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RESEARCH

Accumulation analysis and overall measurement to represent airborne toxic metals with passive tree bark biomonitoring technique in urban areas

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Abstract Authorities have long proved the utility of bioindicators in monitoring the state of environmental pollution. Some biological indicators can measure environmental pollutant levels, and many tree species have been tested for suitability for monitoring purposes. The differences in morphological characteristics in the trees have demonstrated the effects of human activities on different materials. Measuring bark and wood biomass from contaminated sites was identified and directly compared with those from a clean site or areas characterized by distinct contamination sources. However, preliminary results demonstrate the approach's potential in the realization of strategies for disease control and promoting health to reduce environmental and health inequalities in at-risk urban areas. *Picea orientalis* L. and *Cedrus atlantica* Endl., especially their bark, can be regarded as a more robust storage of Cu (37.95 mg/kg) and Mn (188.25 mg/kg) than *Pinus pinaster*, *Cupressus arizonica*, and *Pseudotsuga menziesii,* which and is therefore a better bioindicator for Cu and Mn pollution. Considering the total concentrations as a result of the study, the pollution is thought to be caused by environmental problems and traffic in the region. The deposition of Cu, Mn, Ni, and Zn elements was found *P. menziesii* (60, 443, 58, and 258 mg/kg) and *P. orientalis* (76, 1684, 41, and 378 mg/kg) and seems to reflect atmospheric quite clearly compared to *P. pinaster*, *C. arizonica*, and *C. atlantica*. Ni and Zn concentrations have significantly increased since 1983, and *P. menziesii* and *P. orientalis* can be potentially valuable bioindicators for emphasizing polluted fields.

Keywords Air pollution · Atmospheric deposition · Bioindicator · Toxic metal · Urban analysis

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Introduction

Environmental awareness ranks first among the measures to be taken for sustainable urbanization. It is the basic building block of sustainable urbanization (Marazziti et al., 2021). Environmental pollution is quite diversified in today's world. Many pollutants discharge into water, soil, or air after creating a pollution cycle. Air pollution is a significant component of environmental pollution and is released into the air under various conditions (Li et al., 2019), both from water and soil. They are components of various pollutants at different concentrations and with different molecular structures. Some environmental movements have emerged with the increasing awareness of sustainable environment. Air quality, an essential factor of this mobility, is deteriorating daily with various anthropogenic activities (Rentschler & Leonova, 2023). As a result of the increase in the types and origin of air contaminants, pollutants released into the atmosphere have also diversified. Various pollutants are released into the air due to the increasing industrial spectrum and traffic activities, thanks to the rapid consumption brought by rapid urbanization. The pollutants released threaten other living life, especially humans (Godoy & da Silva, 2022).

Toxic elements are widely found in various places according to their usage areas and constitute a substantial part of air pollutants. Air contamination by toxic elements is of considerable concern, particularly around urban environments. The biomonitoring of air quality utilizing trees has been extensively implemented to determine and track the impacts of contamination. While biomonitoring of ambient air pollution through the use of plants has been applied for many years, it is still not practiced to a convincing level in many European countries, primarily due to different or even contradictory results depending on the type of soil and bedrock (Giráldez et al., 2022). According to urban planning, air movements carry them and accumulate in living and non-living things (Isinkaralar et al., 2023). They affect human and public health, especially in areas with insufficient or limited ventilation. In addition, they can accumulate at various levels in the tissues and organs of plants and trees in polluted regions. Studies on the accumulation of toxic metals have determined that they can accumulate depending on the types of species investigated and the regions in which they are found in the city. It directly depends on the diversity of the species, its evergreen nature, and its organs and tissues. Bioindicators have become natural tools that allow us to make cumulative predictions based on toxic metals' time and spatial patterns in air. Many species are used to measure the presence and accumulation of regional pollutants (Gallego-Cartagena et al., 2021). The analysis of toxic elements that can accumulate according to the diversity of species and their temporal analysis can help take precautions for public and public health (Świsłowski et al., 2020). The presence of toxic elements is considered in the location selection of children's parks, public gardens, kindergartens, and childcare centers, especially in common areas (Gillooly et al., 2019). Continuous monitoring of species which are duckweed (Yang et al., 2024), weeds (Cakaj et al., 2023), trees (Eslamdoust et al., 2023), plants (Cakaj et al., 2024), and mosses (Lv et al., 2023; Świsłowski et al., 2024a, 2024b) accumulate as a result of atmospheric precipitation is of vital importance in terms of public health (Isinkaralar et al., 2024). The main reason for this is that air pollutants form a circle from the moment they come out of the source, and it is known that a pollution wave that spreads easily affects very far away. Although bioindicators cannot reveal atmospheric precipitation, health risk assessments are made with regression and prediction models created by determining the proximity of the elements accumulated on them to the source (Latwal et al., 2023; Mohamed et al., 2023). Housing, workplaces, schools, gardens, and social areas are formed according to the maximum limit values children and adults in the cities should be exposed to, which are revealed by the health risk assessment (Bing et al., 2016). In this context, the species investigated as bioindicators can be found easily in that region, exhibit continuity, withstand harsh climatic and environmental conditions, and be located in different parts of the same region, causing them to be quite successful in long-range transmission and monitoring of air pollutants. Transporting metals released from the source with atmospheric events and fine particulate matter takes a long time (Chaparro et al., 2020). The presence of toxic elements adhering to $PM_{2.5}$ and PM_{10} in the species studied as bioindicators and carrying out transport-accumulation with them was characterized by directly inhabiting polluted areas (Geras'kin et al., 2019). PM_{10} is an exposure indicator that indicates the presence of toxic metals in the urban environment and contains various environmental toxic pollutants (Suchara et al., 2017). In studies on the detection of toxic elements using bioindicators, the effect of PMs and the effects of particle shape and particle size on human health cannot be conclusively judged. However, there are limited studies on the effect of chemical composition and accumulation of trace metals (Marques et al., 2017).

The fact that bioindicators hold PM and are easy to monitor has attracted studies on this. However, studies on the presence of trace elements' variation, accumulation, and transport are a significantly trending topic (Piazzetta et al., 2019; Rajfur et al., 2024) because PM composition changes rapidly and is fairly heterogeneous temporally (Fusaro et al., 2021). On a global scale, due to the increasing urbanization, traffic emissions, and industrial activities in developing and developed countries, active and passive monitoring systems have been widely used in cities (Cavazzin et al., 2024) and have accelerated cost-effective biomonitoring approach for the monitoring of toxic elements (Alexandrino et al., 2020; Locosselli et al., 2020). The released metals are mainly dominated by anthropogenic air pollution (Chakraborty et al., 2024; Esbrí et al., 2018). In this context, it was preferred to use tree bark in urban centers, including traffic regions, where some buildings stopped the air corridor (Kawasaki et al., 2017; Nakazato et al., 2016). It is known that monitoring the same tree species in different regions directly gives the amount of pollutants recorded by the pollutants in those regions over the years (Nadgórska-Socha et al., 2016). The long-term maps are produced by looking at the number, diversity, and concentration of elements accumulated in the organs of the species from the future urbanization route. This way, bioindicators identify and reduce environmental pollution while creating healthier urbanization plans (Kousehlar & Widom, 2019).

A growing number of papers are being produced investigating the interaction between toxic elements and atmospheric deposition and their compounding effect on trees. However, limited studies systematically examined the coupled impacts of toxic elements and atmospheric deposition on trees using an annual period as bioindicators. In this study, we focused on the substantial data set of four toxic elements (Cu, Mn, Ni, and Zn) accumulation in barks under similar growing conditions (habitat, environments, and thickness) from large numbers of trees of Düzce, Türkiye. In light of the above, our study planned to achieve three main targets: (1) to compare the potential bioindicator of Cu, Mn, Ni, and Zn deposition using bark and wood measurements of *Pinus pinaster*, *Cupressus arizonica*, *Picea orientalis*, *Cedrus atlantica*, and *Pseudotsuga menziesii*; (2) analyze the effects of Cu, Mn, Ni, and Zn pollution on the bark and wood biomass; and (3) explore the importance of absorption mechanisms using experimental observations. Further, the study hypothesizes that it offers a new insight for guidance to provide potential bioindicators for urban air quality and control the environmental risks calculations based on Cu, Mn, Ni, and Zn.

Materials and methods

Study area

Düzce is a vibrant city located in the Western Black Sea region of Türkiye with a rainy and green nature, where agriculture, livestock farming, and forestry are among the main livelihood activities of the people as well as rapid economic development, pollutants from various industrial activities in Fig. 1. The city is located between two metropolitan cities, making its economic structure more dynamic and reducing air quality.

Climatic conditions

The province is rich in natural vegetation and is under the influence of the humid and not-too-harsh climate seen in the coastal parts of the Black Sea region of Türkiye. It is located in the west and north of Bolu province, east of Sakarya, and southwest of Zonguldak. The average annual temperature is 13.3 °C, the annual total precipitation is 822.6 kg/m^2, and the average relative humidity is 75.2%. Düzce, bordered by the Black Sea to the north, is approximately 160 m above sea level, and the prevailing wind direction is north and southwest, as shown in Fig. 2.

Sampling methodology

Bark samples were systematically collected from *Pinus pinaster* Ait., *Cupressus arizonica* G., *Picea orientalis* L., *Cedrus atlantica* Endl., and *Pseudotsuga menziesii* Mirb. which is due to their persistence for years. One hundred thirty-five samples from each of typical forestry biomass, including bark (inner-bark (IB) and outer-bark (OB)), and wood (W) are categorized in Düzce (northwest of Anatolia), Türkiye, in Fig. 3. It is typified by various kinds of impurities (traffic, household heating, and factories). The selected trees were situated in

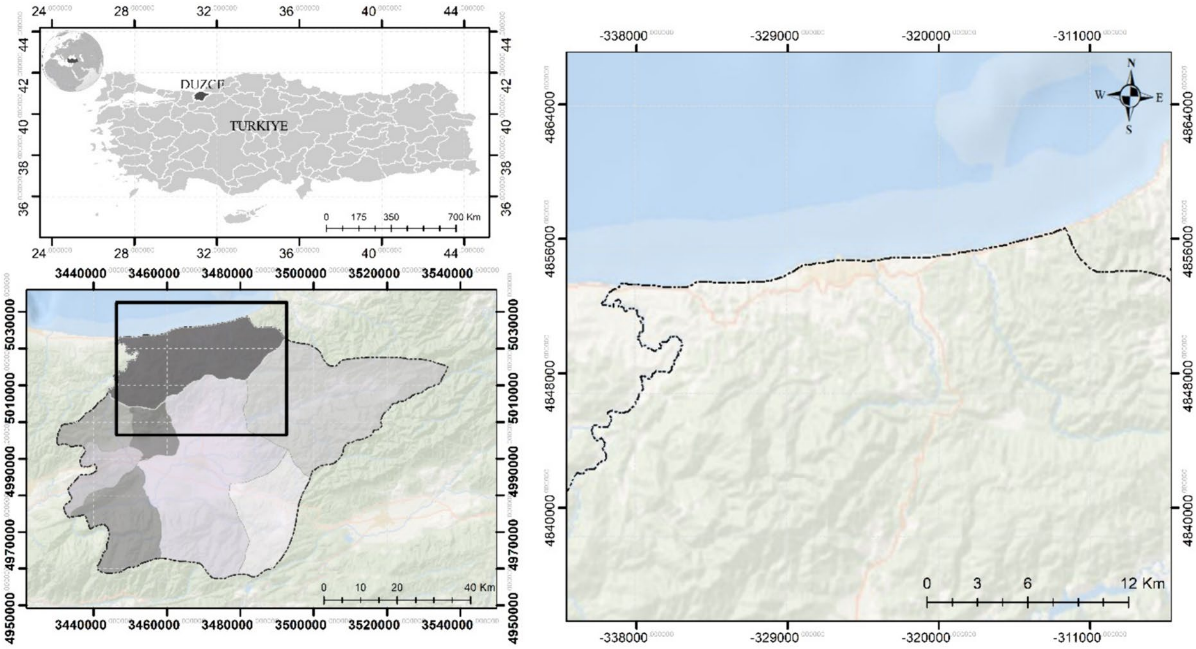

Fig. 1 Geographical location map of the study area

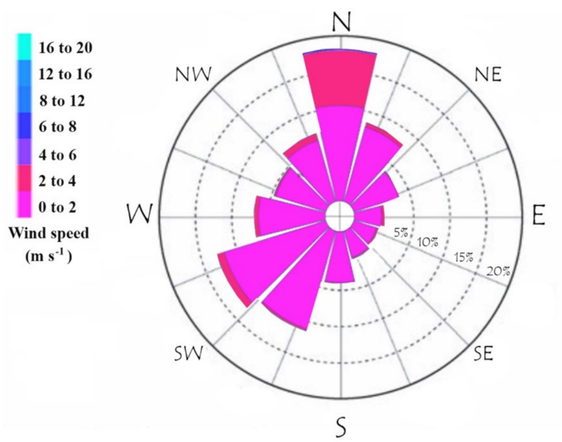

Fig. 2 Wind rose diagram of wind direction

city parks or along streets (5 m from the bank); the bark was picked at a distance of 1.50–1.80 m from the ground. For comparison, 15 specimens were gathered from a small village located 45 km to the northeast, with no considerable industrial activities.

Chemical analysis

Samples brought to the laboratory were packaged without contact with any contamination. A series of procedures were applied in order: (1) kept in an oven at 55 °C for 3 weeks to remove the remaining moisture, (2) the moisture content of the samples was reduced and reduced to much tinier pieces, (3) the chemical process of the reduced samples was started and 10 mL of 65% HNO_3 (65%, Merck) was added, (4) the chemically treated samples were microwaved at 280 PSI and 180 °C for 20 min, (e) the samples were removed from the microwave and prepared after cooling; distilled water was added up to 50 mL according to US EPA Method 3052 (USEPA, 1996), and (5) elemental concentrations in samples eluted from filter paper were examined at the corresponding wavelengths on an inductively coupled plasma optical emission spectrometer (ICP-OES) measurements with Method 6020B (USEPA, 2013). Quality control of the measurements was ensured with calibration routines by the analysis of the powdered metal-rich tree-based reference materials, which were made from easily obtainable commercial materials following similar methods to Figueiredo et al. (2016), with

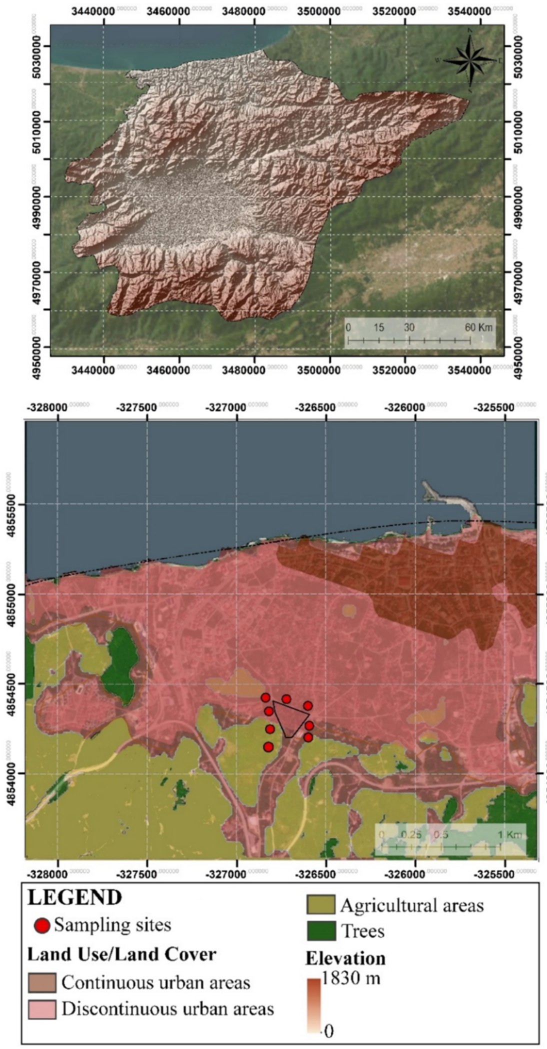

Fig. 3 Studied locations for collecting samples

good agreement between experimental and certified values (<5%). The results of the quality control measurements and limits of detections (LOD) for Cu, Mn, Ni, and Zn were found to be 0.07, 0.02, 0.6, and 0.004 µg/kg, respectively.

Statistical analyses

One-way analysis of variance (ANOVA) and Duncan's analysis were applied to verify the biomass data sets using IBM SPSS® version 22.0. The Cu, Mn, Ni, and Zn elements were used for data interpretation using the *F*-value and *p*-value (probability). They monitored with a test showing statistically significant variations at a 95% significance level and compared mean values by ANOVA ($p<0.05$) and Duncan's multiple range test ($p<0.05$). The bar charts were computed and plotted using Microsoft Excel 2019.

Results

The variation of Cu, Mn, Ni, and Zn concentrations (mg/kg) in species by components of forestry biomass is given in Table 1. As a result of the variance analysis, it was determined that the variation of Cu, Mn, Ni, and Zn concentrations by species in all directions except west was statistically significant. When the values are analyzed, it is seen that the highest Cu concentrations were obtained in *C. arizonica* (38.16 mg/kg) and *C. atlantica* (37.95 mg/kg). Notably, the concentrations obtained primarily in the north direction are quite high. When the values are analyzed, it is remarkable that the maximum results were achieved in *P. orientalis* and *C. atlantica* species in all directions. The accumulation in the north direction is higher than in the other directions; Cu (37.95 mg/kg) and Mn (188.25 mg/kg) in *C. atlantica* are higher than the other species and have bioindicator properties. The highest directional variation of Cu, Mn, Ni, and Zn concentration in the west direction for *P. menziesii* and *P. orientalis* was 22.72, 62.93, 17.96, and 62.07 mg/kg and 29.30, 552.02, 10.48, and 103.28 mg/kg, respectively.

The organ-wise variation of Cu, Mn, Ni, and Zn concentration (mg/kg) is given in Table 2. The variation of Cu concentration by species in the outer bark is not statistically significant. Nevertheless, the largest concentrations were reached in the OB. In W, the highest values were obtained in *C. arizonica* and *C. atlantica*, while the lowest values were obtained in *P. orientalis* and *P. menziesii*. The differences in Mn content according to organs were detected as statistically significant.

When the values are analyzed, it is noteworthy that the highest values were obtained in *P. orientalis* and *C. atlantica* species in tissues in Fig. 4. The organ-wise variation of Cu and Mn concentrations was found as OB > IB > W, respectively. The change in *C. atlantica* was found to be more reasonable than other species. The change of Ni concentration is examined for tissues; it is seen that the change on a species basis in organs other than IB is statistically significant, and

Table 1 Directional variation of Cu, Mn, Ni, and Zn concentration (mg/kg)

Species	North				East				South				West			
	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn
P. pinaster	27.54 b	45.01 a	12.47 a	34.14 ab	27.68 b	30.03 a	21.58 bc	84.71 c	8.69 a	42.69 a	6.10 a	43.05 a	9.93 a	47.33 a	5.76 a	77.99 a
C. arizonica	38.16 c	61.57 a	19.74 b	29.86 a	27.95 b	63.48 ab	24.28 c	74.31 bc	14.17 ab	56.75 a	13.04 b	70.75 b	27.60 b	80.90 a	6.22.ab	62.16 a
P. orientalis	21.73 ab	214.24 b	12.40 a	54.63 c	14.04 a	117.38 bc	18.24 ab	85.32 c	10.52 ab	233.90 c	10.03 b	77.19 b	29.30 b	552.02 b	10.48 b	103.28 b
C. atlantica	37.95 c	188.25 b	21.93 b	34.27 ab	12.88 a	172.02 c	15.86 a	25.99 a	15.43 b	132.29 b	10.35 b	45.81 a	37.28 b	186.67 a	10.13 b	59.41 a
P. menziesii	16.30 a	48.27 a	14.91 a	50.28 bc	14.91 a	57.64 ab	17.80 a	54.97 b	9.13 a	42.86 a	13.01 b	70.73 b	22.72 ab	62.93 a	17.96 c	62.07 a
F value	12.9***	8.0***	11.4***	2.8*	7.8***	5.5***	8.0***	11.5***	2.8*	9.7***	6.9***	5.1**	2.4 ns	17.4***	11.3***	5.3***

***$p < 0.001$; ns shows not significant and according to the results of Duncan's test, the letters a, b, c, etc. represent the members of the group. They are statistically different from the corresponding values in the other groups; a numerical value grows starting with the letter

Table 2 The accumulation of the Cu, Mn, Ni, and Zn (mg/kg) concentration in bark and wood

Organ	*P. pinaster*				*C. arizonica*				*P. orientalis*				*C. atlantica*				*P. menziesii*				*F* value			
	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn
OB	32.93 a	194.82 a	17.70 a	74.69 a	39.71 a	442.37 b	18.28 a	107.60 a	37.14 a	637.50 c	14.39 a	164.37 b	44.98 a	463.57 b	17.66 a	92.75 a	37.38 a	348.41 b	28.66 b	152.06 b	0.4 ns	9.7***	6.6***	9.7***
IB	22.06 bc	41.69 a	16.31	52.78a	29.76 c	131.65 a	11.99	53.09a	26.61 c	889.33 c	15.28	154.04 b	14.04 ab	499.11 b	19.54	42.01 a	8.28 a	83.31 a	14.87	57.84 a	5.0**	15.5***	1.4 ns	14.5***
W	18.83 b	22.02 a	10.37a	59.03c	24.37 c	10.34 a	15.42c	54.01bc	11.74 a	158.38 c	11.75 ab	60.33 c	21.79 bc	91.92 b	13.56 bc	35.01 a	13.54 a	12.19 a	13.88	48.16 b	13.3***	78.7***	5.3***	9.8***

***$p < 0.001$; ns shows not significant, and according to the results of Duncan's test, the letters a, b, c, etc. represent the members of the group. They are statistically different from the corresponding values in the other groups; a numerical value grows starting with the letter

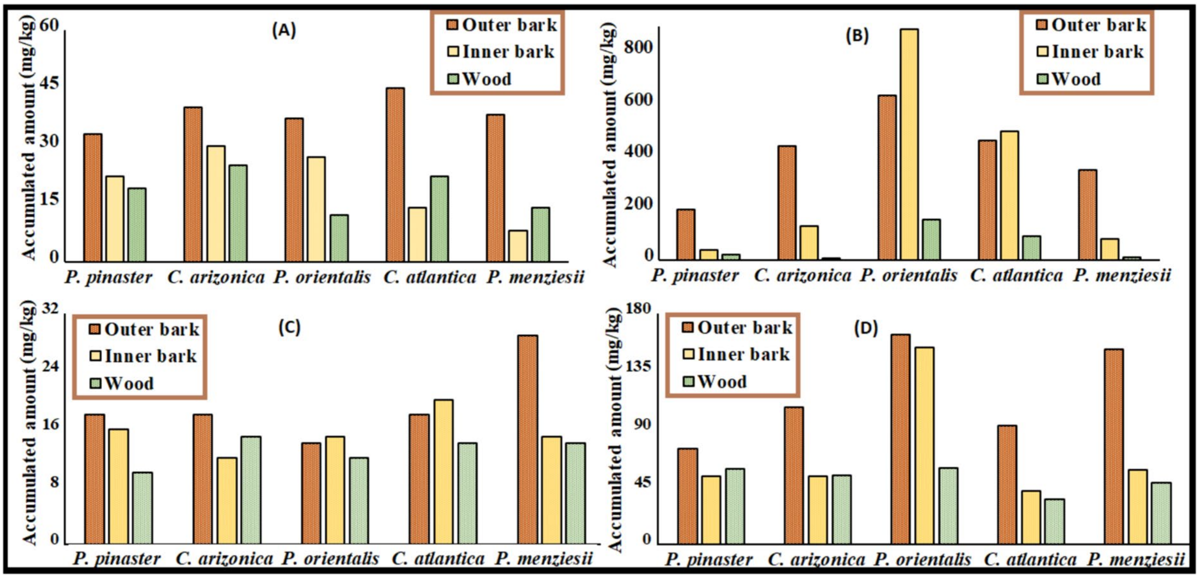

Fig. 4 Variation of **A** Cu, **B** Mn, **C** Ni, and **D** Zn mean accumulation levels in bark and wood

the highest Ni amounts were obtained in the *P. menziesii* in the OB, *C. arizonica* type in the W, and the lowest Ni concentrations were obtained in the *P. pinaster*. It is of particular importance that the highest values in W were obtained in the *C. arizonica*. When the change in Zn concentration on an organ basis is examined, it is seen that the change on a species basis in all organs is statistically significant. When the values were examined, the highest Zn concentrations were obtained in the *P. orientalis* and *P. pinaster*, and the lowest Zn concentrations were obtained in the *C. atlantica*. It is essential that the highest values in W were obtained in *P. orientalis* and *P. pinaster*.

The variation of Cu and Mn concentrations (mg/kg) by years is given in Table 3. As a result of the ANOVA, the variation of Cu and Mn concentrations from 1983 to 2022, according to the average scores, is not statistically significant. Except for the periods 1993–1997 and 2003–2007 for Cu and 2003–2012 for Mn, the variation based on interval is statistically significant. Notably, the values obtained in the east and north directions are very high. The highest values were obtained in the north direction for *P. menziesii*. Overall, the obtained values in the wood are considerably higher than in bark based on years. The highest values obtained in the study were generally obtained in the northern direction. Notably, the values obtained in the eastern direction are pretty high. The Cu concentration was below the determinable limits in the west direction in all periods for *P. pinaster*. In addition, it was below the determinable limits in the northern direction in 2003–2007, in the eastern direction in 1988–1992, and in the southern direction in 1998–2012. The highest value obtained in the study was 48.97 mg/kg in the eastern direction from 2003 to 2007. Cu concentration was below the determinable limits in the western direction in the 1983–2012 period and in the eastern direction in the 2003–2007 period for *C. arizonica*. Cu concentration in *P. orientalis* was below the determinable limits in the western direction except between 2008 and 2012. It was also below the limits in the southern direction in 1988–1997 and the eastern direction in 2013–2022. The highest values obtained in the study were generally obtained in the north and east directions. For *C. atlantica*, Cu concentration was below the determinable limits in the western direction except for 1988–1992. It is also below the limits in the southern direction in the period 2013–2017. Cu concentration was below the determinable limits in the western direction in 2008–2012 and in the eastern direction in 1983–1987, 1993–1997, and 2013–2022.

Figure 5 shows the deposition levels of toxic elements based on years. The highest value of Mn concentration for *C. arizonica*, 48.97 mg/kg, was obtained in the east direction in 2003–2007. The

Table 3 Variation of the average Cu, Mn, Ni, and Zn concentration (mg/kg) for years

Years	North				East				South				West				*F* value			
	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn	Cu	Mn	Ni	Zn
2018–2022	29.83 B	52.42	14.60 AB	27.25 Aabc	11.30 A	25.88	15.39 B	49.07 BCab	14.27 Ac	57.69	9.41 A	42.66 ABa	27.99 Bbc	61.09	9.19 Aab	61.67 Cabc	14.2***	2.0 ns	2.8*	5.9**
2013–2017	23.53 B	51.49	14.42 B	27.10 Aabc	15.08 AB	33.08	19.71 C	55.22 Bab	10.43 Abc	56.14	12.83 B	68.64 Bb	7.36 Aa	71.08	6.13 Aa	61.94 Babc	5.2**	0.8 ns	16.3***	6.4**
2008–2012	19.82 B	43.14 A	13.60 B	25.98 Aab	24.95 B	41.63 A	20.63 C	64.53 Babc	6.49 Aab	39.55 A	7.72 A	41.40 Aa	6.82 Aa	164.70 B	7.68 Aa	66.12 Bbc	6.8**	4.0*	25.7***	10.3***
2003–2007	22.65 A	27.64 A	13.39	35.70 bc	17.30 A	39.31 A	19.41	42.13 a	7.52 ab	22.34 A	9.44	44.92 a	17.27 ab	88.08 B	15.34 b	45.97 a	2.3 ns	4.5**	1.9 ns	1.3 ns
1998–2002	25.87 B	44.08	18.98 B	37.91 Ac	28.55 B	42.15	22.72 B	77.50 Bbc	5.85 Aa	27.19	9.21 A	48.39 Aab	16.59 ABa	79.80	6.85 Aa	53.84 Aab	9.4***	2.4 ns	30.2***	4.3**
1993–1997	21.95 A	51.53	13.23 B	17.99 Aa	21.20 A	37.94	17.69 C	97.63 Cc	10.06 abc	496.55	8.77 A	59.45 Bab	12.72 a	88.34	5.22 Aa	73.06 BCc	2.6 ns	0.9 ns	11.8***	10.2***
1988–1992	21.89 AB	46.58	17.67 B	36.22 ABbc	21.56 AB	45.45	18.20 B	29.80 Aa	10.02 Aabc	60.12	10.06 A	55.75 Cab	28.99 Bc	78.86	11.15 Aab	49.60 BCab	3.6*	0.4 ns	3.7*	4.5**
1983–1987	23.26 B	86.53	14.23 B	28.58 Aabc	20.60 AB	63.36	20.14 C	83.45 Bbc	9.47 Aab	112.28	10.88 AB	70.26 Bb	9.37 Aa	97.93	6.98 Aa	62.03 Babc	5.1**	0.2 ns	10.2***	5.5**
F value	0.8 ns	0.8 ns	1.3 ns	3.6**	1.5 ns	0.6 ns	1.2 ns	4.1***	3.8**	1.4 ns	1.2 ns	2.4*	7.6***	0.8 ns	2.2*	2.6*				

*, **, and *** indicate $p < 0.05$, ***$p < 0.001$; ns shows not significant and according to the results of Duncan's test, the letters a, b, c, etc. represent the group members. They are statistically different from the corresponding values in the other groups; a numerical value grows starting with the letter

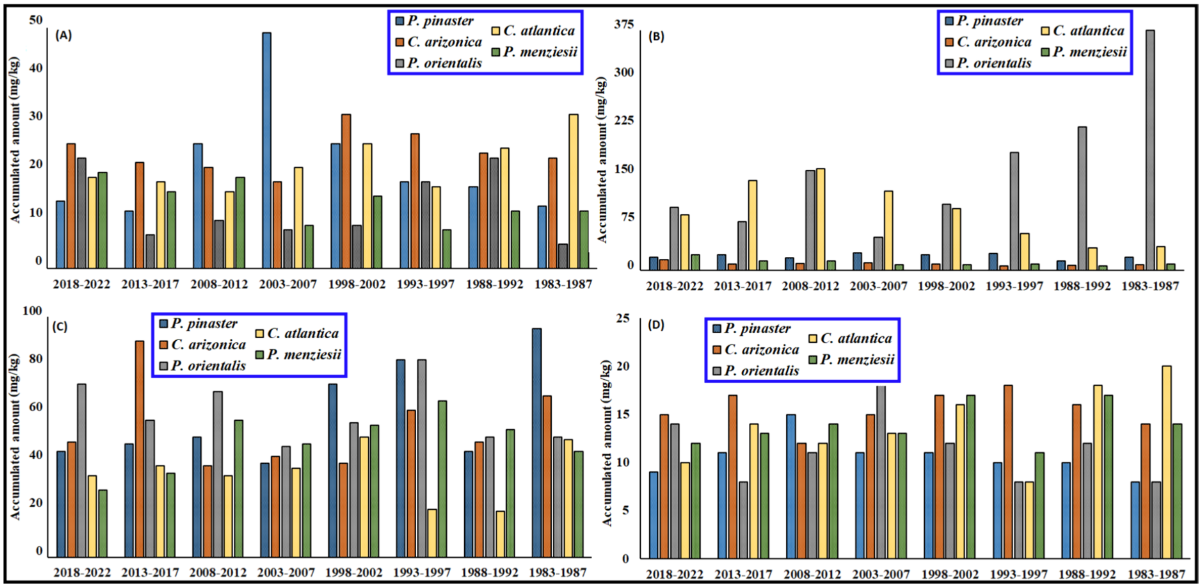

Fig. 5 Deposition of **A** Cu, **B** Mn, **C** Ni, and **D** Zn elements in all species by years

lowest value was obtained in 1988–1992, and the lowest was obtained in the eastern direction. According to the average values for *P. orientalis*, the highest values were obtained from 1998 to 2022. Regarding direction, the highest values were generally obtained in the west direction. For *C. atlantica*, the average values were obtained from 1983 to 1997. Regarding direction, the highest values were generally obtained in the west direction. According to the average values for *P. menziesii*, the highest values were obtained from 2003 to 2017. Regarding direction, the highest values were obtained in different directions in each period. According to the mean values for *P. menziesii*, the highest values were obtained from 2008 to 2022. Regarding direction, the highest values were obtained in different directions in each period.

Discussion

Trees effectively trap particulate matter in the atmosphere and have a unique role in minimizing fine, "high-risk" inhalable particles, which have the most remarkable tendency to lead to significant human health issues (Simon et al., 2021). The current study considers the suitability of tree bark as a long-term bioindicator of trace metals. Recent researchers have investigated and monitored airborne metal distribution assessments using *Quercus* (Birke et al., 2018), *Tillandsia usneoides-Tillandsia stricta* (Beringui et al., 2024), *Paubrasilia echinata* and *Libidibia ferrea* var. *leiostachya* (Andrade et al., 2024), and *Tradescantia pallida* (Campos et al., 2024). Cosma et al. (2016) presented Airborne ^{137}Cs deposition in spruce and oak bark. They evaluated more than 100 samples from outer barks of *Q. robur*, *Picea Abies*, *P. alba*, and *P. avium* in several locations in Romania. Also, they confirmed the wet and dry deposition of 137Cs, which oak bark was approximately 3.3 times greater than its average level in spruce bark. Moreira et al. (2016) observed that Al, Ba, Ca, Cl, Cu, Fe, K, Mg, Mn, Na, P, Rb, S, Sr, and Zn showed higher concentrations, which was sampled the most common species (*Tipuana tipu*, *Caesalpinia pluviosa*, *Ligustrum* sp., and *Tibouchina granulosa*). Their results also demonstrate that Al, Fe, and Cu were primarily related to the resuspension of road dust, and Ba, Cu, and Zn were found relevant to the wear-out of brakes and tires. Many studies have shown that vehicle emissions are the major source of air pollution in several cities (Deljanin et al., 2016; Guarino et al., 2021). Janta and Chantara (2017) reported deposition on the bark of *C. fistula* in dry and wet seasons that Al, Cr, Cu, Fe, Pb, and Zn emissions generated from significant vehicular pollutants in Chiang Mai. The results revealed a descending order of Al > Fe > Zn > Cu > Pb > Cr amount in which Al and Fe are elevated during the wet season. Mohammadi et al. (2018) aimed to evaluate the air pollution tolerance of the *Vitis vinifera*, *Juglans regia*, *Ulmus umbraculifera*, and *Populus alba.* They were derived from industrial activity and road traffic, and the findings calculated principle component and correlation analysis for Cd, Cu, Ni, Pb, and Zn. They reported that concentrations in all species were as follows: Zn > Cu > Ni > Pb > As > Cd. Similar biomonitoring research by Rajfur (2019) was carried out to consider the feasibility of utilizing 10 deciduous tree (*B. pendula*, *Q. robur*, *A. platanoides*, *P. nigra*, *S. nigra*, *S. aucuparia*, *C. betulus*, and *C. oxyacantha*) bark for biomonitoring of Opole urban areas. The locality and species of the tree primarily determine the deposition level of toxic metals in tree bark. This finding is confirmed by the results of the studies performed by Niu et al. (2019) and Drava et al. (2020). Solgi et al. (2020) reported investigating the performance of atmospheric Cu, Pb, and Zn deposition on leaf and bark samples of *Pinus eldarica* and *Fraxinus excelsior* in Bojnourd, Iran. Maximum Pb and Zn contents were obtained in high-traffic areas. Likewise, according to our experimental findings, Ortiz-Oliveros et al. (2024) showed the following decreasing trend of the total concentration of metals: Zn > Mn > Cu > Ni. Furthermore, the bioindicators and biomonitors study conducted by Ray et al. (2024) revealed that plants exhibited a high capacity to uptake toxic elements via wax entraps atmospheric particulates. Similar to the results of other studies, our findings suggest that tree bark can be used as a convenient passive biomonitor to predict the spatial distribution of air pollution exposure (Brignole et al., 2018; Ştefănuţ et al., 2021). Typically, in developing countries, urbanization-land use, uncontrolled emissions, and unventilated streets occur without considering the impact of air pollution on human health (Brunialti & Frati, 2023; Paoli et al., 2023). Hence, using this methodology to forecast the spatial distribution of air pollution can potentially play an essential role in enhancing urbanization planning and environmental health (Messager et al., 2021). The correlations between rising levels of air pollution and mortality and morbidity risks have long been recognized. They are currently well-documented for deposition on trees by Fasani et al. (2016), Sen et al. (2017), and Jeddi et al. (2021).

The typical features of the species commonly used in biomonitor studies are their abundance, widespread distribution, easy access, and long-lasting durability. With this behavioral feature revealed in the studies, it is seen that some tree species' practical and robust absorption ability helps air quality studies. Although the internal conductivity of the species, the transport of substances, and the radical exchange state of the species seem to differ, other studies have also revealed that there is more or less transport and accumulation in all of them (Key et al., 2022). However, it has been reported that some of them have started to be widely preferred in environmental pollution due to their excess capacity to absorb compared to others. The search for similar species is still ongoing, and several researchers are investigating their ability to accumulate (Koç, 2021; Tarish et al., 2024). Our data also indicate the marked instability of metal deposition in species growing on the same site. Unterbrunner et al. (2007) investigated Cd and Zn concentrations in *Salix caprea*, *Sarracenia purpurea*, and *Populus tremula*, which grow on metal-contaminated soils under the same conditions. They have a sizeable possible deposition of toxic metals in the studied areas. Kord et al. (2010) evaluated Pb, Zn, Cu, Ni, and Cr concentrations using *P. eldarica* Medw needles from highway sites in Tehran, Iran. This study shows significant correlations between toxic metals and pine needles of *P. eldarica.* Shi et al. (2011) conducted a study that assessed Pb/Zn, Cu with *Amorpha fruticosa* Linn, *Vitex trifolia* Linn. var. *simplicifolia* Cham, *Glochidion puberum* Linn., *Broussonetia papyrifera*, and *Styrax tonkinensis* and *Sesbania cannabina* Pers in mine tailing areas in Fuyang City and Shaoxing City, China. They calculated the tolerance index of each species, demonstrating the highest tolerance by *A. fruticosa* and *S. cannabina*. Yan et al. (2012) collected roadside soil and grass to investigate Cu, Zn, Cd, and Pb metals. This study aimed to show the uptake capabilities of metals from roadside edible grasses. It is found that the order of toxic metals are Zn > Cu > Pb in species. Among the other studied tree species, Cd is effectively absorbed because its uptake was mainly air-related, although Fe, Cu, Cr, Pb, and Zn concentrations were released to the atmosphere from transportation sources, including motor vehicles and brakes.

Epidemiological studies employed the traditional air pollution grid derived from monitoring grids, which cannot accurately characterize the intra-urban variation of air pollutants and arrive at the correct health impact, thereby minimizing the risk of exposure assessment error. To overcome this drawback, we recommend a possible approach using chemical analysis of tree bark samples gathered from various regions in the study area with a higher spatial resolution (Istanbullu et al., 2023). However, be aware that using these for a large area is difficult because of the high cost and logistical complexity of conducting them. Some studies nowadays use spatiotemporal land-use regression patterns to enhance the consistency of the relationship between air contamination exposure and human health effects (Hussain & Hoque, 2022). Our approach, combined with land-use regression modeling and potentially toxic elements, can be beneficial in arriving at an accurate environmental health impact and research in other urban areas of Türkiye to enable higher nature-based solutions.

Conclusion

Vehicle emissions are at the top of the emissions that cause air pollution and are fossil fuels used in industry and residences. Urban and local air pollution caused by low air quality and air pollutants in areas where these are frequently utilized threatens living life. The change of tree rings and organs used to determine this level reveals the dimension of pollution. The concentrations of toxic metals are obtained according to the duration of the used species in the areas and regions of the cities where pollution is observed in the exposure status. Given the diversity of bark and wood features, *P. menziesii* and *P. orientalis* were considered the most effective species for toxic metal deposition as the amount of contaminants is more detailed than that of other species. The highest directional variation of Cu, Mn, Ni, and Zn concentration in the west direction for *P. menziesii* and *P. orientalis* was 22.72, 62.93, 17.96, and 62.07 mg/kg and 29.30, 552.02, 10.48, and 103.28 mg/kg, respectively. After being used as a biomonitor, local control of urban air quality can be realized with its widespread use in various landscaping areas. We can easily control and monitor the city's air quality with its general use. We encourage further studies on diversifying and sampling urban air pollution to understand the physiological and phenotypic responses of *P. menziesii* and *P. orientalis* to different toxic elements and map them for large-scale biomonitoring programs.

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Data Availability Not applicable.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the instructions for authors.

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