeed, most plant species are capable of accumulating considerable amounts of copper in their tissues under both natural and anthropogenic conditions [50]. Copper is an essential component of many enzymes involved in oxidation–reduction reactions [51] ; however, beyond a certain threshold, it becomes toxic. The normal range of Cu concentrations in plants is 3–30 mg/kg [52], whereas its phytotoxic range extends from 20 to 100 mg/kg [53]. In the present study, the measured Cu concentrations never exceeded the upper limit of the normal range, regardless of the plant organ or species analyzed.

For lead (Pb), both studied species exhibited the same decreasing order of accumulation (BK > UL > WL), with *Melia azedarach* showing higher concentrations than *Populus alba*. In *Populus alba* and *Melia azedarach*, the highest Pb levels were recorded in the bark, with mean values of 17.66 µg/g and 79.38 µg/g, respectively. In both species, unwashed leaves showed lower Pb concentrations than bark but higher than washed leaves, with respective values of 10.77 µg/g and 6.40 µg/g for *Populus alba*, and 10.23 µg/g and 6.70 µg/g for *Melia azedarach*. This variation was statistically significant according to the one-way ANOVA test, which revealed significant differences ($p < 0.05$) for *Populus alba* and highly significant differences ($p < 0.001$) for *Melia azedarach*. [54] reported lead concentrations exceeding 50 mg/kg in the leaves of wild woody plants naturally growing in Hunan Province, China. Similarly, [35] found lead levels ranging from 35 to 52 mg/kg while monitoring Cd, Pb, As, and Hg in honeybees, propolis, and pine leaves collected from industrial areas in Izmir, Turkey. Typically, lead contents in plants are below 10 mg/g [55, 56,57,58,53,43]. According to [58], the normal Pb concentration range in plants is 5–10 mg/g, whereas its toxic threshold lies between 30 and 300 mg/g. [55] reported a narrower phytotoxic range of 3–20 mg/g. In the present study, the measured concentrations exceeded natural background levels, regardless of the plant organ or species. Overall, Pb accumulation in vegetation from industrial and urban environments has markedly increased in recent decades. The relationship between lead concentrations and traffic density has been well established by several studies [59,60,61]. For a 1 km road segment carrying approximately 12,000 vehicles per day, lead originates mainly from exhaust emissions (7,227 g/kg/year), lubricants (2.1 g/kg/year), tires (2.6 g/kg/year), brake linings (438 g/kg/year), and de-icing agents (8.5 g/kg/year) [6]. In Algeria, gasoline lead content averages 0.45 g/L [62]. Lead uptake by plants occurs predominantly through atmospheric deposition on leaf surfaces, whereas root-to-shoot translocation represents a minor pathway [63,43]. A study conducted on roadside Populus clones exposed to vehicle exhaust demonstrated stomatal dysfunction, with stomata remaining open and consequently weakening the plants [46]. Exhaust gas components have been shown to inhibit stomatal regulation of opening and closing movements [6]. Approximately half of the atmospheric lead is transported in particulate form, while the remaining fraction is carried by runoff, at an estimated rate of 1 mg/km/vehicle/day [64]. Consequently, lead remains a reliable tracer of vehicular pollution and an indicator of the spatial extent of road influence [65]. Its deposition is enhanced when prevailing winds blow perpendicularly to the roadway and under higher temperature conditions [62]. Zinc concentrations recorded in *Populus alba* were higher than those in *Melia azedarach* ($Zn_{Populus\ alba} > Zn_{Melia\ azedarach}$) regardless of the plant organ. In *Populus alba*, the decreasing order of Zn accumulation was BK > UL > WL, with bark showing a mean concentration of 55.64 µg/g, followed by unwashed leaves (37.81 µg/g) and washed leaves (28.10 µg/g). In *Melia azedarach*, Zn accumulation was highest in unwashed leaves (35.98 µg/g), followed by bark (33.44 µg/g) and washed leaves (28.04 µg/g), corresponding to the order UL > BK > WL. The one-way ANOVA analysis revealed statistically significant differences ($p < 0.05$) for both species. [47] reported a zinc concentration of 30.96 mg/kg in tree bark, whereas [44] observed Zn contents ranging from 1.7 to 222.4 mg/kg in tree leaves. Zinc is an essential element for all living organisms and is regarded as a key factor in the biosynthesis of enzymes, auxins, and certain proteins [50]. The normal Zn concentration range in plants lies between 10 and 150 mg/kg [55, 53, 43], while the critical toxic threshold in leaves is approximately 100 ppm [56, 60]. In the present study, none of the investigated species exhibited Zn concentrations exceeding either normal or toxic limits, regardless of the plant organ analyzed. Moreover, even when plants are exposed to similar sources of heavy metals under comparable environmental conditions, their accumulation patterns remain strongly governed by species-specific physiological and morphological characteristics [66]. Consequently, an interspecific variation was observed in this study for a given organ. Indeed, heavy metal concentrations in washed leaves, unwashed leaves, and bark were found to be species-dependent. In general, the concentration of heavy metals in different plant parts depends on both the metal content of the air and soil, and varies within a species as well as among species [67,68]. The bark acts as an important sink for biologically available metals, with new tissues being added during each growing season. These tissues decompose slowly, allowing the accumulated metals to become immobilized in metabolically inactive compartments for an extended period. Consequently, these metals remain available without adversely affecting tree health, owing to the high porosity of the bark [69,18,22] determining factor in the uptake and bioaccumulation of heavy metals in bark lies in their deposition on the outer surface and translocation from the roots. Metals absorbed through the root system are either stored in the roots or transported to the aerial parts of the plant via the xylem. The ability of plants to transport and sequester metals depends on an efficient metal transport system, vacuolar compartmentalization, an antioxidative defense response, and the overall physiological condition of the plant [70]. [71] demonstrated that lead concentrations in bark respond rapidly to fluctuations in atmospheric lead levels, due to the entrapment of particles within bark fissures. Once deposited, these elements can migrate into various tissues depending on their degree of solubility. A similar study conducted on *Cupressus sempervirens* bark in Amman (Jordan) by [49] concluded that this species can be considered an effective biomarker of urban air pollution. Finally, [72], working in eastern Romania, compared the epiphytic moss *Hypnum cupressiforme* and oak bark (*Quercus* spp.) in terms of their metal accumulation capacity, and found comparable levels of accumulation in both bioindicators, concluding that oak bark is also a reliable biomonitor of atmospheric metal contamination. In *Melia azedarach*, the bark is fissured and scaly, which enhances its capacity to capture and accumulate pollutants and toxins, in contrast to the *Populus alba* bark, which exhibits a smoother structure with small cracks that develop progressively with age.

The results presented in Table 1 show that, overall, zinc concentrations were higher than those of the other studied metals in both species. The following sequences of metal accumulation were observed : For *Populus alba* : $Zn_{BK,UL} > Pb_{BK,UL} > Cu_{BK,UL} > Cd_{BK,UL}$

$Zn_{WL} > Cu_{WL} > Pb_{WL} > Cd_{WL}$

For *Melia azedarach* : $Pb_{BK} > Zn_{BK} > Cu_{BK} > Cd_{BK}$

$Zn_{UL,WL} > Cu_{UL,WL} > Pb_{UL,WL} > Cd_{UL,WL}$

These results are consistent with those reported by [9] in a contaminated area of the Constantine region. In that study, the author highlighted the potential of using woody tree species such as *Eucalyptus gomphocephala*, *Acacia horrida*, *Cupressus sempervirens*, *Olea europaea*, *Pinus halepensis*, *Tamarix gallica*, and *Nerium oleander* for the phytoremediation of urban environments.

Moreover, heavy metal concentrations recorded in the urban area were compared with those from the control site (Figures 2, 3, 4, and 5). A Student's *t*-test was performed to assess the significance of these differences. In the urban area, the results obtained for both species revealed a pronounced accumulation of the four studied elements (Cd, Cu, Pb, and Zn), regardless of the plant organ. For *Populus alba*, Cd concentrations were approximately four times higher in washed leaves and bark, with maximum values of 0.57 µg/g and 0.95 µg/g, respectively, and twice as high in unwashed leaves compared to the control site. The *t*-test indicated a significant difference ($p < 0.01$) for all organs. Copper levels were four times higher in unwashed leaves ($p < 0.01$), reaching a maximum of 10.70 µg/g, and two to three times higher in washed leaves and bark ($p < 0.05$). Lead concentrations were four times higher in washed leaves ($p < 0.05$) and three times higher in unwashed leaves and bark ($p < 0.01$). Zinc levels were three times higher in all organs (unwashed leaves, washed leaves, and bark ; $p < 0.05$), with maximum Pb and Zn concentrations recorded in bark (26.67 µg/g and 138.77 µg/g, respectively). In *Melia azedarach*, Cd, Pb, and Zn concentrations were approximately twice as high in washed leaves from the urban site compared to the control, whereas Cu concentrations were four times higher ($p < 0.01$), reaching a maximum of 19.07 µg/g. In unwashed leaves, concentrations were about three times higher for all four metals, with the *t*-test showing significant differences ($p < 0.05$) for all elements. The maximum recorded concentration reached 59.66 µg/g. Furthermore, bark samples from *Melia azedarach* exhibited substantial enrichment, with Cd, Cu, and Zn concentrations being two to three times higher in the urban area, and Pb levels remarkably elevated approximately ten times higher reaching 166.67 µg/g in the urban site compared to 16.67 µg/g in the control. This difference was highly significant ($p < 0.001$). Recent studies by [9] and [14] in urban environments reported elevated lead (Pb) concentrations in the leaves of several woody species, including *Olea europaea* (13.33 ± 6.67 µg/g), *Pinus halepensis* (22.22 ± 21.17 µg/g), *Fraxinus excelsior* (7.50 ± 1.67 µg/g), *Eucalyptus gomphocephala* (11.11 ± 4.08 µg/g), *Tamarix gallica* (17.70 ± 3.79 µg/g), *Acacia cyanophylla* (10.00 ± 3.85 mg/g), and *Ampelodesmos mauritanicus* (26.55 ± 12.73 µg/g). Similarly, [35] reported Pb concentrations ranging from 35 to 52 mg/kg while monitoring Cd and Pb in poplar and pine leaves from industrial zones in Izmir, Turkey. Plants can readily absorb atmospheric lead following deposition on leaf surfaces ; however, translocation from roots to leaves is not the dominant accumulation pathway [63,43]. Research on roadside poplar clones exposed to vehicle exhaust gases revealed a reduction in gas diffusion resistance due to persistent stomatal opening, leading to physiological stress and dysfunction in the plants [46]. The stomatal regulatory capacity the ability to open and close appears to be inhibited by components of exhaust gases [25]. In urban environments, a substantial fraction of lead is transported in particulate form, with the remainder carried by runoff water, estimated at approximately 1 mg Pb/km/vehicle/day [64]. Lead deposition rates tend to increase when prevailing winds blow perpendicular to roadways and under higher temperature conditions [22]. Consequently, lead serves as a reliable tracer of vehicular pollution, providing an indicator of the spatial extent of road influence, and should not be disregarded [65]. [73] investigated heavy metal (HM) concentrations in tree-ring sequences of *Prosopis juliflora* collected at varying distances from a former copper smelter in San Luis Potosi, Mexico. The study revealed a descending order of metal accumulation as Zn > Cu > Pb, with enrichment factors of 26, 8.6, and 1.4, respectively, relative to the control site. Similarly, [22] compared the bioaccumulation of Cr, Cu, Fe, and Pb in leaves of *Platanus orientalis* L. and *Pinus nigra* Arn. around three European cities (Salzburg, Belgrade, and Thessaloniki). Their results showed a significant increase in metal concentrations in leaves from plants grown in polluted areas compared to those from control sites. A comparable study was conducted by [49] in Amman, Jordan, using bark samples of *Cupressus sempervirens* L. as bioindicators for air quality monitoring. The authors reported higher metal accumulation in industrial and high-traffic areas relative to residential and control sites. Zinc exhibited the highest accumulation (442–111 µg/kg), followed by Pb (445–22.6 µg/kg), Mn (56–4 µg/kg), and Cu (82.7–1.5 µg/kg), whereas Co (0.49–0.011 µg/kg) and Cd (0.83–0.069 µg/kg) showed the lowest values. These findings highlight that urban environments are exposed to multiple airborne contaminants from anthropogenic sources, including solid particles and gaseous emissions. The primary sources of these pollutants are industrial facilities, power plants, domestic heating systems, and motor vehicles, the latter being particularly dominant in urban settings [74]. In Algeria, especially in urban areas, environmental degradation affecting water, soil, and air quality has intensified over decades due to industrial, agricultural, and vehicular activities, as well as inadequate waste management. Constantine city, located within the Kebir Rhumel Basin, exemplifies this situation. The basin encompasses approximately 100 settlements with a total population of 1.62 million, of which 750,000 reside in Constantine alone. Industrial and agricultural activities, along with road traffic, have significantly increased over the past century, with major sources of emissions concentrated within a 20 km radius around the city [13].

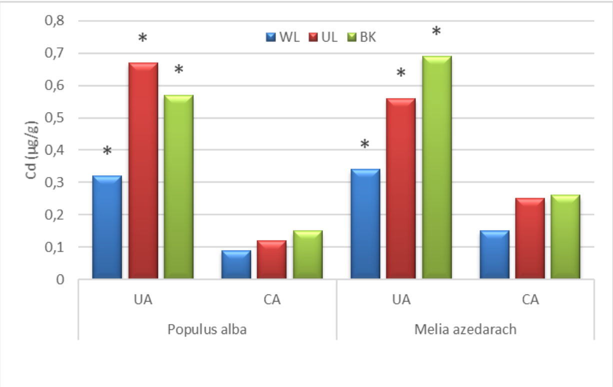

Figure 2. Cadmium concentration in leaves and bark of of studied trees from urban and control areas.

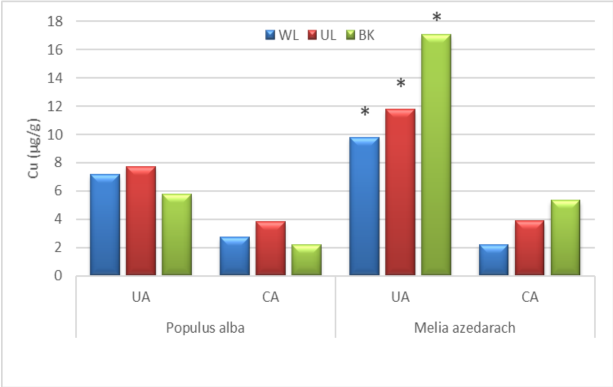

Figure 3. Copper concentration in leaves and bark of of studied trees from urban and control areas.

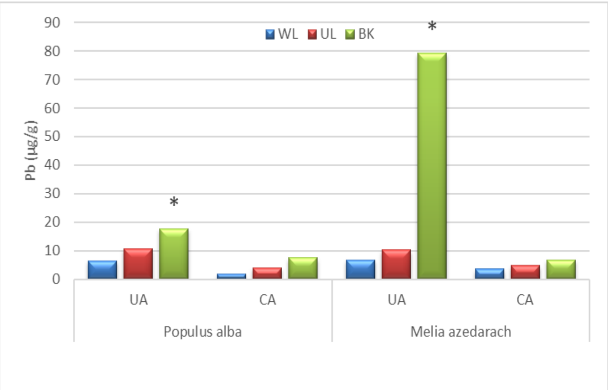

Figure 4. Lead concentration in leaves and bark of of studied trees from urban and control areas.

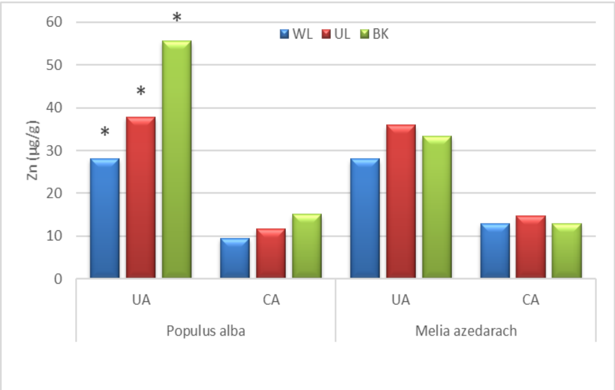

Figure 5. Zinc concentration in leaves and bark of of studied trees from urban and control areas.

Comparative assessment of the heavy metal uptake and accumulation efficiency of the studied species

Metal accumulation index (MAI)

The Metal Accumulation Index (MAI) results obtained for the two studied species are presented in Figure 6.

Overall, the MAI values varied according to both species and plant parts analyzed (unwashed leaves (UL) and bark (BK)). For leaves, a slight difference was observed between the two species, following the sequence : $MAI_{Mellia\ azedarach}$ > $MAI_{Populus\ alba}$. Accordingly, *Melia azedarach* exhibited the highest MAI value (MAI = 14.64), indicating a greater capacity for heavy metal accumulation compared to *Populus alba* (MAI = 14.25). Similarly, bark tissues proved to be effective accumulators of trace metals. The highest MAI value (32.64) was recorded in *Melia azedarach*, whereas the lowest (19.91) was observed in *Populus alba*. The sequence observed for bark followed the same trend as that of the leaves : $MAI_{Mellia\ azedarach}$ > $MAI_{Populus\ alba}$. Moreover, it appears that the accumulation capacity differs depending on the plant part analyzed within the same species. We observed that both species exhibited a higher metal accumulation capacity in the bark than in the leaves (MAI_{BK}> MAI_{UL}). Similar results were reported by [9] in a study on the heavy metal accumulation capacity of urban trees, showing that bark possesses a greater accumulation potential in *Olea europaea*, *Pinus halepensis*, *Fraxinus excelsior*, and *Eucalyptus globulus*. Therefore, bark proves to be a highly valuable organ for the biomonitoring of atmospheric metal pollution. Indeed, tree bark can provide more reliable long-term results, as its structural characteristics enable it to retain pollutants for extended periods [18,75]. In contrast, leaves are periodically shed, whereas bark persists longer on the tree. Furthermore, the rough texture of bark enhances its ability to trap airborne particles [22]. Both leaves and bark of urban tree species are simultaneously exposed to atmospheric and soil pollutants. The variation in the obtained Metal Accumulation Index (MAI) values supports the findings of [76], [43], and [77], who suggested that the capacity for heavy metal accumulation depends on species-specific traits, plant organ type, metal properties, environmental contamination level, species tolerance gradients to heavy metals, and meteorological conditions. Unlike fast-growing trees, the leaves of slow-growing species are more prone to heavy metal accumulation through root uptake from the soil [43]. It should also be noted that species with larger leaf surface areas tend to capture and retain more heavy metals within their tissues. Moreover, several studies have reported that tree leaves can serve as effective bioindicators of atmospheric metal pollution as well as efficient monitoring tools and removal agents for airborne heavy metals [78, 50,79,80].

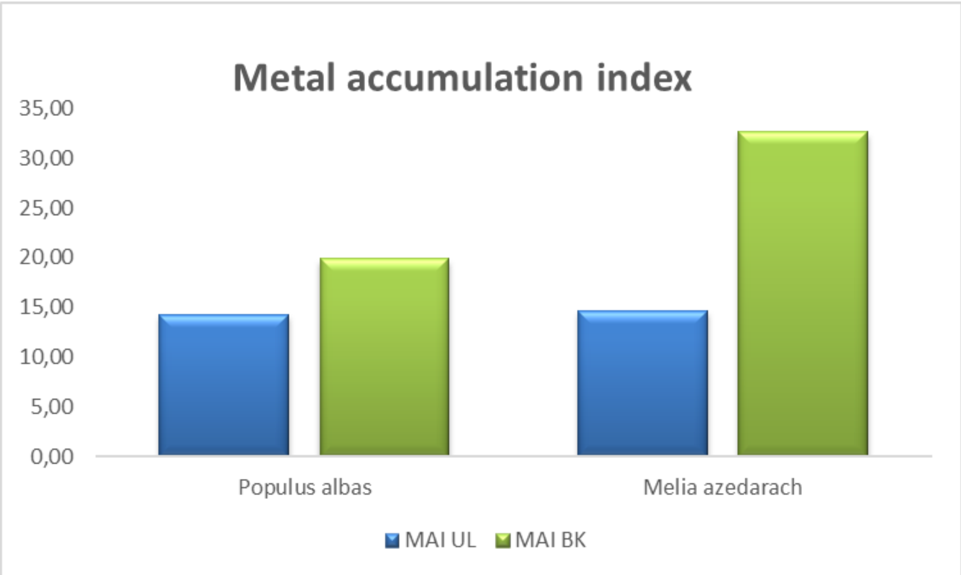

Figure 6. Mean metal accumulation index (MAI) for *Populus alba* and *Melia azedarach*.

Bio-concentration factor (BCF)

The results of the bioconcentration factor (BCF) obtained for the two studied species are presented in Figure 7. According to [81,50,82,83], the bioconcentration factor can be interpreted as follows :

- BCF > 1 : indicates that the species accumulates the metal.
- BCF < 1 : indicates that the species excludes the metal.
- BCF = 1 : indicates that the species can be used as a bioindicator.

For *Populus alba*, the sequences of mean BCF values are the same for both leaves (UL) and bark (BK) : Cd > Zn > Cu > Pb. All mean BCF values for the metals considered in this study (Cd, Cu, Pb, and Zn) are below unity (BCF < 1), indicating that this species generally excludes metals from its leaves and bark. For leaves, the highest mean BCF was observed for Cd (0.94) and the lowest for Pb (0.10). In bark, Cd also showed the highest mean BCF (0.86), while Pb had the lowest (0.16). It should be noted that metal bioconcentration (BCF > 1) was observed in a few individual trees, with extreme values reaching 2.50 for Cd in both leaves and bark, and for Zn in leaves and bark, 1.07 and 2.25, respectively. Zinc (Zn) is an essential micronutrient for plant metabolism [50]. Consequently, plants are capable of accumulating significant amounts of this element in their tissues. These findings are consistent with those of [84], who evaluated the potential of 13 eucalyptus clones for trace metal uptake and biomass production from both natural and contaminated soils. They reported that Zn accumulated more in the leaves than in the stems and branches, suggesting that harvesting the entire aboveground biomass, including leaves, could enhance the phytoextraction potential of these contaminants using *Eucalyptus spp*.

Cadmium (Cd) is a highly toxic micronutrient and a soil pollutant that can be readily absorbed by plant roots via specific transporters and translocated to aerial parts [82]. According to [85], the availability of essential nutrients in the soil significantly influences Cd uptake and accumulation in plants. These authors reported increased Cd accumulation in the leaves, stems, and roots of a *Salix viminalis* clone under magnesium (Mg) and iron (Fe) deficiency. Indeed, Cd^{2+}, Mg^{2+}, and Fe^{2+} ions share the same transport pathways for root uptake and translocation to the aerial parts, potentially leading to competitive interactions within both apoplastic and symplastic compartments. When soluble Cd^{2+} is present in the root zone, it can reach the root apoplast and cross the plasma membranes of root cells [86]. The bioconcentration factors (BCF) for lead (Pb) are relatively low compared to those of the other studied heavy metals, regardless of the plant part analyzed. In a comparative study on the capacity of different plant species to accumulate metals from soil and air, [20] also reported the lowest BCF values for Pb in leaves. Similarly, [54,86,80] determined BCF in the leaves of 18 tree species across several contaminated sites in Hunan, China, and found that Pb exhibited the lowest values. Moreover, [87] demonstrated that in plants growing on contaminated soils, lead predominantly accumulates in the roots rather than in the leaves, and among aerial parts, Pb is more concentrated in leaves than in twigs.

Regarding *Melia azedarach*, the bioconcentration phenomenon is more pronounced, particularly for copper (Cu) and zinc (Zn), which exhibit BCF values greater than 1. The following sequence of mean BCFs was observed for leaves and barks : Cu > Zn > Pb > Cd. Furthermore, both leaves and bark of this species display BCF > 1 for Cu (UL = 2.45 vs. BK = 2.03), demonstrating their capacity to accumulate this metal in their tissues. Notably, the leaves show a higher accumulation capacity than the bark ($BCF_{UL} > BCF_{BK}$), with a maximum BCF of 7.46 for leaves and 6.72 for bark. For Zn, the leaves are effective accumulators (BCF > 1), whereas the bark tends to exclude the metal (BCF < 1), showing an average BCF of 1.39 versus 0.98. Maximum BCF values of 4.73 and 2.82 for leaves and bark, respectively, further confirm their substantial accumulation capacity.

In contrast, for cadmium (Cd) and lead (Pb), the mean BCF values are below unity (BCF < 1) for both plant parts, with values of UL = 0.64 and BK = 0.76 for Cd, and UL = 0.66 and BK = 0.89 for Pb. This indicates that this species generally excludes these metals from its tissues. However, some individual trees are able to accumulate these metals, reaching BCFs > 1, with maxima of 1.73 in the bark and 1.04 in leaves for Cd, and 2.03 versus 2.33 for Pb. In a similar study, [13] reported that 10 out of the 12 species examined accumulate cadmium (Cd) not only in leaves but also in bark, namely : *Eucalyptus cladocalyx*, *Cupressus fastigiata*, *C. horizontalis*, *Olea europaea*, *Eucalyptus gomphocephala*, *Nerium oleander*, *Fraxinus excelsior*, *Eucalyptus globulus*, *Tamarix gallica*, and *Acacia cyanophylla*. Similarly, *Acacia horrida* accumulates Cd, but only in the bark. For most species, accumulation is higher in the leaves. According to [88], depending on their capacity to accumulate trace metals, plant species can be classified into two major groups : "excluders," which preferentially accumulate trace metals in roots with limited translocation to aerial parts, and "hyperaccumulators," which are capable of tolerating and storing high levels of trace metals in their tissues. The potential for trace metal accumulation depends on multiple internal and external factors. Internal factors include root and stem structure, xylem density, antioxidant defense responses, the physiological state of the plant, and the presence of chelating molecules. External factors include soil pH and electrical conductivity, organic matter content, soil texture, topography, the concentration and speciation of trace metals in the soil, sources of pollution, the type of area, and the season (wet or dry), which influence deposition patterns, as well as wind direction [89,90,91,92].

In the study area, the main factor contributing to contamination is the presence of a dense road network and the proximity of the highway, which experiences relatively high traffic for the city of Constantine. A second significant factor is the transport of pollutants from external sources by wind. In this region, prevailing winds blow mainly from the northwest and north, carrying air masses from mountainous areas. Additionally, southerly winds occur primarily in summer and late autumn, often carrying substantial amounts of sand, silt, and particulate matter containing various types of pollutants. Thus, the studied species exhibit a remarkable capacity to accumulate HMs (Cd, Cu, Pb, and Zn). Therefore, selecting these species for air quality monitoring, particularly in urban areas, is highly relevant. According to [42], species with high MAI and BCF values, as observed in this study, represent suitable candidates for planting in cities and urban zones where metal contamination poses a concern [93],. Moreover, these species can serve as vegetative barriers between polluted areas and vulnerable zones [43,82]. Compared to lower plants, trees have a higher potential for HM accumulation due to their larger leaf surface area, greater biomass, and longer lifespan.

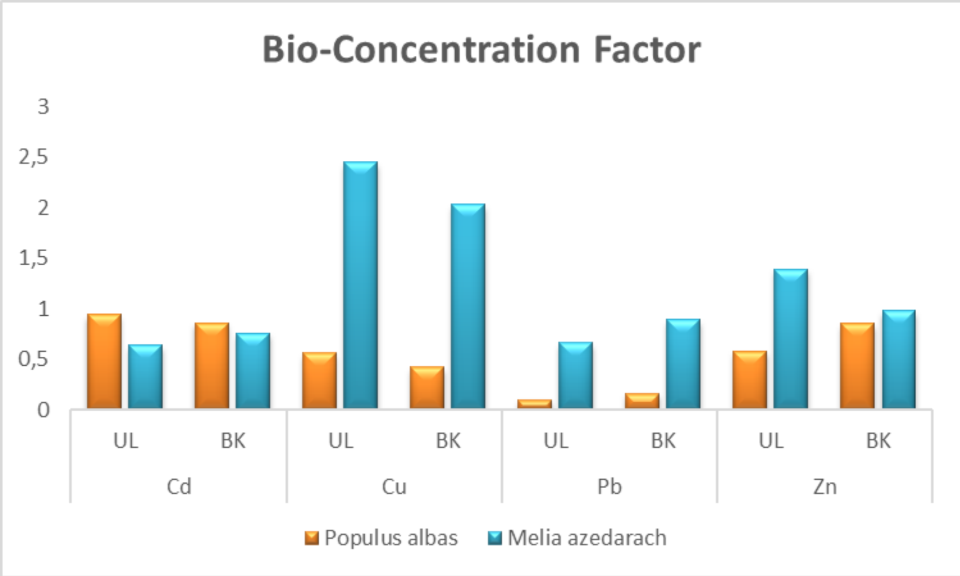

Figure 7. Mean bio-concentration factor (BCF) for leaves and barks for *Populus alba* and *Melia azedarach*.

4. Conclusion

The objective of this study was to assess the concentrations of four heavy metals (Cd, Cu, Pb, and Zn) in the leaves (washed and unwashed) and bark of two tree species, *Populus alba* and *Melia azedarach*, growing in a contaminated area with intense road traffic and in a non-contaminated area distant from any anthropogenic disturbances. The study also aimed to evaluate their capacity to accumulate these metals and their potential use in phytoremediation.

Different metal concentrations were observed between the studied species as well as among the various plant parts within the same species. Indeed, all concentrations recorded in unwashed leaves were higher than those in washed leaves (UL > WL), regardless of the species. For Cd and Cu, *Populus alba* exhibited higher concentrations in unwashed leaves than in bark (UL > BK), whereas in *Melia azedarach*, bark showed greater accumulation (BK > UL). Lead (Pb) concentrations were higher in bark than in leaves for both species (BK > UL). Zinc (Zn) was more accumulated in unwashed leaves of *Melia azedarach* (UL > BK), while in *Populus alba*, it was more concentrated in bark (BK > UL). Moreover, heavy metal concentrations in the urban area were consistently higher than those in the control area (UA > CA), regardless of the species or plant part analyzed. This variation is mainly attributed to anthropogenic activities and the intensity of road traffic, which represent the primary sources of metal pollution in urban atmospheres. Consequently, *Populus alba* and *Melia azedarach* were identified as effective bioindicators of atmospheric metal pollution. The values of the Metal Accumulation Index (MAI) varied depending on both the species and the plant parts analyzed. *Melia azedarach* exhibited the highest MAI value (MAI = 14.64), indicating a greater capacity for heavy metal accumulation compared to *Populus alba* (MAI = 14.25). Similarly, bark tissues were found to be efficient accumulators of heavy metals.

The obtained Bioconcentration Factor (BCF) values suggest that both species can be effectively used in biomonitoring programs to accumulate and/or extract heavy metals, as well as to identify ecological disturbances and their impacts on ecosystems. *Melia azedarach* demonstrated a stronger ability to accumulate trace metals, whereas *Populus alba* showed greater efficiency in excluding metals from its tissues.

Based on these findings, although herbaceous plants may accumulate higher concentrations of metals and exhibit greater bioconcentration factors than woody species, an environmentally

sustainable approach to remediate contaminated areas involves the use of woody trees characterized by their strong pollutant accumulation capacity and high biomass production.
In general, trees are considered suitable candidates for phytoremediation purposes due to their rapid and substantial biomass production, significant economic value, broad genetic variability, well-established cultivation practices, high public acceptability, and their contribution to site stabilization by limiting the migration of trace metals through leaching, erosion, or wind dispersion.
This study provides valuable insights that could inform future urban planning strategies and vegetation management in the region.

5. References :

1. Saxena, V. Water Quality, Air Pollution, and Climate Change: Investigating the Environmental Impacts of Industrialization and Urbanization. *Water Air Soil Pollut*, **2025**, **236**, 73. https://doi.org/10.1007/s11270-024-07702-4

2. Nedjimi, B., Daoud, Y. Cadmium accumulation in *Atriplexhalimus* subsp. Schweinfurthii and its influence on growth, proline, root hydraulic conductivity and nutrient uptake, **2009**, Flora. 204 : 316–324.

3. Liu, YJ., Zhu, YG., Ding, H. Lead and cadmium in leaves of deciduous trees in Beijing, China: development of a metal accumulation index (MAI). Environ Pollut., **2007,**145(2):387–390. doi:10.1016/ j.envpol.2006.05.010.

4. Ali, Hazre., Khan, Ezzat., Ilahi, Ikram. Environmental Chemistry and Ecotoxicology of HazardousHeavy Metals: Environmental Persistence, Toxicity,and Bioaccumulation, Journal of Chemistry, **2019**, Article ID 6730305, 14 pages https://doi.org/10.1155/2019/6730305

5. Hembram, T.K., Saha, S. Prioritization of sub-watersheds for soil erosion based on morphometric attributes using fuzzy AHP and compound factor in Jainti River basin, Jharkhand, Eastern India. *Environ Dev Sustain*, **2020**, **22**, 1241–1268 https://doi.org/10.1007/s10668-018-0247-3

6. Maatoug, M., Hellal, B., Dellal, A. and Ayad, N. Bourbatach, M. Détection de la pollution de l'air d'origine routière par certaines espèces végétales bioaccumulatrices de quelques métaux lourds (Pb, Zn, Cu). Pollution atmosphérique, **2007,** Octobre-Décembre N°196, 2007, 385-394.

7. Maizi, N., Alioua, A., Ali Tahar, A., Semadi, F., and Fadel, D. Utilisation des végétaux inférieurs comme bio indicateurs de la pollution plombique d'origine automobile dans la régionde Annaba (Algérie). J. Mater. Environ. Sci, **2010**, pp: 251-266.

8. Lakhdari, A., and Benabdeli, K. Determining the heavy metal pollution in Mascara (Algeria) by Using Casuarina equisetifolia. Ecol Balkanica, **2012**, 4(1):1–7, http://web.uniplovdiv.bg/mollov/EB/2012/eb. 11118.pdf

9. Alatou, H. Utilisation des sols et arbres des bords de routes comme indicateurs de la pollution atmosphérique métallique : approches physico-chimique, biochimique et écotoxicologique. Thèse de doctorat. Université Frères Menturi Constantine, **2020**, 270 p

10. Sahli, L., Afri-Mehennaoui, F.Z., El-Hadef El-Okki, M., Férard, J.F., and Mehennaoui, S. Assessment of Sediment Quality and Pore Water Ecotoxicity in Kebir Rhumel basin (NE-Algeria): a combined approach. Water Sci Technol, **2012**, 65(2) :393–401.

11. Krika, A., Rached, O. and Gijs DL. Assessment of atmospheric lead contamination of banks soils using soils tamarisk grove. Case study of the Kebir Rhumel (Algeria). Carpathian J Earth Environ Sci, **2013**, 8(1): 207–216. http://hdl.handle.net/1854/LU-4375511.

12. El-Hadef El-Okki, M., Sahli, L., Bentellis, A., Azzoug, R., Du Laing, G. and Rached, O. Assessment of metal contamination in soil banks of the Rhumel wadi (Northeast Algeria). Toxicol Environ Chem, **2015**, 98(1):53–63.

13. Alatou, H. and Sahli, L. Using tree leaves and barks collected from contaminated and uncontaminated areas as indicators of air metallic pollution, International Journal of Phytoremediation, **2019**, DOI: 10.1080/15226514.2019.1583723

14. Alatou, H., Alatou, D., Arfa, AMT., Gana, M., Meliani, A. Ecophysiological responses of *Ampelodesmos mauritanicus* to xenobiotic stress in urban environments. *Afr.J.Bio.Sc.7(4)*, **2025,** ISSN: 2663-2187, *doi:10.48047/AFJBS.7.4.2025.1206-1222*

15. Lounamaa, J. Trace elements in plants growing wild on different rocks in Finland. Ann Bot Soc Zool Bot Fennicae Vanamo, **1956**, 29(4): 196.

16. Pacheco, AM., Barros, I.C., Freitas, M.C., Reis, M.A., Hipolito, C., Oliveira, O.R. An evaluation of olive-tree barks for the biological monitoring of airborne trace-elements at ground level. Environ Pollut, **2002** 120(1):79–86.

17. Tomasevic, M., Vukmirovic, Z., Rajsic, S., Tasic, M., Stevanovic, B. Characterisation of trace metal particles deposited on some deciduous tree leaves in an urban area. Chemosphere, **2005**, 61:753–760. doi: 10.1016/j.chemosphere.2005.03.077.

18. Berlizov, A., Blum, O., Filby, R., Malyuk, I., Tryshyn, V. Testing applicability of black poplar (Populus nigra L.) bark to heavy metal air pollution monitoring in urban and industrial regions. Sci Total Environ, **2007** 372(2–3):693–706. doi : 10.1016/j.scitotenv.2006.10.029.

19. Gratani, L., Crescente, MF., Varone, L. Long-term monitoring of metal pollution by urban trees. Atmos Environ, **2008,** 42(35) :8273–8277. doi : 10.1016/j.atmosenv.2008.07.032.

20. Allahabadi, A., Ehrampoush, MH., Miri, M., Ebrahimi, Aval H., Yousefzadeh, S., Ghaffari, HR., Ahmadi, E., Talebi, P., Abaszadeh, Fathabadi, Z., Babai, F. A comparative study on capability of different tree species in accumulating heavy metals from soil and ambient air. Chemosphere, **2017**, 172 :459–467. doi:10.1016/ j.chemosphere.2017.01.045.

21. Berdonces, MAL., Higueras, PL., Fern_andez-Pascual, M., Borreguero, AM., Carmona, M. The role of native lichens in the biomonitoring of gaseous mercury at contaminated sites. J Environ Manag, **2017**, 186 : 207–213. doi : 10.1016/j.jenvman.2016.04.047.

22. Sawidis, T., Breuste, J., Mitrovic, M., Pavlovic, P., Tsigaridas, K. Trees as bioindicator of heavy metal pollution in three European cities. Environ Pollut, **2011**, 159(12):3560–3570. doi: 10.1016/j.envpol.2011.08.008.

23. Birke, M., Rauch, U., Hofmann, F. Tree bark as a bioindicator of air pollution in the city of Stassfurt, Saxony-Anhalt, Germany. J Geochem Explor, **2018,** 187:97–117. doi: 10.1016/j.gexplo.2017.09.007.

24. Migeon, A., Blaudez, D., Guinet, F., Chalot, M., Botton, B. Accumulation des m_etaux lourds chez le Peuplier : localisation tissulaire et expression de quelques transporteurs. AJAE, **2011**, 1(1):10–18. https://www.asjp.cerist.dz/en/article/646

25. Maatoug, M., Medkour, K., Ait Hammou, M., Ayad, N. Cartography of atmospheric pollution by the lead from road traffic using transplantation of a lichen bioaccumulator Xanthoria parietina in Tiaret city (Algeria). Pollut Atmos, **2010,** 205:10. doi:10.4267/pollutionatmospherique. 734.

26. Opydo, JK., Ufnalski, K., Opydo, W. Heavy metals in polish forest stands of Quercus robur and Q. petraea. Water Air Soil Pollut, **2005**, 161(1–4):175–192. doi:10.1007/s11270-005-3522-5.

27. Mingorance, M., Rossini, O. Heavy metals content in n. oleander leaves as urban pollution assessment. Environ Monit Assess, **2006,** 119(1–3):57–68. doi:10.1007/s10661-005-9004-9.

28. Cameselle, C., Gouveia, S., & Urréjola, S. Benefits of phytoremediation amended with DC electric field : Application to soils contaminated with heavy metals. *Chemosphere*, 2019, 229, 481-488. https://doi.org/10.1016/j.chemosphere.2019.04.222

29. Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. *Phytoremediation: A Promising Approach for Revegetation of Heavy Metal-Polluted Land, **2020***, Frontiers in Plant Science, 11, 359. https://doi.org/10.3389/fpls.2020.00359

30. Nkongolo, KK., Spiers, G., Beckett, P., and Narendrula-Kotha, R.Effects of Phytoremediation on Microbial Biomass, Composition, and Function in a Sulphide-Rich Tailing From a Metal-Contaminated Region. Front. Environ. Sci, **2022**, 10:908633. doi: 10.3389/fenvs.2022.908633

31. Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A. *Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity*. Journal of King Saud University – Science, **2022**, 34 (3), Article ID 101865. https://doi.org/10.1016/j.jksus.2022.101865 colab.ws+1

32. Ghori, N.-H., Ghori, T., Hayat, M. Q., Imadi, S. R., Gul, A., Altay, V., & Öztürk, M. *Heavy metal stress and responses in plants. International Journal of Environmental Science and Technology*, **2019** 16(3), 1807-1828. https://doi.org/10.1007/s13762-019-02215-8

33. Bellido-Pedraza, C. M.; Torres, M. J.; Llamas, A. The Microalgae *Chlamydomonas* for Bioremediation and Bioproduct Production. *Cells* **2024**, *13*(13), 1137. https://doi.org/10.3390/cells13131137

34. Oliva, SR., and Rautio, P. Spatiotemporal patterns in foliar element concentrations in Ficus microcarpa L. f. growing in an urban area: implications for biomonitoring studies. Ecol Indic, **2006,** 5(2):97–107.

35. Matin, G., Kargar, N., and Buyukisik, HB. Bio-monitoring of cadmium, lead, arsenic and mercury in industrial districts of Izmir, Turkey by using honey bees, propolis and pine tree leaves. Ecol Eng, **2016**, 90: 331–335.

36. Safari, M., Ramavandi, B., Sanati, A.M., Sorial, G.A., Hashemi, S., Tahmasebi, S. Potential of trees leaf/bark to control atmospheric metals in a gas and petrochemical zone. J Environ Manage., **2018**, 222 :12–20.

37. Pais, I., and Jones, JB. The handbook of trace elements. Boca Raton (FL): Saint Lucie Press, **2000**, p. 223.

38. Zhuang, P., Yang, Q., Wang, HB., Shu, W. Phytoextraction of heavy metals by eight plant species in the field. Water Air Soil Pollut, **2007**, 184(1–4):235–242. doi:10.1007/s11270-007-9412-2.

39. Xiaohai, L., Yuntao, G., Khan, S., Gang, D., Aikui, C., Li, L., Lei, Z., Zhonghan, L., Xuecan, W. Accumulation of Pb, Cu, and Zn in native plants growing on contaminated sites and their potential accumulation capacity in Heqing, Yunnan. J Environ Sci, **2008** 20:1469–1474. doi: 10.1016/S1001-0742(08)62551-6.

40. Shi, X., Zhang, X., Chen, G., Chen, Y., Wang, L., Shan, X. Seedling growth and metal accumulation of selected woody species in copper and lead/zinc mine tailings. J Environ Sci, **2011,** 23(2):266–274. doi: 10.1016/S1001-0742(10)60402-0.

41. Hladun, KR., Parker, DR., Trumble, JT. Cadmium, copper, and lead accumulation and bioconcentration in the vegetative and reproductive organs of Raphanus sativus: implications for plant performance and pollination. J Chem Ecol, **2015**, 41(4):386–395. doi:10.1007/s10886- 015-0569-7.

42. Liu, YJ., Zhu, YG., Ding, H. Lead and cadmium in leaves of deciduous trees in Beijing, China: development of a metal accumulation index (MAI). Environ Pollut, **2007**, 145(2):387–390. doi:10.1016/ j.envpol.2006.05.010.

43. Hu, Y., Wang, D., Wei, L., Zhang, X., Song, B. Bioaccumulation of heavy metals in plant leaves from Yanan city of the Loess Plateau, China. Ecotoxicol Environ Saf, **2014**, 110:82–88. doi:10.1016/ j.ecoenv.2014.08.021.

44. Cicek, A., Koparal, AS. Accumulation of sulfur and heavy metals in soil and tree leaves sampled from the surroundings of Tuncbilek Thermal Power Plant. Chemosphere, **2004** 57(8):1031–1036. doi:10.1016/ j.chemosphere.2004.07.038.

45. Monfared, A., Azhari, Sh., and Khodaparast, R. Recording of forty species of bees (Hymenoptera: Apoidea) from cold regions of Kuhgiluyeh & Boyrahmad province, Iran. *Proceedings of 20th Iranian Plant Protection Congress*, **2012**, Shiraz University, p. 222.

46. Alfani, A., Baldantoni, D., Maisto, G., Bartoli, G., Virzo De Santo, A. Temporal and spatial variation in C, N, S and trace element contents in the leaves of Quercus ilex within the urban area of Naples. Environ Pollut, **2000**, 109(1):119–129. doi:10.1016/S0269-7491(99)00234-1.

47. Ejidike, IP., Onianwa, PC. Assessment of trace metals concentration in tree barks as indicator of atmospheric pollution within Ibadan City, South-West, Nigeria. J Anal Methods Chem, **2015**:1–8. doi:10.1155/2015/243601.

48. Astier, C., Gloaguen, V., Faugeron, C. Phytoremediation of cadmium-contaminated soils by young douglas fir trees: effects of cadmium exposure on cell wall composition. Int J Phytoremediation, **2014** 16(7–8):790–803. doi:10.1080/15226514.2013.856849.

49. El-Hasan, T., Al-Omari, H., Jiries, A., Al-Nasir, F. Cypress tree (Cupressus semervirens L.) bark as an indicator for heavy metal pollution in the atmosphere of Amman City, Jordan. Environ Int, **2002**, 28(6):513–519. doi:10.1016/S0160-4120(02)00079-X.

50. Serbula SM, Miljkovic DD, Kovacevic RM, Ilic AA. Assessment of airborne heavy metal pollution using plant parts and topsoil. Ecotoxicol Environ Saf, **2012**, 76:209–214. doi:10.1016/ j.ecoenv.2011.10.009.

51. Celik, A., Kartal, AA., Akdo-gan, A., Kaska, Y. Determining the heavy metal pollution in Denizli (Turkey) by using Robinio pseudo-acacia L. Environ Int, **2005**, 31(1):105–112. doi:10.1016/j.envint.2004.07.004.

52. Kabata-Pendias, A., Pendias, H. Trace elements in soils and plants. 3rd ed. Boca Raton (FL): CRC Press, **2001,** 331 p.

53. Padmavathiamma, PK., Li, LY. Phytoremediation technology: hyperaccumulation metals in plants. Water Air Soil Pollut, **2007**, 184(1–4): 105–126. doi:10.1007/s11270-007-9401-5.

54. Zhao, X., Liu, J., Xia, X., Chu, J., Wei, Y., Shi, S., Chang, E., Yin, W., Jiang, Z. The evaluation of heavy metal accumulation and application of a comprehensive bioconcentration index for woody species on contaminated sites in Hunan, China. Environ Sci Pollut Res, **2014** 21(7): 5076–5085. doi:10.1007/s11356-013-2393-3.

55. Markert, B. Establishing of reference plant for inorganic characterization of different plant species by chemical fingerprinting. Water Air Soil Pollut, **1992**, 64(3–4):533–538. doi:10.1007/BF00483363.

56. Allen, SE. Chemical analysis of ecological materials. 2nd ed. Oxford (London): Blackwell Scientific Publications, **1989**

57. Brooks, RR. Geobotany and hyperaccumulators. In: Brooks RR, editors. Plants that hyperaccumulate heavy metals. Wallingford (UK): CAB International, **1998**, p. 55–94.

58. Kabata-Pendias, A., Pendias H. Trace elements in soils and plants. 3rd ed. Boca Raton (FL): CRC Press, **2001**, 331 p.

59. Li, XD., Poon, CS., Liu, PS. Heavy metals contamination of urban soils and street dusts in Hong Kong. Appl Geochem, **2001**, 16(11–12): 1361–1368.

60. Yilmaz, S., Zengin, M. Monitoring environmental pollution in Erzurum by chemical analysis of Scots pine (Pinus sylvestris L.) needles. Environ Int, **2004**, 29(8):1041–1047. doi:10.1016/S0160- 4120(03)00097-7.

61. Viard, B., Pihan, F., Promeyrat, S., Pihan, JC. Integrated assessment of heavy metal (Pb, Zn, Cd) highway pollution: bioaccumulation in soil, Graminaceae and land snails. Chemosphere. 55(10):1349–1359. doi:10.1016/j.chemosphere, **2004**.01.003.

62. Semadi, A., Deruelle, S. 1993. Détection de la pollution plombique à l'aide de transplants lich_eniques dans la région de Annaba (Alg_erie). Pollut Atmos, **1993**, 86:101. http://lodel.irevues.inist.fr/pollution-atmospherique/ index.php?id¼4304

63. Turer D, Maynard JB, Sansalone JJ. Heavy metal contamination in soils of urban highways comparison between runoff and soil concentrations at Cincinnati, Ohio. Water Air Soil Pollut, **2001**, 132(3/4): 293–314.

64. Deruelle, S. Effets de la pollution atmosph_erique sur la vegetation lichenique dans le bassin Parisien. Convention de recherche n_79- 15, ministere de l'Environnement et du Cadre de Vie, **1981**, 91–112.

65. Carsignol, J., Calovi, L. La pollution des sols et des vegetaux a proximité des routes. Les elements traces metalliques (ETM). Service d'Etudes techniques des routes et autoroutes, **2004,** 3–12 p.

66. Mukherjee, A., Agrawal, SB., Agrawal, M. Heavy metal accumulation potential and tolerance in tree and grass species. In: Singh A, Prasad S, Singh R, editors. Plant responses to Xenobiotics. Singapore: Springer, **2016,** p. 177–210.

67. Satpathy, D., Reddy, M. Phytoextraction of Cd, Pb, Zn, Cu and Mnn by Indian mustard (Brassica juncea L.) grown on loamy soil amended with heavy metal contaminated municipal solid waste compost. Appl Ecol Environ Res, **2013**, 11(4):661–679. doi:10.15666/aeer/ 1104_661679.

68. Ipeaiyeda, AR., Dawodu, M. Assessment of toxic metal pollution in soil, leaves and tree barks: bio-indicators of atmospheric particulate deposition within a university community in Nigeria. Adv Environ Sci, **2014**, 6:101–110. http://www.aes.bioflux.com.ro/docs/2014. 101-110.pdf

69. Mandiwana, KL., Resane, T., Panichev, N., Ngobeni, P. The application of tree bark as bio-indicator for the assessment of Cr (VI) in air pollution. J Hazard Mater, **2006,** 137(2):1241–1245. doi:10.1016/ j.jhazmat.2006.04.015.

70. Kraamer U. Metal hyperaccumulation in plants. Annu Rev Plant Biol, **2010,** 61:517–534. doi:10.1146/annurev-arplant-042809-112156.

71. Szopa, PS., Ginnes, Ea M., Pierce, JO. Distribution of lead within the xylem of trees exposed to airborne lead compounds. Wood Sci, **1973,** 6 :72–77. https://www.osti.gov/biblio/6166880

72. Cucu-Man, S., Steinnes, S. Analysis of selected biomonitors to evaluate the suitability for their complementary use in monitoring trace element atmospheric deposition. Environ Monit Assess, **2013,** 185(9): 7775–7791. doi:10.1007/s10661-013-3135-1.

73. Beramendi-Orosco, LE., Rodriguez-Estrada, ML., Morton-Bermea, O., Romero, FM., Gonzalez Hernandez, G., Hernandez-Alvarez, E. Correlations between metals in tree-rings of Prosopis juliflora as indicators of sources of heavy metal contamination. Appl Geochem, **2013,** 39:78–84. doi:10.1016/j.apgeochem.2013.10.003.

74. Nriagu, J., Pacyna, J. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature, **1988,** 333(6169):134–139. doi:10.1038/333134a0.

75. Oujdi, M.; Chafik, Y.; Boukroute, A.; Bourgerie, S.; Sena-Velez, M.; Morabito, D.; Addi, M. *Exploring Phytoremediation Potential: A Comprehensive Study of Flora Inventory and Soil Heavy Metal Contents in the Northeastern Mining Districts of Morocco.* Plants **2024**, 13(13), 1811. https://doi.org/10.3390/plants13131811

76. Yin, S., Shen, Z., Zhou, P., Zou, X., Che, S., Wang, W. Quantifying air pollution attenuation within urban parks: an experimental approach in Shanghai, China. Environ Pollut, **2011,** 159(8–9):2155–2163. doi: 10.1016/j.envpol.2011.03.009.

77. Nadg_orska-Socha, A., Kandziora-Ciupa, M., TrzeR, sicki M., Barczyk ; G. Air pollution tolerance index and heavy metal bioaccumulation in selected plant species from urban biotopes. Chemosphere, **2017**, 183:471–482. doi:10.1016/j.chemosphere.2017.05.128.

78. Yang, X., Feng, Y., He, Z., Stoffell, PJ. Molecular mechanisms of heavy metal hyperaccumulation and phytoremediation. J Trace Elem Med Bio, **2005,** 18(4):339–353. doi:10.1016/j.jtemb.2005.02.007.

79. Mok, HF., Majumder, R., Laidlaw, WS., Gregory, D., Baker, AJ., Arndt, SK. Native Australian species are effective in extracting multiple heavy metals from biosolids. Int J Phytoremediation, **2013,** 15(7):615–632. doi:10.1080/15226514.2012.723063.

80. Alghamdi, S. A.; El-Zohri, M. *Phytoremediation Characterization of Heavy Metals by Some Native Plants at Anthropogenic Polluted Sites in Jeddah, Saudi Arabia.* Resources **2024**, *13*(7), 98. https://doi.org/10.3390/resources13070098

81. Yoon, J., Cao, X., Zhou, Q., Ma, LQ. Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. Sci Total Environ, **2006,** 368(2–3):456–464. 15, doi:10.1016/ j.scitotenv.2006.01.016.

82. Zhai, Y., Dai, Q., Jiang, K, Zhu, Y., Xu, B., Peng, C., Wang, T., Zeng, G. Trafficrelated heavy metals uptake by wild plants grow along two main highways in Hunan Province, China: effects of soil factors, accumulation ability, and biological indication potential. Environ Sci Pollut Res, **2016**, 23(13):13368–13377. doi:10.1007/s11356-016-6507-6.

83. Liang, J., Fang, H., Zhang, T., Wang, X., Liu, Y. Heavy metal in leaves of twelve plant species from seven different areas in Shanghai, China. Urban for. Urban Green, **2017,** 27:390–398. doi:10.1016/ j.envpol.2006.05.010.

84. Mughini-Gras, L., Smid, J. H., Wagenaar, J. A., Koene, M. G. J., Havelaar, A. H., Friesema, I. H. M., French, N. P., Flemming, C., Galson, J. D., Graziani, C., Busani, L., & van Pelt, W. *Increased risk for Campylobacter jejuni and C. coli infection of pet origin in dog owners and evidence for genetic association between strains causing infection in humans and their pets.* Epidemiology and Infection, 2013, 141(12), 2526–2535. https://doi.org/10.1017/S0950268813000356

85. Borišev, M., Borišev, I., Župunski, M., Arsenov, D., Pajević, S., Ćurčić, Ž., Vasin, J., & Djordjević, A. *Drought impact is alleviated in sugar beets (Beta vulgaris L.) by foliar application of fullerenol nanoparticles.* PLoS ONE, **2016,** 11(11), e0166248. https://doi.org/10.1371/journal.pone.0166248

86. Shehata, S. M., Badawy, R. K., & Aboulsoud, Y. I. E. *Phytoremediation of some heavy metals in contaminated soil.* Bulletin of the National Research Centre, **2019**, 43, 189. https://doi.org/10.1186/s42269-019-0214-7

87. Nedjimi, B. and Daoud, Y. Cadmium accumulation in *Atriplexhalimus* subsp. Schweinfurthii and its influence on growth, proline, root hydraulic conductivity and nutrient uptake. Flora, 2009, 204 : 316–324.

88. Brooks, RR. Geobotany and hyperaccumulators. In: Brooks RR, editors. Plants that hyperaccumulate heavy metals. Wallingford (UK): CAB International, **1998**, p. 55–94.

89. Verbruggen, N., Hermans, C., Schat, H. Molecular mechanisms of metal hyperaccumulation in plants. New Phytol, **2009,** 181(4):759–776. doi:10.1111/j.1469 8137.2008.02748.x.

90. Chao, Y., Zhang, M., Feng, Y., Yang, X., Islam, E. cDNA-AFLP analysis of inducible gene expression in zinc hyperaccumulator Sedum alfredii Hance under zinc induction. Environ Exp Bot ; **2010**, 68(2): 107–112. doi:10.1016/j.envexpbot.2009.11.013.

91. Ugolini, F., Tognetti, R., Raschi, A., Bacci, L. Quercus ilex L. as bioaccumulator for heavy metals in urban areas: effectiveness of leaf washing with distilled water and considerations on the trees distance from traffic. Urban For Urban Green, **2013,** 12(4):576–558. doi:10.1016/ j.ufug.2013.05.007.

92. Li, Y., Chen, YY., Yang, SG., Tian, WM. Cloning and characterization of HbMT2a, a metallothionein gene from Hevea brasiliensis Muell. Arg differently responds to abiotic stress and heavy metals. Biochem Biophys Res Commun, **2015,** 461(1):95–101. doi:10.1016/ j.bbrc.2015.03.175.

93. Tamma, A. A., Lejcuś, K., Fiałkiewicz, W., & Marczak, D. *Advancing phytoremediation: A review of soil amendments for heavy metal contamination management. Sustainability,* ***2025****, 17*(13), 5688. https://doi.org/10.3390/su17135688