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RESEARCH PAPER

Atmospheric Trace Metal Exposure in a 60-Year-Old Wood: A Sustainable Methodological Approach to Measurement of Dry Deposition

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Abstract

Urban trees are essential in improving environmental quality and enhancing human welfare in urban areas. They are being utilized increasingly as biomonitors of air and dust-borne heavy metals through dendrochemistry and comparative analytical methods. This study investigated the foremost concern essential nutrient metals, including aluminum (Al) and iron (Fe); also trace metals (cadmium (Cd), chromium (Cr), cobalt (Co), nickel (Ni), copper (Cu), and lead (Pb)) in worldwide-distributed trees in units of mg kg^{-1} dry weight (d.w). For retrospective analysis, we hypothesized that its feasibility as a bioindicator of air pollution in Düzce, Türkiye, among the tree species should be assessed. Digested tree wood samples were processed via inductively coupled plasma optical emission spectrometry (ICP-OES) for all metals to test this hypothesis. Pearson's correlation analysis and principal component analysis were utilized to determine the origin of elements. The results showed that (i) the mean concentrations of the species were presented to be Fe (156 mg kg^{-1} d.w) > Al (100.56 mg kg^{-1} d.w) > Cr (15.82 mg kg^{-1} d.w) > Cu (12.43 mg kg^{-1} d.w) > Pb (6.76 mg kg^{-1} d.w) > Ni (5.98 mg kg^{-1} d.w) > Co (2.16 mg kg^{-1} d.w) > Cd (0.47 mg kg^{-1} d.w); ii) analysis of the bioconcentration factor (BCF) and metal accumulation index (MAI) showed that the maximum BCF and MAI value was stored in the *Cupressus arizonica* (2.30 for Pb) and *Robinia pseudoacacia* (70.65) in all species; iii) the tree woods were also capable of discriminating between affected areas, as sites near industrial and vehicular traffic indicated higher metal content. For this reason, it can be deduced that *C. arizonica* wood is a potentially suitable sink of atmospheric metal.

Highlights

- Sixteen tree wood samples were analyzed for essential and trace metals from Düzce, Türkiye.
- Mean concentrations followed the order: Fe > Al > Cr > Cu > Pb > Ni > Co > Cd.
- Principal component analysis revealed metal sources from industrial activities, traffic emissions, and natural origins.
- *C. arizonica* had the highest bioconcentration factor (2.30) for Pb among all species.
- Wood of *C. arizonica* is identified as a potentially suitable bioindicator of atmospheric metal pollution.

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Introduction

Recently, the increasing environmental awareness worldwide has increased due to rapid economic expansion and industrial development (Liang et al. 2019). Due to the inadequacy of environmental policies in developing countries, monitoring air pollution and the application of biota on an urban scale is quite tricky (Idrees and Zheng 2020). Trace metals (TMs) carried by air and dust, which are among the increasing factors of environmental pollution, have become an effective and sustainable passive monitoring tool in urban air quality (UAQ) due to their biological accumulation and persistence in plants through various means (Voordeckers et al. 2021). The increase in the number of people living in numerous urban morphologies and the faster pace of industrialization compared to previous years have increased the release of TMs, constituting a significant amount of environmental pollution (Takahashi et al. 2020). In addition, potential toxic element pollution resulting from anthropogenic activities such as traffic emissions, construction, and demolition activities negatively affects human and environmental health (Dehrashid et al. 2023; Mohammadi et al. 2023). TMs released into the atmosphere can bind to particles of various sizes and cause health impacts, including cardiovascular and respiratory diseases, premature deaths, lung cancer, and inflammatory diseases (Huang et al. 2018). Therefore, continuous UAQ monitoring and rapid adoption of necessary measures are essential for public and environmental health (Świsłowski et al. 2025).

Instead of high-cost and error-prone devices or methods in urban areas, biomonitoring is a low-cost, easy, effective, and indirect method that can reveal biological accumulation over the years. In this context, lichens, mosses, and trees, common in urban environments, are used among the species to be monitored to mitigate the risk (Respondek et al. 2024; Świsłowski et al. 2024). In selecting the species to be used, they must be present to broadly and systematically search at all points to be measured, providing knowledge regarding the chronology and the elemental composition of the contamination, and their ages and species must be the same. In this context, the most critical step that local governments should take is to determine the species to be sampled in advance, determine the sampling points, and grow them accordingly, which will reveal the result much more quickly (Hajizadeh et al. 2019). Understanding the physiological accumulation capacities of different species at the sampling points has been reported in many studies worldwide, where they are used as environmental indicators to characterize metal contamination in urban environments (Molnár et al. 2020; Solgi et al. 2020). In particular, it is aimed to select species with high metal retention capacity, which have been characterized on the roadsides, city parks, and green areas where long-term control is aimed to protect public and environmental health (Traversari et al. 2024). In addition, depending on the status and duration of the retention capacity, in regions with poor UAQ, equipped with these species that are suited to the local climate, it acts as an ecologically convenient filter that removes large amounts of atmospheric particulate matter (APM), but only if an appropriate sampling strategy is determined. Numerous scholars have focused on tree leaves and bark, an easy, cheap, natural barrier and accessible way to determine urban areas' regional fine particulate matter pollution patterns (Kocić et al. 2014). In recent decades, using trees as bioindicators of air pollution has gained significant attention. They can accumulate heavy metals (HMs) such as lead (Pb), cadmium (Cd), chromium (Cr), and other atmospheric pollutants, providing valuable insights into airborne contamination's spatial distribution and temporal patterns. To date, trees are particularly suitable for biomonitoring as they are widely distributed, long-lived, and integrate pollution levels over time in urban green spaces (Zhu et al. 2025). Previous studies in various urban and industrial settings have investigated the utility of tree wood as a bioindicator for specific HMs through leaves directly from the air and rainfall and by direct deposition on stem segments (Budzyńska et al. 2023; Zand Abbas Abadi et al. 2024). However, a comprehensive evaluation of a broader range of TM sources using multivariate statistical methods such as principal component analysis (PCA), especially in the context of Türkiye (Istanbullu et al. 2023).

In the context of Düzce, a city in the north of Türkiye, experiencing rapid development in terms of industrialization and urbanization. Studies have shown that the UAQ of Düzce is generally low, and samples taken from road dust contain high amounts of potentially toxic substances. Thus, by observing, we can easily monitor the dangerous metals emitted by industrial and transportation networks. Studies have indicated that the leading causes of HMs pollution in Düzce are industrial activities, traffic emissions, and other anthropogenic sources (Isinkaralar et al. 2024a). Apart from these studies, this study, which shows the wet and dry deposition of various elements in the wood part of different trees in Düzce, has filled a significant gap. *Pinus nigra* Arnold., *Juglans regia* L., *Gleditsia triacanthos* L., *Cupressus arizonica*, *Prunus avium* L., *Populus alba*, *Platanus orientalis* L., *Abies nordmanniana*, *Tilia tomentosa*, *Robinia pseudoacacia* L., *Fraxinus excelsior* L., *Pinus pinaster* Ait., *Cupressus sempervirens* L., *Picea orientalis* L., *Pseudotsuga menziesii* (Mirb.), *Cedrus atlantica* is the principal plant kind detected and tolerant to a wide range of environmental conditions in Düzce. This study aims to evaluate metals absorption and accumulation, the suitability of tree wood as a bioindicator of atmospheric TMs pollution in the city of Düzce, Türkiye, and the comparison of these trees with the contamination origin and provide an indicator of the natural atmospheric pollution was carried out in an ambient environment.

Given the above, the main aims of this study were (1) to assess the content of TMs (Cd, Cr, Co, Cu, Pb, Ni) and essential nutrient metals (Al and Fe) detection in wood from several trees in Düzce; (2) to determine the bioaccumulation of TMs in the wood of tree types and compare their bioaccumulation capacity and fixation mechanisms; and (3) to characterize the primary origin of TMs in tree woods, iv) green investments can think in urban areas for local UAQ measures, offering insights for informed decision-making. The findings can serve as fundamental data for urban environmental impact evaluation. Düzce's contamination levels have been evaluated in a comparison with other cities around the world.

Materials and Methods

Sampling Campaign

In this study, biomonitoring types woods (BTW) of *Pinus nigra* Arnold., *Juglans regia* L., *Gleditsia triacanthos* L., *Cupressus arizonica*, *Prunus avium* L., *Populus alba*, *Platanus orientalis* L., *Abies nordmanniana*, *Tilia tomentosa*, *Robinia pseudoacacia* L., *Fraxinus excelsior* L., *Pinus Pinaster* Ait., *Cupressus sempervirens* L., *Picea orientalis* L., *Pseudotsuga menziesii* (Mirb.), *Cedrus atlantica* trees for dendrochemistry in the same area of Düzce, Türkiye, where we could find only a single tree of known age in the summer of 2023 on days without rain. Several activities are ongoing in this area, such as textile, metal machinery, food, forest, furniture, rubber-tire-plastic, mining, construction, automotive, and chemical-pharmaceutical industries. Airborne metal emission occurs in this area (as elsewhere), as both APM and TMs are from the surrounding atmosphere. We selected 16 sampling sites from the city center that are not directly affected by industrial emissions, as shown in Fig. 1. For each site, we collected

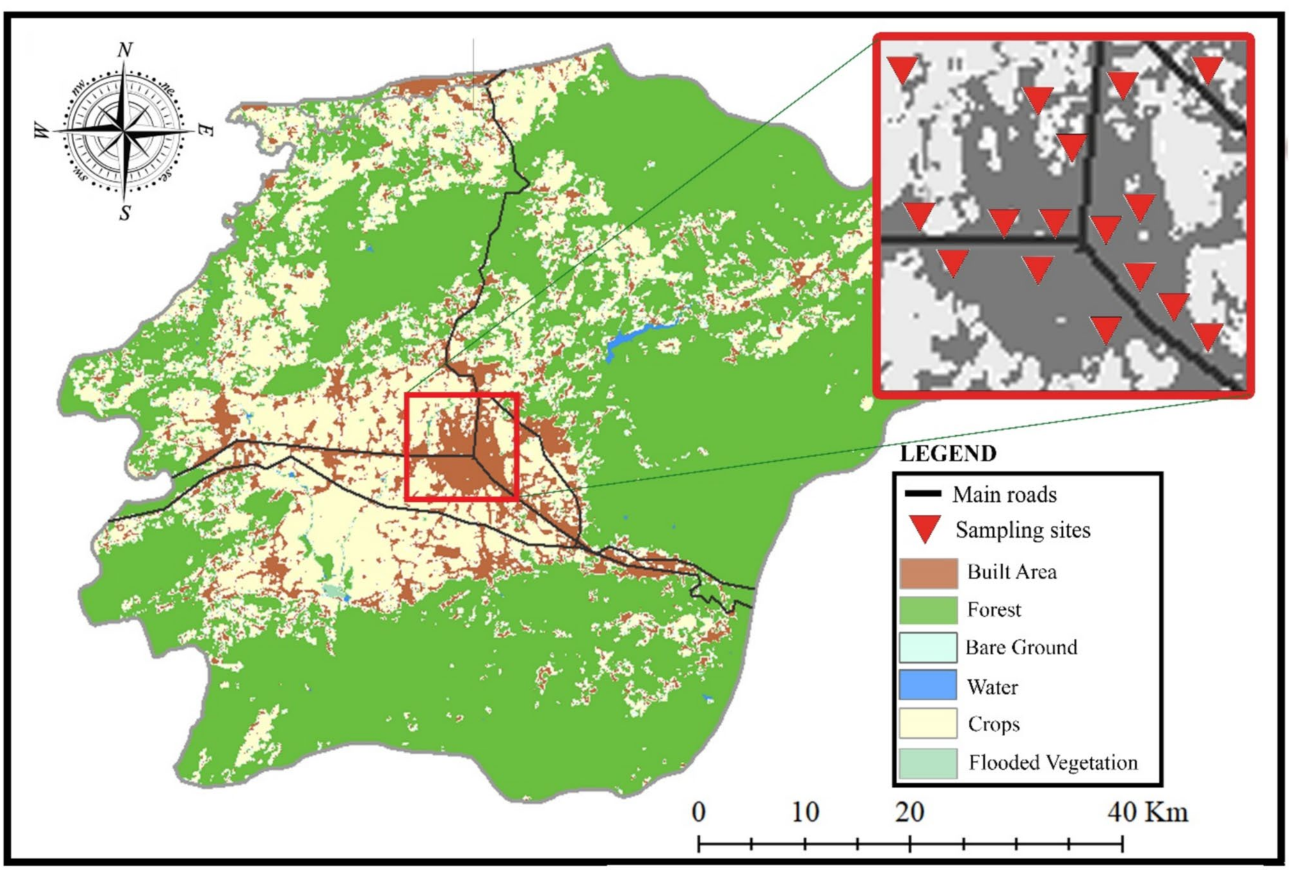

Fig. 1 An overview map of the study site illustrating the sampling areas

15 wood samples from each tree per location whose ages were 60 years. For the convenience of discussion, BTW1 to BTW16 in Table 1 were used as a label for wood samples collected from *P. nigra*, *J. regia*, *G. triacanthos*, *C. arizonica*, *P. avium*, *P. alba*, *P. orientalis*, *A. nordmanniana*, *T. tomentosa*, *R. pseudoacacia*, *F. excelsior*, *P. pinaster*, *C. sempervirens*, *Picea orientalis*, *P. menziesii*, *C. atlantica*, respectively. A total of 240 wood samples were collected at from the main trunk at a height of 1.0 m—1.2 m above the ground from all directions and in thicker (~ 2 cm) by handpicking for dendrochronological analysis to get better results as passive biomonitoring. The sample label is completed by a number corresponding to the locations and species.

Analytical Methods

The sampled wood slices were shredded with a ceramic knife and dried at 65 °C for a month in a controller oven, avoiding external contamination. Samples were already ground homogenized in a laboratory mill and were occurred with three replicates, and results were presented on a dry weight (d.w) basis (accuracy was within 10%). To measure the eight metals, including aluminum (Al), iron (Fe), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), and nickel (Ni) levels were used to quantify with inductively coupled plasma optical emission spectrometry (ICP-OES) brand by SpectroBlue, Germany. Samples were then applied according to the following steps: i) firstly, microwave-assisted (Ethos One, Milestone GmbH, Germany) strong acid digestion method was used with 1 g of each sample which was processed with nitric acid (65% HNO_3 from Merck), and hydrogen peroxide (10% H_2O_2 from Merck) (5: 1: v/v) to 24 mL mixture based on US Environmental Protection Agency (USEPA) method 3052; ii) mixture were heated to 150 °C for 3 h until a transparent solution at 280 PSI and 180 °C during 20 min; iii) acquired solutions were filtered through the filter paper (Whatman No. 42); iv) filtrate liquid were diluted up to 50 mL volume by deionized water; v) finally prepared sample stored in polyethylene bottles at 4 °C until analysis in the ICP-OES and vi) replicate measurements were repeatable.

Table 1 List of labels for wood samples according to the species

No	Label	Species	No	Label	Species
1	BTW1	*P. nigra*	9	BTW9	*T. tomentosa*
2	BTW2	*J. regia*	10	BTW10	*R. pseudoacacia*
3	BTW3	*G. triacanthos*	11	BTW11	*F. excelsior*
4	BTW4	*C. arizonica*	12	BTW12	*P. pinaster*
5	BTW5	*P. avium*	13	BTW13	*C. sempervirens*
6	BTW6	*P. alba*	14	BTW14	*Picea orientalis*
7	BTW7	*Platanus orientalis*	15	BTW15	*P. menziesii*
8	BTW8	*A. nordmanniana*	16	BTW16	*C. atlantica*

Bioconcentration Factor (BCF) and Metal Accumulation Index (MAI)

The BCF was calculated in Eq. (1) (Alahabadi et al. 2017) as the ratio of metal concentrations in the woods from the soil, which were obtained from our previous studies (Isinkaralar et al. 2024a).

$$BCF = \frac{C_{wood}}{C_{soil}} \tag{1}$$

where C_{wood} and C_{soil} are the metal concentrations in the woods and soil samples.

The MAI was employed to assess the capability of woods to deposition atmospheric TMs deposition in Eq. (2) (Liu et al. 2007, 2022).

$$MAI = \frac{1}{N}\sum_{j=1}^{N} I_j \tag{2}$$

where $I_j = X/\Delta X$ is the sub-index of variable j, X is the metal mean value, and ΔX is the measured standard deviation.

Data Analysis

The TMs were statistically analyzed with SPSS Statistics (IBM Corp., Armonk, NY, USA) and Microsoft Excel 2016 (Redmond, WA, USA) software for descriptive statistics, Pearson correlation analysis PCA, box-whisker plot, and scatterplot. Pearson correlation, a bivariate correlation, investigates the relationship among data sets. Throughout this research, multivariate analysis was confirmed using Pearson's correlation matrix to analyze the relationship among the concentrations of HMs detected in wood (Pan et al. 2024). Principal component analysis (PCA) identifies a set of reduced latent factors, known as principal components (PCs), directly from the original set of variables. The validity of this technique was assessed through Kaiser–Meyer–Olkin (KMO) value (> 0.5) and Bartlett sphericity tests ($P < 0.001$), and the covariance matrix was constructed using eigenvalue decomposition. We selected the principal components using the varimax rotation based on the observed variables and the contributed eigenvalues (> 1) of the HMs.

Results

Trees demonstrate diverse capacities for accumulating distinct metal contaminants, and most polluted sites feature mixed contamination. Consequently, it is crucial to assess the overall efficacy of trees for metal sequestration in phytoremediation initiatives. Based on the analysis provided, concentrations were stated in mg kg^{-1} d.w, the experimental concentrations were clearly explained, and the overall finding is that each species was assessed separately. Al and Fe are given separately because their values are higher than the Cd, Cr, Co, Cu, Pb, and Ni, considering all the sampling sites.

Concentrations of Elements

Table 2 contains the concentration range of the elements in woods and their mean values for candidate species to be utilized as bioindicators of contamination processes. The decreasing order of the concentration of the different elements Fe > Al > Cr > Cu > Pb > Ni > Co > Cd reflects their abundance in woods.

The Al and Fe concentration ranges were 10–752.47 and 10.62–812.20 mg kg^{-1} d.w, the levels of which are explained by the presence of their structure. Also, Al and Fe are associated with natural and anthropogenic sources, as shown in Fig. 2. Their values exceeded Cd, Cr, Co, Cu, Pb, and Ni. When we compared the Al and Fe values of *A.*

Table 2 All element concentrations (mg kg^{-1} d.w) in woods

Elements	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis
Al	240	10.00	752.47	105.33	159.05	2.69	6.37
Fe	240	10.62	812.20	156.88	139.88	2.14	5.70
Cd	240	0.02	2.34	0.49	0.44	1.43	2.75
Cr	240	3.50	45.96	16.39	11.47	1.09	0.01
Co	240	0.09	18.99	2.17	4.65	2.84	6.89
Cu	240	0.10	55.00	13.39	17.51	1.01	-0.47
Pb	240	0.15	51.37	6.76	12.19	2.81	6.85
Ni	240	0.05	49.65	5.98	9.58	2.29	4.59

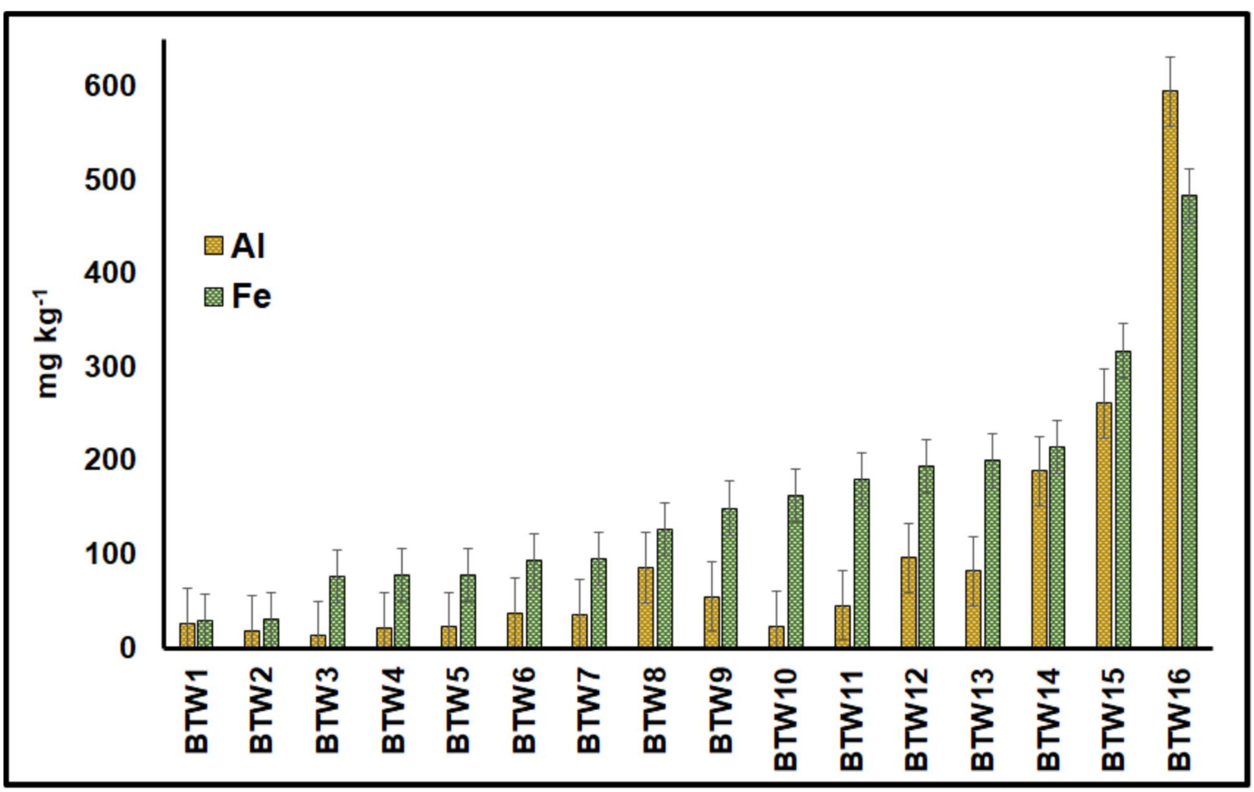

Fig. 2 Species diversity concentration of Al and Fe (mg kg^{-1} d.w) in woods

nordmanniana with other species, we found that it is more sensitive with 595 and 483 mg kg^{-1} d.w. It is an essential comparison for Al and Fe because the absorption levels are more sensitive to their deposition.

Figure 3 displays the bar chart of Cd, Cr, Co, Cu, Pb, and Ni values well below each species' highest environmental concentrations. These metals are highly dependent upon the UAQ of the surroundings in their areas.

The concentrations of Al, Fe, Cd, Cr, Co, Cu, Pb, and Ni were obtained at the lowest and highest values in Fig. 4. Cr, Cu, and Ni have an extensive range, whereas Co and Pb have less variability, excluding Al and Fe. The Cd value is close to Cr due to industrial discharges. The Pb and Co concentrations have been shown in a similar range, which was revealed to be correlation emission.

BCF and MAI

The BCF values depicted in Fig. 5 represent the trees' metal concentrations relative to the surrounding soil's corresponding metal concentrations. This demonstrates the capabilities of the woods to uptake a single TMs from the

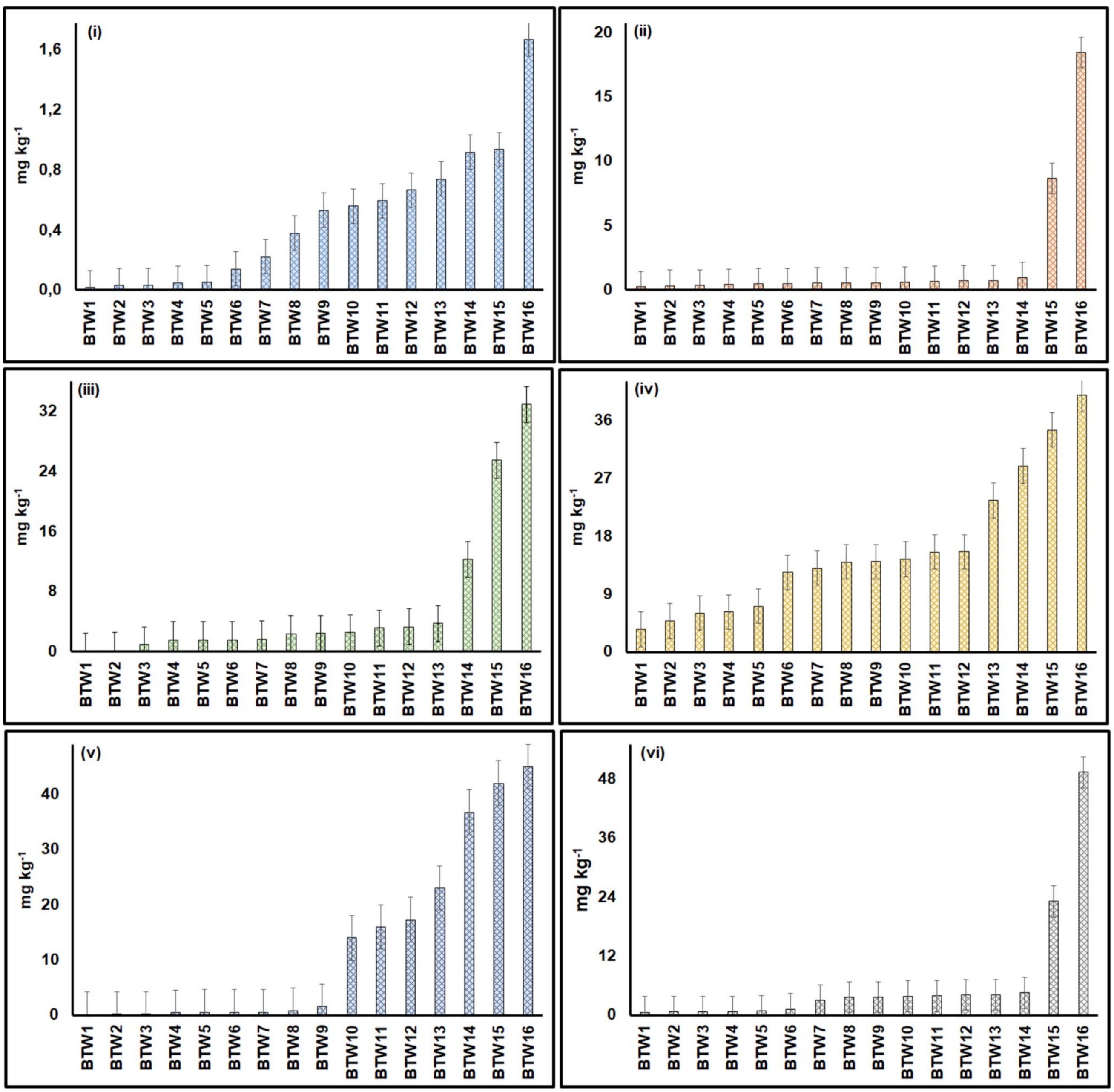

Fig. 3 Potentially toxic metal total levels (mg kg^{-1} d.w) in different species for **i** Cd, **ii** Co, **iii** Ni, **iv** Cr, **v** Cu, and **vi** Pb

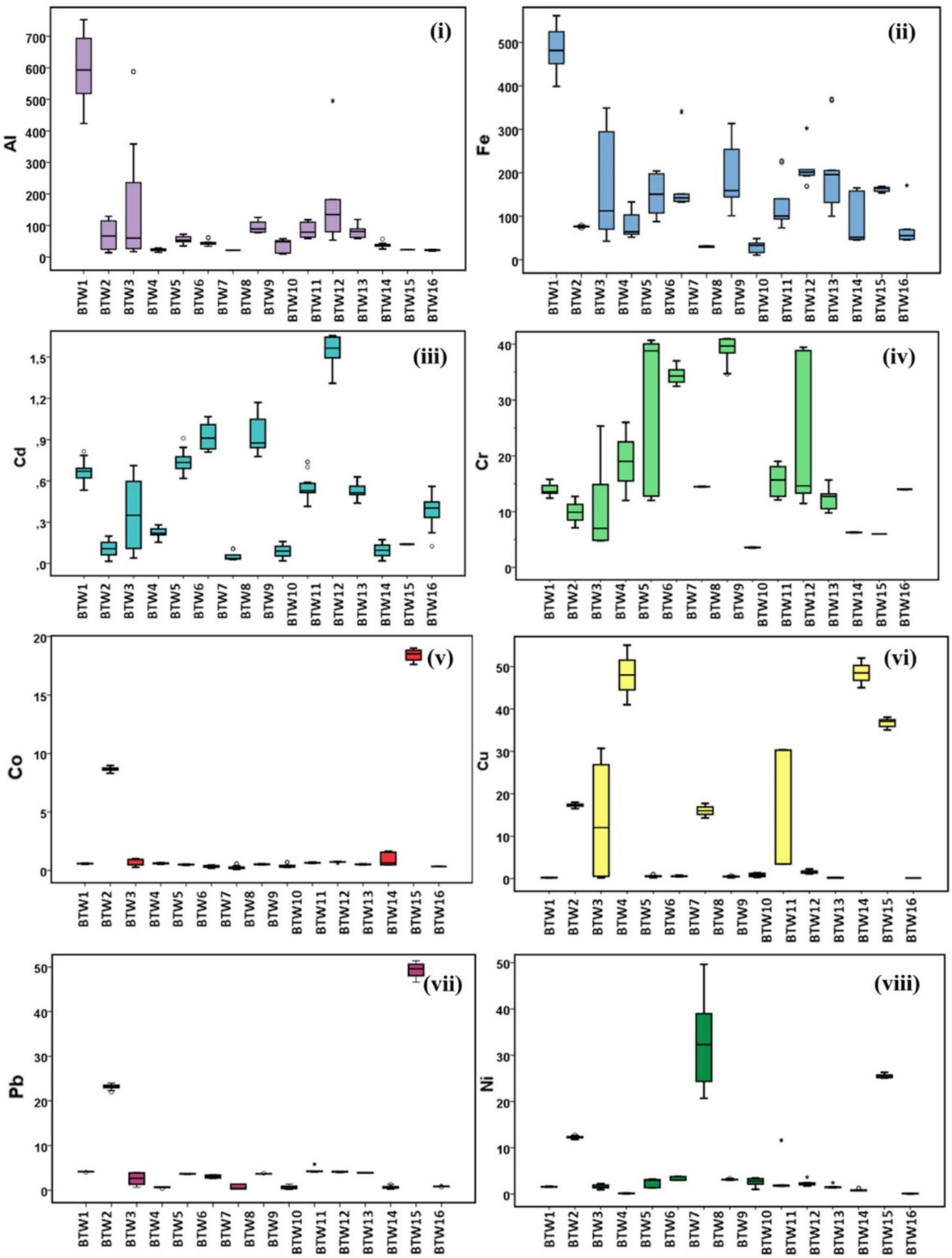

Fig. 4 Cumulative values (mg kg^{-1} d.w) calculated by the box-whisker plot in different species for **i** Al, **ii** Fe, **iii** Cd, **iv** Cr, **v** Co, **vi** Cu, **vii** Pb and **viii** Ni

soil (Isinkaralar et al. 2024b). The maximum BCF value of Pb was recorded for *C. arizonica* (2.30) and *C. atlantica* (2.30); for Ni, the maximum values were controlled for the *P. orientalis* (1.58) and *R. pseudoacacia* (1.10). The maximum BCF value for Cu was observed for *P. menziesii* (1.80) and *F. excelsior* (1.68), and measured maximum BCF rate

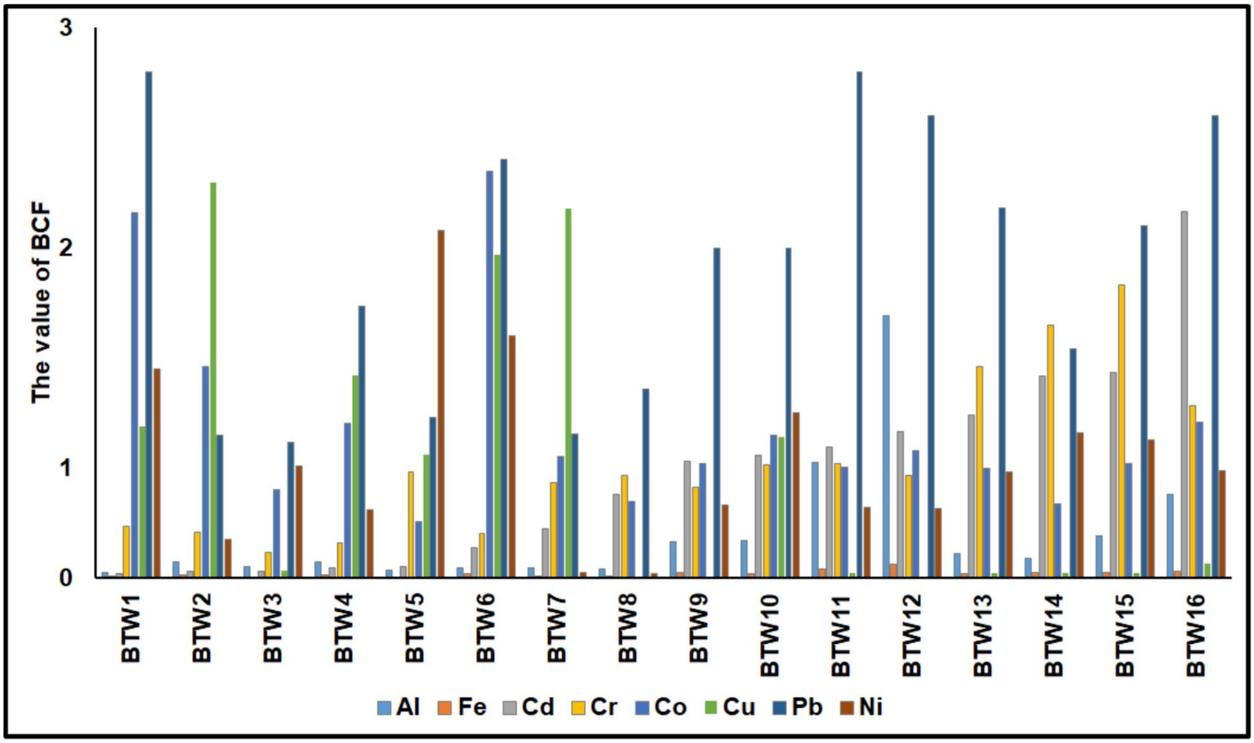

Fig. 5 BCF values of woods for different species

for *R. pseudoacacia* (1.85) and *C. atlantica* (1.66) for Co. In the case of Cr, the value of the maximum BCF was noted for the *P. nigra* (1.33) and *J. regia* (1.15). For Cd, the maximum BCF value was noted for *P. alba* (1.67) and *P.nigra* (0.93). The study found that *R. pseudoacacia* exhibited the most substantial capacity to accumulate individual metals like Ni and Co from the soil, while *C. arizonica* demonstrated the most incredible ability to enrich Pb. BCF values of all metals in wood samples were < 1 (except for some Pb, Ni, and Co), indicating that TMs accumulation in woods of urban greening trees is fundamentally due to APM and metal accumulation from soil is not the main pathway. In contrast, BCF values > 1 refer to a specific metal being well deposited in the roots (*P.nigra* = 0.93 in Cd).

The wood accumulation capacity of atmospheric TMs (ATMs) was determined according to the MAI (Liu et al. 2007). As can be seen from Fig. 6, the MAI amounts of the woods show according to different species. The accumulation capacity of ATMs was in the following decreasing sequence: *R. pseudoacacia* (70.65) > *P. nigra* (64.24) > *P. alba* (62.19) > *A. nordmanniana* (58.35) > *J. regia* (52.10) > *G. triacanthos* (48.46) > *P. orientalis* (34.49) > *Platanus orientalis* (32.55) > *P. avium* (26.04) > *C. arizonica* (24.89) > *P. menziesii* (21.51) > *F. excelsior* (10.76) > *C. atlantica* (10.15) > *P. pinaster* (8.42) > *T. tomentosa* (6.28) > *C. sempervirens* (5.49). Notwithstanding, *R. pseudoacacia* exhibited the most substantial capacity to accumulate individual metals such as Ni and Co from the soil. Furthermore, this species demonstrated a more robust atmospheric capability for the phytoremediation of TMs pollution in urban areas than other tree species. This can be attributed to factors such as atmospheric chemistry, variations in tree characteristics, sampling duration, location, and altitude, which can impact the absorption capacity of urban vegetation to uptake air pollutants. Additionally, the findings reveal that the ability of *R. pseudoacacia's* leaves to accumulate airborne TMs was nearly 13 times greater than that of *C. sempervirens* (Hu et al. 2014). Furthermore, various factors, including the sampling duration, location, and altitude, may influence the absorption capacity of urban vegetation to uptake air pollutants (Yin et al. 2011). Trees exhibiting substantially elevated metal accumulation indexes can be a demarcation between polluted and environmentally sensitive areas (Zhai et al. 2016). The study determined that *R. pseudoacacia* exhibited the most substantial atmospheric capacity for the phytoremediation of TMs pollution in urban environments compared to other tree species.

Potential Sources of HMs

Pearson's correlation coefficient analysis and PCA have often been performed to determine better the association and possible sources of HMs in the samples. Table 3 indicates the Pearson correlation coefficients of the HMs in the

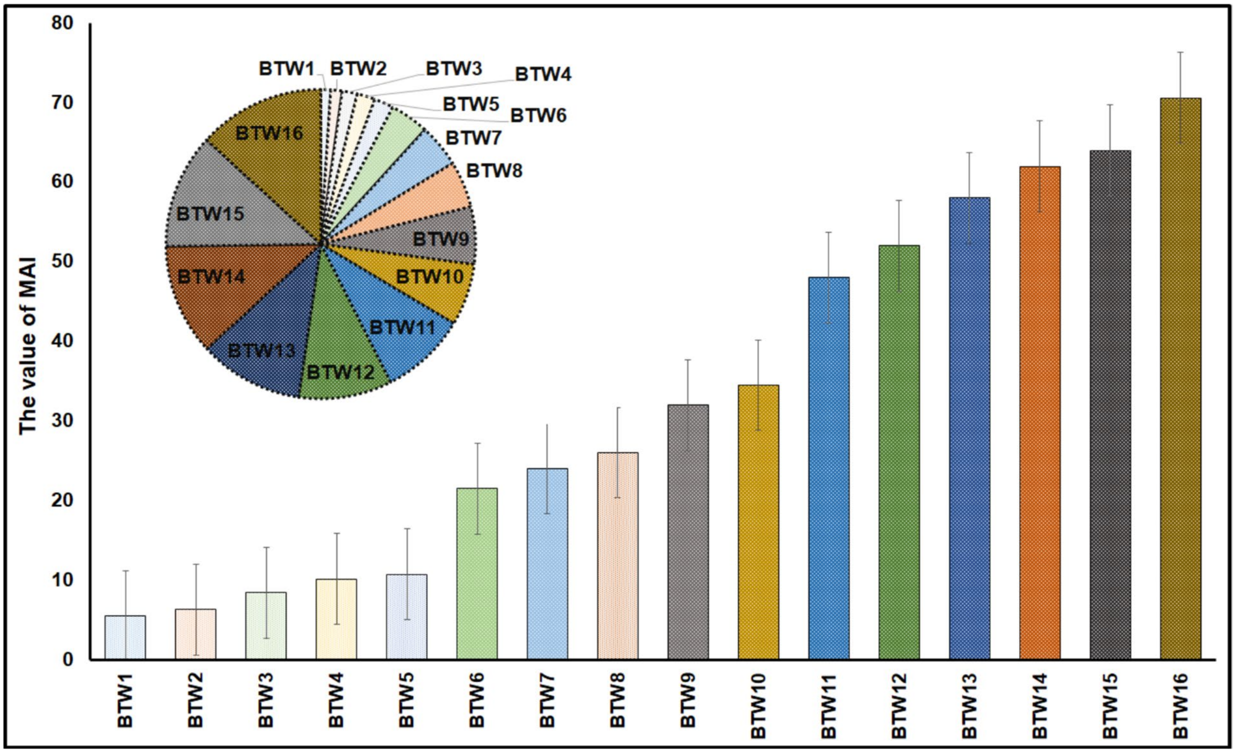

Fig. 6 MAI values of woods for different species

Table 3 Pearson's correlation matrix for main chemical elements

	Al	Fe	Cd	Cr	Co	Cu	Pb	Ni
Al	1							
Fe	0.812**	1						
Cd	0.306**	0.394**	1					
Cr	0.032	0.210**	0.588**	1				
Co	– 0.142*	– 0.046	– 0.284**	– 0.288**	1			
Cu	– 0.318**	– 0.293**	– 0.534**	– 0.356**	0.367**	1		
Pb	– 0.088	0.017	– 0.202**	– 0.229**	0.992**	0.282**	1	
Ni	– 0.202**	– 0.197**	– 0.342**	– 0.161*	0.550**	0.219**	0.537**	1

**Correlation is significant at P < 0.01 level (two-tailed), *Correlation is significant at P < 0.05 level (two-tailed)

woods. Co, Cu, and Pb demonstrated positive correlations with each other, significant at the $P < 0.01$ level, indicating that these elements probably come from a common origin (Yadav et al. 2023). Furthermore, Ni had a highly significant positive correlation ($P < 0.01$) with Co ($r = 0.550$), Cu ($r = 0.219$), and Pb ($r = 0.537$). Significant correlations across HMs do not necessarily indicate that they arise from a mutual origin. However, the inter-elements can supply certain information about the origin and pathway of HMs (Chen et al. 2014; Li et al. 2022). However, significant positive correlations found between Cd and Fe, for example, indicate the presence of a shared resource from agriculture and mining activities (Alengebawy et al. 2021; Kicińska et al. 2022). Furthermore, the pairs of elements Cu-Al ($r = -0.318$) and Ni–Cr ($r = -0.161$) had a negatively significant correlation at $P < 0.05$ and $P < 0.01$, respectively. Moreover, Ni and Co had a substantial positive correlation at the $P < 0.01$ level, possibly due to the same sources.

An additional definition of the origin of the quantified HMs was carried out following the PCA procedure (Jiang et al. 2023). The reliability of the PCA was indicated through the KMO coefficient (0.586) and the appropriate significance of Bartlett's test ($P < 0.001$). Table 4 displays the PCA results and shows that three PCs with eigenvalues higher than 1.0 were omitted, accounting for approximately 79.135% of the total variance. The primary principal component (PC1),

Table 4 Rotated component matrix of TMs

Elements	Component		
	1	2	3
Al	– 0.509	**0.645**	– 0.482
Fe	– 0.507	**0.737**	– 0.290
Cd	– 0.710	0.280	0.444
Cr	– 0.554	0.062	**0.676**
Co	**0.770**	0.564	0.178
Cu	**0.663**	– 0.175	– 0.263
Pb	**0.705**	**0.629**	0.221
Ni	**0.650**	0.266	0.274
Eigenvalues	3.279	1.856	1.195
% of variance	40.993	23.200	14.943
% of cumulative	40.993	64.193	79.135

The PCA loadings > 0.6 are denoted as bold. Extraction method: PCA. Rotation method: Varimax with Kaiser normalization. Rotation converged in eight iterations

which accounts for 40.993% of the total variance, was correlated with Co, Cu, Pb, and Ni (loading > 0.6), which has been associated with a shared human-caused source, primarily vehicular traffic (Li et al. 2004; Beramendi-Orosco et al. 2013). This waste can be released into the environment, burning coal and fossil fuel, resulting in water, soil, air, and sediment contamination. The other principal component (PC2), which accounts for 23.200% of the total variance, was associated with Al, Fe, and Pb (loading > 0.7). These elements consequently accumulate in the woods through surface runoff from anthropogenic sources. PC1 and PC2 were also consistent with the Pearson correlation coefficient analysis result. Finally, the third principal component (PC3), which represents 14.943% of the total variance, was observed to be correlated with Cr (loading > 0.6), indicating that it comes from a naturally occurring source as its concentrations are similar to the background concentrations (Nematollahi et al. 2021). We can consider atmospheric precipitation as the primary natural event causing Cr deposition in samples (Mao et al. 2022).

Discussion

Trees have been used as biological indicators of atmospheric aerosol pollution by TMs in urbanized areas (Isinkaralar et al. 2025a). Recent city advancements are under the pressure of rapidly increasing environmental pollutants, such as air pollutants, which tend to be directly polluted (Heydarzadeh et al. 2022). TMs are especially transferred to the environment where industrialization and industrialization are widespread and uncontrolled emissions, and different levels of pollutants are seen in various situations (Kord et al. 2010; Sawidis et al. 2012). The present study evaluated the use of tree wood as a bioindicator for atmospheric TMs pollution in Düzce, Türkiye. Compared with standard or guideline values of non-polluted areas in other countries, HM concentrations in trees were less than those recommended by the French and Canadian standards value for non-polluted sites (Akoto et al. 2016; Xu et al. 2017). However, the rate at which plants accumulate metals is challenging to anticipate, as it is contingent on numerous variables, including the specific forms of metals present in the soil and the plant species involved (Belaida et al. 2012; Farahat et al. 2015). Despite this, it is observed that it is considerably higher than the MAI values in some regions (Fang et al. 2021; Liu et al. 2022). Previous research has demonstrated the potential of tree-ring analysis for monitoring HMs pollution patterns, as trees can serve as effective biomonitors of airborne pollutants. Biomonitoring using plant materials such as tree bark and leaves has been a reliable and cost-effective method for detecting metal pollution deposition, accumulation, and distribution. HMs contamination, particularly from industrial and vehicular sources, is a growing global problem, with the Thrace region of Türkiye being no exception (Isinkaralar et al. 2025b). The findings of this study indicate that the tree woods analyzed could discriminate between affected areas, with sites near industrial and vehicular traffic showing higher metal content. The mean concentrations of the species were found to be Fe (156 mg kg^{-1} d.w) > Al (100.56 mg kg^{-1} d.w) > Cr (15.82 mg kg^{-1} d.w) > Cu (12.43 mg kg^{-1} d.w) > Pb > Ni > Co > Cd, with the maximum BCF and MAI values recorded in *C. arizonica* (2.30 for Pb) and *R. pseudoacacia* (70.65), respectively. These results suggest that *C. arizonica* wood can be a potentially suitable bioindicator of atmospheric TMs pollution in the study area. The findings of this research are consistent with previous studies that have demonstrated the use of tree-based biomonitoring for assessing HMs pollution in urban environments. With regards to studies conducted in other countries, described studies have revealed that large areas are polluted with TMs originating from different sources and growth conditions in regions, which accumulation and dispersion in tree species found by wet and dry atmospheric deposition (Kusiak et al. 2022). In biomonitoring research, trees are continuously exposed to APM, which can vary in their capacity to absorb pollutants depending on their physiological structure by Orecchio and Culotta (2015), Alagić et al. (2018) and Jeddi et al. (2021). Based on these, accumulation levels vary in tree tissues with their stress tolerance, and most pollution is accumulated in the external bark layers to a depth of approximately 8 mm (Cosma et al. 2016). Inspired by this, if we summarize the reasons for the usefulness of different tissues of trees for biological indicators from the studies: i) differentiation according to the growing area, ii) continuous exposure to gas or dust pollution, iii) in which tissue the pollution accumulates more hardiness, iv) impossibility of disposal of waste products and long-term monitoring of pollutants through convenient sampling.

Biomonitoring using trees has been conducted by several researchers who carried out long–term monitoring environmental pollution studies by focusing on several elements from various emissions and generating potentially toxic metals associated with increasing vehicular traffic, industrial and urbanization (Locosselli et al. 2018; Rajfur 2019; Campos et al. 2024). Also, several trees, such as ornamental, deciduous, fruit, shrubs, and landscape, have been studied as bioindicators for airborne TMs as a passive sampler in the xylem tissues of woody vegetation (Brignole et al. 2018; Yu et al. 2018). Fast-growing tree species, *R. pseudoacacia* (Monfared et al. 2013) and *T. cordata* (Popek et al. 2017), have revealed ideal low-cost candidates for airborne metal pollutants. Early studies of the relationship between urbanization emission and TMs focused on the relationships among tree absorption (Mleczek et al. 2017; Alexandrino et al. 2020; Isinkaralar et al. 2025c). The studies referred to above mainly conducted analyses of the single species or different organs of the same species located on the pathway of the dominant wind direction from several human activities (Cuciurean et al. 2024). In environmental governance, significant tree deposition and disturbances of single metal and multiple metal deposition in urban areas were reported as higher, such as in children's parks, urban agglomeration areas, intersection point-junction, ecologically fragile areas, and most polluted areas etc., than in rural areas (Greksa et al. 2019; Esfandiari and Hakimzadeh 2022). Compared with urban areas, individuals of the same species and those with the same physiology absorb potentially toxic substances at different rates (de Castro et al. 2020; Guarino et al. 2021). Tošić et al. (2016) presented *Malus* spp. possible indicator or not. Thus, they studied roots, branches, leaves, and fruit, which analyzed Cu, Zn, Pb, As, Cd, and Ni content (mg kg^{-1} d.w) in its tissue by ICP-OES. Europe's one of the largest copper mines, the Bor region in Serbia, was influenced by atmospheric deposition and related metal contents. Essentially, the highest value of Cu was determined to be greater than the upper limit of the phytotoxicity in soil with 2162 mg kg^{-1}, while in our study, the most excellent value detected in *P. menziesii* was 45 mg kg^{-1}. However, similarly to our BCF values, almost all were evaluated as smaller than 1. Yousaf et al. (2020) outlined Cu, Mn, Ni, Pb, and Zn pollution in Toronto by tree bark as a biomonitor. The accumulation factors of Pb, Cu, Zn, Ni, Hg, and Mn by 100 were 1254, 1083, 793, 601, 430, and 188%, respectively. While higher concentrations were observed in tree bark along streets with high vehicle traffic, lower concentrations were recorded in areas with less vehicle traffic. Another study by Liu et al. (2022) demonstrated metal deposition in 20–25-year-old four street tree species, namely *A. altissima*, *B. papyrifera*, *P. tabuliformis*, and *R. typhina* in Beijing, China. The mean values of total HMs in the leaves were higher than in barks for all species, whereas all concentrations in soil were higher than in leaves. They reported that BCF values were < 1 for tree species and element types. The trace elements deposition occurs longer and presents differences between species and tissue depending on proximity to the source, particle size, and environmental factors. The difference between our study and all these is that HMs analyses were performed on wood, and the diversity was high.

Conclusion

The study area has been impacted by significant industrialization with numerous industrial and domestic discharges, resulting in high levels of metals of anthropogenic origin typically found in trees of exposure to anthropogenic factors. In light of the findings of our study, it was also observed that maximum Pb, Ni, and Cr concentrations corresponded to extensive industrial facilities. The metals studied in this work were higher for the *P. alba*, *C. arizonica*, *A. nordmanniana* than for the *C. Sempervirens* and *C. atlantica*. Ni and Cd-Co concentrations were obtained with inverse correlation in *P. menziesii*; in most cases, Co and Cr showed significant inverse deposition in *Platanus orientalis*. The findings of this study are of great importance as 16 trees were detected with high levels of contamination with potentially toxic elements, thereby allowing the elements causing this contamination to be calculated. Possible sources were determined through Pearson correlation analysis and PCA combined with contamination attributes: Al, Fe, and Pb are derived primarily from natural sources and mining activities; Co, Cr, Cu, Pb, and Ni pollutants are derived primarily from natural sources and agricultural facilities. Overall, these facts are supposed to contribute to evaluating the actual situation, raise public awareness of the danger posed by all this, and provide recommendations to the relevant institutions for applying mitigation strategies to reduce contamination with HMs within the permissible levels under the European Union directive. This study's insights are vital for policymakers, urban planners, and stakeholders interested in promoting urban air conditions through sustainable UAQ monitoring, equitable growth and social inclusion, and eventually achieving the United Nations Sustainable Development Goals.

Limitations and Recommendations for Future Studies

This study focuses on a specific 60-year-old wood, which limits the generalizability of the findings to other environments or tree species. The reliance on older soil data and the inability to capture seasonal variations in the relevant data introduce uncertainties and constrain the depth of the discussions. The small number of observations and the absence of a full explanation of the underlying mechanisms of relevant processes make it challenging to obtain deeper insights. Although the study identifies high contamination levels in specific trees, further research is needed to determine the long-term ecological and health impacts. The limitations of the detailed soil survey and the constraints on the monitoring program of seasonal variations affect the reliability of the baseline data and the universality of the conclusions. Future research should use more data on multiple metal deposition in various urban areas and ecologically sensitive zones, such as urban green spaces, to investigate the long-term ecological and health impacts of HMs exposure, including effects on plant physiology, soil health, and human health. In addition, if the spatial pattern of analysis is added to research, it will effectively manage decision mechanisms.

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Data Availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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