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Original Article

Tracking Air Quality Through Time with *Tilia tomentosa* Moench (Silver Linden) Trees as a Bioindicator

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What is already known on this topic?

- Trees and other plants are widely used as bioindicators because they accumulate airborne pollutants in their tissues, particularly in leaves and bark.
- Bark tissues, due to their direct exposure to the atmosphere, are generally reported to accumulate higher concentrations of heavy metals compared to inner tissues such as wood.
- However, long-term (multi-decadal) studies using tree tissues to reconstruct historical air pollution trends remain limited, and uncertainties persist regarding metal mobility within tree organs and the consistency of organ-specific accumulation patterns.

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ABSTRACT

Tilia tomentosa Moench (silver linden) trees were evaluated as a potential bioindicator species for the tracking of metal-containing particulate air pollutants. Air quality was evaluated between 1962 and 2021 in the Çaycuma sites of Zonguldak. The cobalt, nickel, and lead elemental contents were analyzed in the wood, outer bark, and inner bark of the *Tilia tomentosa* growing naturally in the Çaycuma district using inductively coupled plasma optical emission spectrometry. The lack of difference between the organs in the study indicates that the pollution level in the region is relatively low. Based on mean values measured in the outer bark, the lowest concentrations of cobalt, nickel, and lead were observed during 1997–2001, at 16.7, 23.8, and 44.3 mg/kg, respectively. According to the mean values in the inner bark, the lowest concentrations of cobalt, nickel, and lead were observed during 1987–1991, at 14.6, 21.1, and 39.0 mg/kg, respectively. *Tilia tomentosa* exhibited adequate spatial and temporal variations in air pollutant concentrations, showed high positive correlations with air pollutant levels, and was less susceptible to climatic stressors than the other native species.

Keywords: Adsorbing capacity, biological monitoring, environmental management, urban air pollution, toxic metals

Introduction

Industrialization and urbanization have increased air pollution due to irregular environmental pollution and unplanned city development. Environmental pollution in various forms includes the uncontrolled and illegal discharge of pollutants from their sources into the receiving environment (Yilmaz et al. 2026). The need for continuous monitoring of urban air quality, caused by contaminants in urban areas, arises from the direct and indirect adverse effects of pollutants on public health. Exposure to air pollution can lead to various health problems, including respiratory and cardiovascular diseases, and contribute to global climate change (Isinkaralar & Isinkaralar, 2023). To mitigate the impact of air pollution, it is necessary to identify pollutant sources and implement effective control strategies.

Air pollution in metropolitan areas is a significant environmental concern, with approximately 99% of the global population residing in regions with poor air quality (WHO, 2024). The primary sources of air pollution in urban areas include emissions from industrial facilities, automobiles, and daily household activities (Isinkaralar et al., 2024, 2026). Photochemical smog, primarily induced by traffic and industrial activities, has become a major concern for air quality, while sulfur remains a significant problem in many cities of the developing world (Khan et al., 2021; İsmail et al., 2025). Furthermore, air pollution is reported to claim the lives of one in eight people globally, underscoring the urgent need to address this issue. To address urban air pollution, a comprehensive approach is necessary, including stringent environmental regulations, the adoption of innovative emission-control technologies, and the development of mass transit systems. Introducing efficient mass transit systems and urban forests can help mitigate rising levels of organic pollutants and improve ambient air quality in major cities. The release of pollutants, such as heavy metals, into the environment from insufficient filtration systems is increasing the levels of toxicants uncontrollably (İsmail et al., 2026). Heavy metals and trace elements are typically present in the atmosphere as particulate matter (PM). These particles are released into the atmosphere from anthropogenic sources such as industrial activities, fossil fuel combustion, mining, traffic emissions, and waste incineration (Parviainen et al., 2020; Świsłowski et al., 2025). Atmospheric heavy metals are commonly associated with aerosols in the size range of PM_{10} (particles smaller

What this study adds on this topic?

- Long-term reconstruction of air pollution: This study provides a rare 60-year (1962–2021) temporal record of cobalt, nickel, and lead deposition using *Tilia tomentosa*, demonstrating its applicability for retrospective air quality assessment.
- Evidence of directional sensitivity: It reveals clear directional (spatial) differences in metal accumulation within the same tree, highlighting the influence of local emission sources and wind patterns on pollutant deposition.
- Organ-level insights under moderate pollution: Contrary to common assumptions, the study shows no significant differences among wood, inner bark, and outer bark, suggesting more uniform metal distribution under low-to-moderate pollution conditions and contributing to discussions on metal mobility within tree tissues.

than 10 micrometers) or $PM_{2.5}$ (particles smaller than 2.5 micrometers). This form directly influences plant uptake processes through leaf surfaces (Isinkaralar et al., 2025). Plants typically absorb these particles either through stomata or by direct adhesion to the leaf surface. Over time, these particles may also settle onto the soil via gravitational deposition or precipitation, becoming available for plant root uptake (Isinkaralar & Erdem, 2021). Cobalt (Co), nickel (Ni), and lead (Pb) are commonly found in the environment in ionic, oxide, sulfide, and organically bound forms (Bahinskyi et al., 2025). In the atmosphere, these metals are often associated with particulate-bound oxides or sulfates (Zhang et al., 2019).

The first-released heavy metals continue to accumulate in that region and may then spread over a certain distance. The effects of weather conditions, including wet and dry precipitation and horizontal and vertical wind movements, are significant in transporting trace elements (Marsay et al., 2022; Vergel et al., 2022). Such movements affect the locations of accumulation. Heavy metal accumulation is evident in all living and non-living organisms, including grass, trees, and various plant species in urban areas (Zeren Cetin et al., 2025). The variety of heavy metals emitted into the air in dense urban, human, and industrial environments, especially in cities, poses a severe threat to human health (Isinkaralar et al. 2025; Dışbudak et al. 2026). The air quality in dense cities, that is, regions where the human population is dense, the number of vehicles is high, and trade and industry activities are fast-paced, warrants serious concern (Lu et al., 2017). The insufficient number and quality of air monitoring stations established within the framework of local administrations' measures make it difficult to monitor air pollutant concentrations (Yucedag et al. 2025). In addition, since the data obtained from the station cannot be correlated with the entire city, this creates problems with data interpretation and risk assessment.

Bioindicator species retain PM on their leaf and bark surfaces; therefore, their active distribution to specific urban locations would be an appropriate choice for continuous monitoring and mitigation of air pollution (Koç et al., 2026). The uninterrupted follow-up of the relocated species, by addressing issues associated with high pollution levels, has been achieved in other studies at a relatively low cost by utilizing their organs and leaves (Lachowicz et al., 2025).

Tilia trees, commonly used in urban landscaping, have been identified in several studies as suitable for biomonitoring atmospheric trace elements. Ţenche-Constantinescu et al. (2015) reported that the highest Pb concentrations were recorded in *Tilia tomentosa* in areas with heavy traffic. Similarly, Turkyilmaz et al. (2018) found that the amount of Pb measured in *Tilia tomentosa* growing in a low-traffic area (17,106 µg/kg) was even higher than that found in other species growing in high-traffic zones. Studies investigating the use of *Tilia* species as bioindicators have primarily been conducted in areas with traffic-related pollution and have shown that heavy metal concentrations in plant organs, such as leaves, seeds, and branches, increase with traffic density (Sahin et al., 2025).

The present study aimed to determine whether *Tilia tomentosa* can be used to mitigate air quality contamination over a relatively long period (60 years). For this purpose, the data obtained for *Tilia tomentosa* samples collected in the Çaycuma region in February 2022 were compared with those from past years at the same collection sites.

Material and Methods

Study Area

The bark sample used in the scope of the study was obtained from the bark and wood of *Tilia tomentosa* Moench (Silver linden) trees, as shown in Figure 1, which naturally grow in the Çaycuma district of Zonguldak Province in February 2022. The diameter at breast height ($d_{1.30}$) of the sampled tree was measured as 62.8 cm, based on the average of measurements taken from two opposite directions. While the bark sample of the species above was taken, the directions (North, South) were determined on the bark, and the coordinate value was noted and preserved.

The Çaycuma district of Zonguldak Province exhibits the typical characteristics of the Black Sea climate. This climate type is characterized by regular precipitation year-round, with no distinct dry season. According to long-term meteorological data from 1930 to 2024, the average annual temperature of Zonguldak Province is 13.8°C, and the average total annual precipitation is 1226.4 mm (URL-1).

Preparation of Samples

The bark sample used in this study was obtained at a thickness of 10 cm from approximately 50 cm above the ground on the trunk of a naturally grown *Tilia tomentosa* tree in the region. The upper surface of the section taken from the wood was smoothed by the sanding process so that the annual rings could be

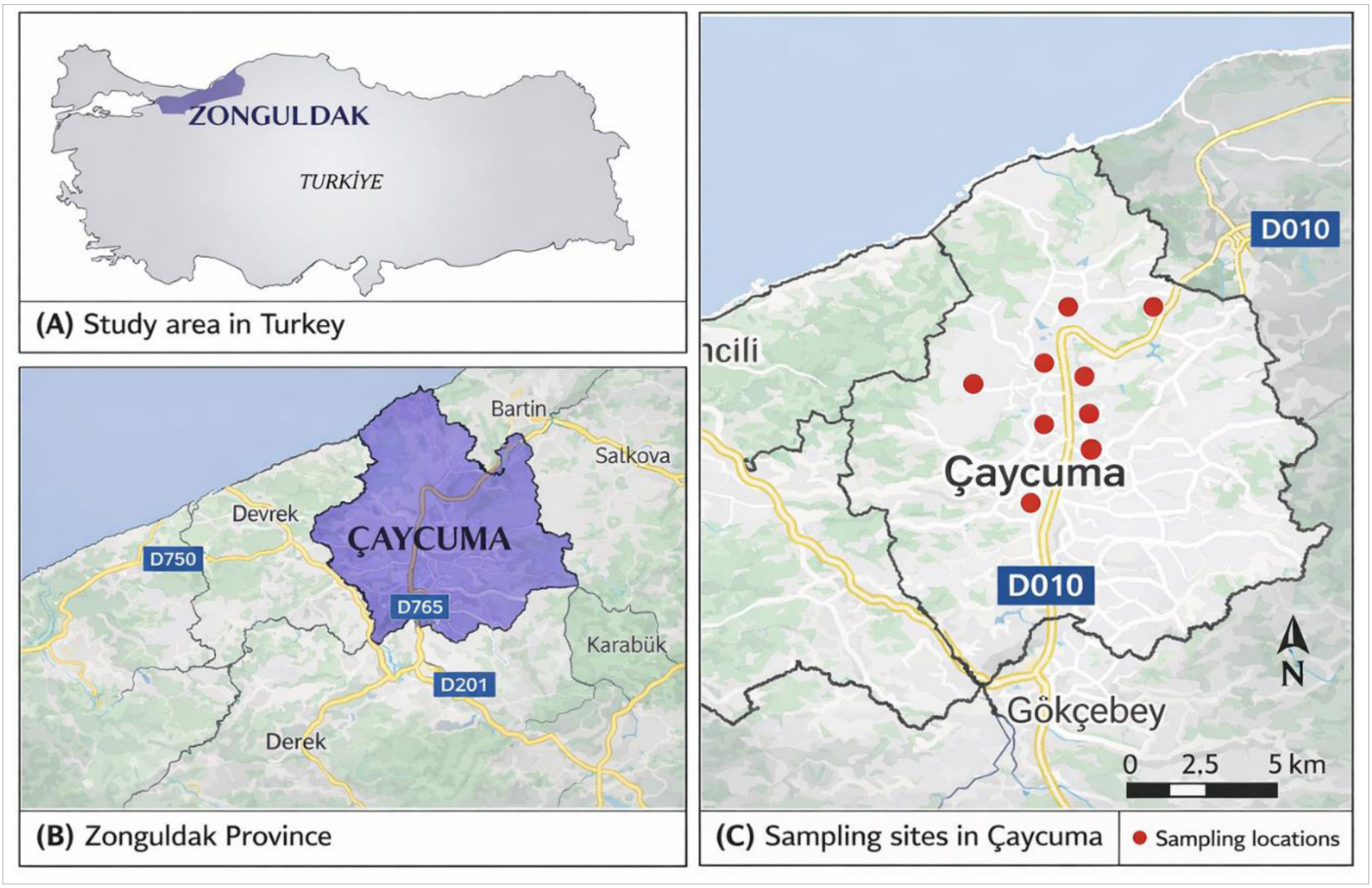


Figure 1.
(A) Map of Zonguldak in Türkiye, (B) Location of Study Area, and (C) Distribution of Sampling Sites.

seen more clearly in the laboratory. Although it can be determined in which year the annual rings are formed, no samples can be taken from the ring formed every year due to the narrowness of the annual rings. The annual rings are grouped by their width and the tree's age. In the studies, it was determined that 20-year-old trees were grouped as being five years old. The census determined that the tree was 60 years old by counting the annual rings, which were grouped from 1 to 12 from the outside to the inside, based on their widths. After the wood surface was divided into groups and the age ranges were determined, samples were taken from the outer bark, inner bark, and wood of all age ranges using a steel-tipped drill and placed in glass petri dishes. The outer bark samples were taken from the outermost part of the bark, which is in direct contact with the external environment. In contrast, the inner bark samples were collected from the portion located just after the cambium, within the bark, with no direct connection to the external environment. Therefore, while the outer bark is in direct contact with the external environment, the inner bark has no such exposure. This process was done in two directions of the barks, facing the industrial zone and in the opposite direction, and samples were taken from both directions. The wood samples to be taken were shredded and turned into sawdust. During these processes, care was taken not to use tools made of any of the metals that were evaluated, and all chemicals are now reported as analytical grade (≥99% purity) in this study.

The samples were carefully taken without exposure to contamination, individually packaged, and brought to the laboratory. Initially, they were placed in an oven at 47°C for 2 weeks to dry, and then cut into small pieces. Then, 10 mL of 65% nitric acid (HNO_3) was added to the samples, which were digested in a microwave at 280 Pounds per Square Inch (PSI) and 180°C for 20 minutes to achieve acid digestion. The tubes were cooled after removal, and distilled water was added to bring the volume up to 50 mL, as per the US EPA 3052 Method (US EPA, 1996). Samples were filtered through Whatman 42 filter paper and analyzed at the appropriate wavelengths using inductively coupled plasma optical emission spectrometry (calibration curve $R^2 > .999$) (SpectroBlue, Spectro, Analytical Instruments GmbH, Germany), following Method 6020B (USEPA, 2013).

Statistical Analysis

The study was conducted on a single mature *Tilia tomentosa* individual. Therefore, directional sectors, tissue types (wood, inner bark, and outer bark), and temporal segments derived from annual ring groupings represent nested subsamples within the same biological organism rather than independent biological replicates. Statistical analyses were therefore used primarily for exploratory and descriptive purposes to quantify within-tree variation by IBM SPSS Statistics for Windows, version 21.0 (IBM Corp.; Armonk, NY, USA). One-way ANOVA and Duncan's multiple comparison tests were performed using the IBM® SPSS v22.0 (IBM Corp, Armonk, NY, USA). The resulting significance values should not be interpreted as population-level inference but rather as indicators of relative variation among sampled tissues, directions, and temporal intervals within the investigated tree. Because only one tree was available for analysis, the findings should be regarded as hypothesis-generating and require validation using multiple trees and sites in future studies.

Results

Variations Based on Plant Organs

Analysis of variance indicated that co-concentrations varied significantly with sampling direction across plant organs (Table 1). In contrast, differences among organs within the same direction were not statistically significant. Significant directional variation was observed in both inner bark (17,530 vs. 15,410 µg/kg) and outer bark (17,711 vs. 15,424 µg/kg), whereas wood showed no significant directional difference (17,454 vs. 16,887 µg/kg). Mean co-concentrations were consistently higher in the outer direction than in the opposite direction. Across all samples, mean concentrations ranged from 16,470 to 17,171 µg/kg, with no significant differences among wood, inner bark, and outer bark.

Cobalt concentrations exhibited significant variation with sampling direction and period ($p < .001$; Table 2). Outer-direction values were generally higher until 1992–1996, whereas opposite-direction values predominated thereafter. The lowest concentrations were observed during 1987–1996 and 1992–2001, while the highest values occurred during 1977–1981 (outer direction) and 1997–2006 (opposite direction). Temporal variation was significant in both directions, and Duncan's test identified the 1987–1996 period as having the lowest mean co-concentrations.

Analysis of variance revealed significant directional variation in Ni concentrations across all organs ($p < .01$), whereas differences among wood, inner bark, and outer bark were not significant (Table 3). Nickel concentrations were consistently higher in the outer direction than in the opposite direction for all organs. The biggest directional differences were observed in bark tissues, while wood exhibited comparatively smaller variations. Overall, Ni accumulation did not differ significantly among plant organs.

Analysis of variance indicated significant variation in Ni concentrations among periods and sampling directions ($p < .001$; Table 4). Nickel concentrations were generally higher in the outer direction until 1992–1996, whereas higher values were observed in the opposite direction thereafter. The lowest mean concentrations occurred during 1992–1996 (22,533.1 µg/kg) and 1987–1991 (22,770.3 µg/kg), while the highest values were recorded during 2002–2006 (25,915.2 µg/kg) and 2007–2011 (25,705.4 µg/kg). Temporal variation was significant in both directions ($p < .001$), and the overall mean Ni concentration was slightly higher in the outer direction (24,690.1 µg/kg) than in the opposite direction (23,702.2 µg/kg).

Analysis of variance indicated that directional variation in Pb concentration was significant only in bark tissues, whereas differences among organs within each direction were not statistically significant (Table 5). Lead concentrations in both inner bark and outer bark were significantly higher in the outer direction than in the opposite direction. In contrast, no significant directional difference was observed in wood. The overall mean Pb concentration was higher in the outer direction (46,802.5 µg/kg) than in the opposite direction (44,633.9 µg/kg). Mean

Table 1.
Variation of Cobalt Concentration (µg/kg) by Organ (Wood, Inner Bark, Outer Bark) and Direction (Outer Direction and Side Facing the Industrial Zone)

Organ	Outer Direction	Side Facing the Industrial Zone	*F*	Mean
Wood	17,454.0	16,887.1	1.9 ns	17,170.6
Inner bark	17,530.0 B	15,410.0 A	1257.0***	16,470.0
Outer bark	17,711.1 B	15,424.4 A	894.4***	16,567.8
F	0.2 ns	1.1 ns		0.7 ns
Mean	17,477.8	16,677.2	5.1*	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions.
*$P < .5$.
**$P < .01$.
***$P < .001$.

Table 2.
Variation of Cobalt Concentration (µg/kg) in Wood by Period and Orientation

Period	Outer Direction	Side Facing the Industrial Zone	*F*	Mean
2017–2021	17,333.0 cA	18,946.0 eB	187.3***	18,139.5 bc
2012–2016	16,751.4 aA	19,205.4 fB	234.1***	17,978.4 bc
2007–2011	17,152.6 bcA	19,680.9 gB	1064.9***	18,416.7 bc
2002–2006	17,106.6 bcA	19,941.2 hB	450.1***	18,523.9 c
1997–2001	16,749.4 aA	20,078.5 hB	2934.2***	18,413.9 bc
1992–1996	16,815.4 aB	14,794.4 abA	650.4***	15,804.9 a
1987–1991	17,074.9 bB	14,630.6 aA	650.7***	15,852.8 a
1982–1986	18,239.1 eB	14,870.0 bcA	1307.6***	16,554.6 abc
1977–1981	18,565.8 fB	14,898.6 bcA	1253.1***	16,732.2 abc
1972–1976	18,225.2 eB	15,046.8 cA	2707.6***	16,636.0 abc
1967–1971	17,819.1 dB	15,280.0 dA	462.8***	16,549.6 abc
1962–1966	17,615.6 dB	15,273.3 dA	639.2***	16,444.5 ab
F	71.1***	1120.8***		2.8**
Mean	17,454.0	16,887.1	1.9 ns	

ns is not statistically significant. Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions.
*$p < .5$.
**$p < .01$.
***$p < .001$.

Table 3.
Variation of Nickel Concentration (µg/kg) by Organ and Direction

Organ	Outer Direction	Side Facing the Industrial Zone	*F*	Mean
Wood	24,690.1 B	23,702.2 A	4.4*	24,196.1
Inner bark	24,863.1 B	22,062.2 A	539.1***	23,462.7
Outer bark	25,059.2 B	22,160.4 A	363.6***	23,609.8
F	0.5 ns	0.9 ns		0.5 ns
Mean	24,728.8 B	23,475.0 A	9.3**	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*$p < .5$.
**$p < .01$.
***$p < .001$.

Table 4.
Variation of Nickel Concentration (µg/kg) in Wood by Period and Orientation

Period	Outer Direction	Side Facing the Industrial Zone	*F*	Mean
2017–2021	24,764.4 cdA	25,936.7 cB	80.9**	25,350.6 cd
2012–2016	23,928.1 abA	26,257.8 cB	227.4***	25,093.0 bcd
2007–2011	24,402.2 bcA	27,008.6 dB	361.0***	25,705.4 cd
2002–2006	24,273.7 abcA	27,556.6 eB	1346.0***	25,915.2 d
1997–2001	23,824.2 aA	27,339.3 deB	101.3**	25,581.8 cd
1992–1996	23,889.0 aB	21,177.2 aA	174.8***	22,533.1 a
1987–1991	24,445.6 cB	21,095.1 aA	682.5***	22,770.3 ab
1982–1986	25,772.8 gB	21,126.6 aA	1125.5***	23,449.7 abc
1977–1981	25,280.2 efB	21,501.6 abA	411.6***	23,390.9 abc
1972–1976	25,571.9 fgB	21,629.4 bA	93.9**	23,600.7 abcd
1967–1971	25,166.7 defB	21,888.4 bA	176.3***	23,527.6 abc
1962–1966	24,962.1 deB	21,909.2 bA	392.8***	23,435.6 abc
F	18.2***	360.2***		2.8**
Mean	24,690.1 B	23,702.2 A	4.4*	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*$p < .5$.
**$p < .01$.
***$p < .001$.

Pb concentrations were 45,957.2 µg/kg in wood, 44,120.8 µg/kg in inner bark, and 44,448.1 µg/kg in outer bark.

Analysis of variance revealed significant variation in Pb concentrations among periods and sampling directions ($p < .001$; Table 6). Lead concentrations were generally higher in the outer direction until 1992–1996, whereas higher values were observed in the opposite direction thereafter. The lowest mean Pb concentrations were recorded during 1992–1996 (42,018.5 µg/kg) and 1987–1991 (42,468.3 µg/kg), while the highest values occurred during 2002–2006 (49,909.9 µg/kg) and 2007–2011 (49,691.2 µg/kg). Temporal variation was significant in both directions ($p < .001$). The overall mean Pb concentration was 46,717.4 µg/kg in the outer direction and 45,197.0 µg/kg in the opposite direction.

Table 5.
Variation of Lead Concentration (µg/kg) by Organ and Direction

Organ	Outer Direction	Side Facing the Industrial Zone	*F*	Mean
Wood	46,717.4	45,197.0	1.6 ns	45,957.2
Inner bark	46,972.6 B	41,269.0 A	935.9***	44,120.8
Outer bark	47,654.2 B	41,242.0 A	377.4***	44,448.1
F	0.3 ns	0.9 ns		0.6 ns
Mean	46,802.5 B	44,633.9 A	4.4*	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*$p < .5$.
**$p < .01$.
***$p < .001$.

Table 6.
Variation of Lead Concentration (µg/kg) in Wood by Period and Orientation

	Outer Direction	Side Facing the Industrial Zone	*F*	Mean
2017–2021	46,254.0 cA	51,025.2 eB	847.3***	48,639.6 c
2012–2016	44,330.6 aA	51,768.6 fB	586.2***	48,049.6 bc
2007–2011	45,764.7 bcA	53,617.7 gB	1941.5***	49,691.2 c
2002–2006	45,772.6 bcA	54,047.1 ghB	591.9***	49,909.9 c
1997–2001	44,288.4 aA	54,490.6 hB	383.4***	49,389.5 c
1992–1996	45,059.7 bB	38,977.2 aA	1348.7***	42,018.5 a
1987–1991	45,912.7 cB	39,023.9 abA	491.9***	42,468.3 ab
1982–1986	49,277.9 eB	39,054.6 abA	1811.0***	44,166.3 abc
1977–1981	50,190.8 fB	39,590.4 abA	1592.9***	44,890.6 abc
1972–1976	49,075.4 eB	39,720.2 bcA	1259.0***	44,397.8 abc
1967–1971	47,626.4 dB	40,353.6 cdA	152.3***	43,990.0 abc
1962–1966	47,055.2 dB	40,694.4 dA	415.4***	43,874.8 abc
F	64.2***	982.7***		2.6*
Mean	46,717.4	45,197.0	1.6 ns	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*$p < .5$.
**$p < .01$.
***$p < .001$.

In bark tissues, Co, Ni, and Pb concentrations were consistently higher in the outer direction than in the opposite direction. Mean concentrations in wood were 17.4 mg/kg for Co, 24.7 mg/kg for Ni, and 46.7 mg/kg for Pb. Lead concentrations in the inner and outer bark were 41.3 and 47.6 mg/kg, respectively. Considering all organs, the overall accumulation pattern was Pb > Ni > Co.

Significant directional and temporal variations were observed for Co, Ni, and Pb concentrations in *Tilia tomentosa* ($p < .001$; Figure 2). Concentrations were generally higher in the outer direction until 1992–1996 and in the opposite direction thereafter. The lowest concentrations were recorded during 1992–2001 and 2012–2016 in the outer direction, and during 1987–1996 in the opposite direction. The highest concentrations occurred during 1977–1981 in the outer direction and during 1997–2006 in the opposite direction. Based on outer bark averages, the lowest Co, Ni, and Pb concentrations were observed during 1997–2001, with values of 16.7, 23.8, and 44.3 mg/kg, respectively.

Discussion

The present study evaluated the potential of *Tilia tomentosa* as a biomonitor of long-term atmospheric trace metal deposition by examining Co, Ni, and Pb concentrations across tissues, directions, and time periods. The results demonstrated significant temporal and directional variation in metal concentrations, whereas differences among wood, inner bark, and outer bark were generally not significant (Caldana et al., 2023; Guney et al., 2023). The absence of pronounced organ-specific

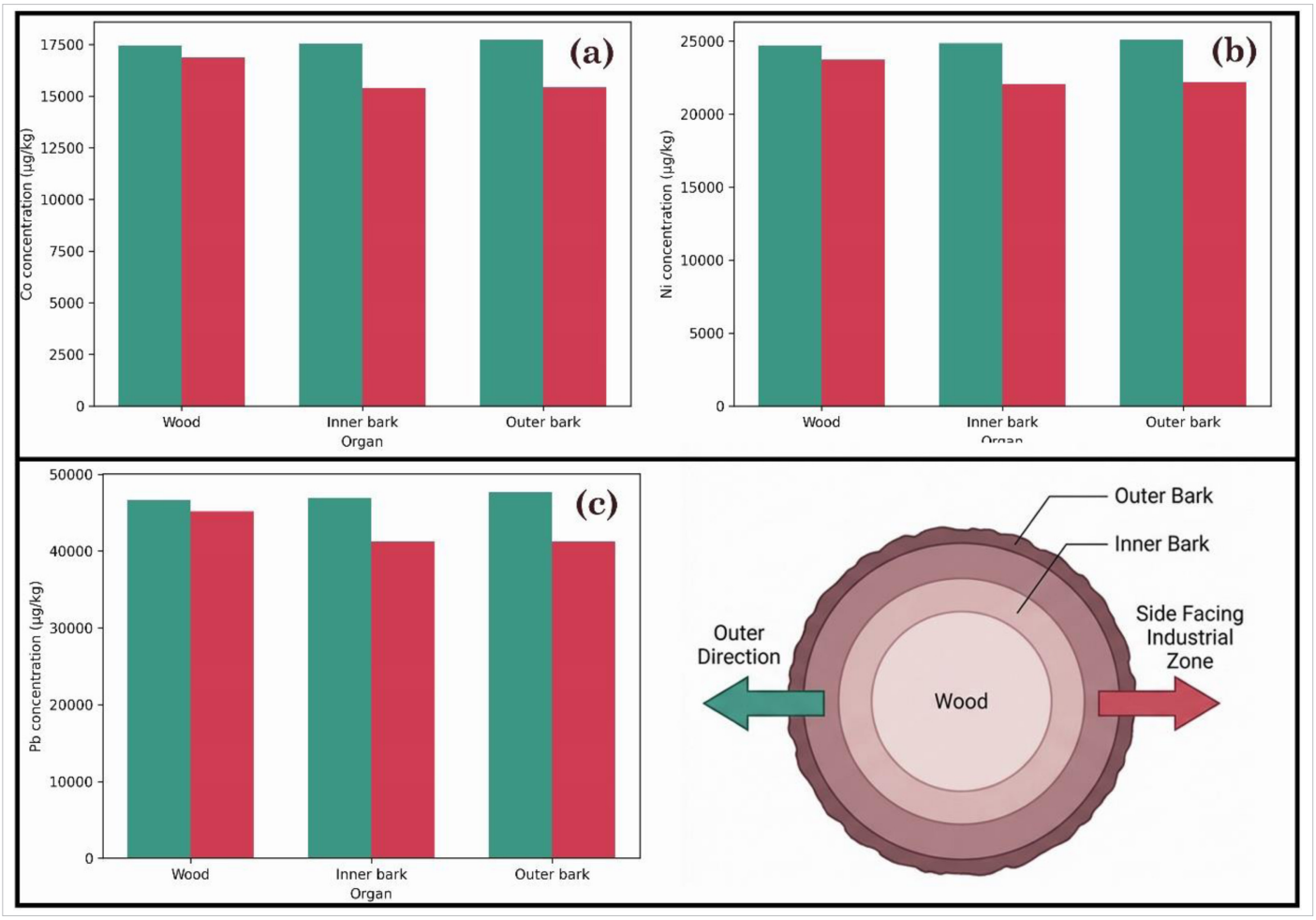


Figure 2.
Comparison of (a) Cobalt, (b) Nickel, and (c) Lead Concentrations Across Plant Organs Under Different Directional Exposures.

differences contrasts with studies reporting higher metal accumulation in bark due to its direct exposure to atmospheric deposition (Birke et al., 2018; Baroudi et al., 2022). Similar concentrations among tissues may reflect relatively low-to-moderate pollution levels or long-term redistribution of metals within tree tissues. Previous studies have shown that metal mobility varies considerably among elements and species, which may contribute to the observed patterns (Benítez et al., 2019; Koc, 2021; Key et al., 2023). Directional differences were observed for all investigated elements, with higher concentrations generally recorded on one side of the trunk. Similar spatial variability has been reported in biomonitoring studies and is commonly associated with localized deposition processes (Chung et al., 2021; Nekhoroshkov et al., 2022; Rajfur et al., 2025). However, because all samples originated from a single tree, directional sectors cannot be considered independent biological replicates. Consequently, these results should be interpreted as within-tree variation rather than evidence of population-level spatial heterogeneity.

Temporal analyses revealed significant fluctuations in Co, Ni, and Pb concentrations throughout the study period. Concentrations were generally lower during the late 1980s and early 1990s and higher during the late 1990s and 2000s. Comparable temporal variability has been documented in dendrochemical and biomonitoring studies investigating historical changes in atmospheric contamination (Panichev et al., 2019; Cuciurean et al., 2024; Respondek et al., 2024). Nevertheless, in the absence of independent atmospheric monitoring records or emission inventories, the observed trends should be regarded as indicative rather than definitive evidence of changes in pollution intensity. The findings suggest that *Tilia tomentosa* has potential for retrospective biomonitoring of atmospheric trace metals. However, given the single-tree design and the lack of biological replication, the results should be considered exploratory. Future studies incorporating multiple trees, sites, and complementary environmental datasets are needed to validate the temporal and spatial patterns identified in this study.

Conclusion and Recommendations

This study assessed the temporal and spatial variation of Co, Ni, and Pb concentrations in wood, inner bark, and outer bark tissues of *Tilia tomentosa* collected from the Çaycuma region between 1962 and 2021. Significant temporal and directional variations were observed for all investigated elements, whereas differences among plant organs were generally not significant. The lowest concentrations were recorded during the late 1980s and 1990s, while relatively higher concentrations were observed in subsequent periods. Across all tissues, the overall accumulation pattern was Pb > Ni > Co.

The findings indicate that *Tilia tomentosa* tissues can preserve measurable records of trace metal variability over time and may provide useful information for retrospective environmental assessment. Directional

differences observed within the sampled tree further suggest that tree tissues can reflect localized patterns of atmospheric deposition. However, because the study was based on a single tree, the results should be regarded as exploratory and interpreted with caution. Additional biological replication is required before broader ecological or environmental inferences can be made.

Based on the results of this study, the following recommendations are proposed:

1. Enriching future studies with multiple trees and sampling areas could allow for inferences to be made at the population level.
2. Simultaneous measurements of atmospheric deposition, air quality monitoring data, and emission inventories should be incorporated to validate dendrochemical records and strengthen source attribution.
3. The influence of environmental factors such as precipitation, prevailing winds, and local land-use changes on metal accumulation patterns should be investigated in greater detail.
4. Comparative studies involving different tree species are recommended to evaluate species-specific differences in metal uptake, retention, and internal mobility.
5. Long-term biomonitoring programs integrating tree tissues with other biological indicators, such as mosses and lichens, may provide a more comprehensive assessment of atmospheric trace metal pollution.

Thus, the present study provides preliminary evidence that *Tilia tomentosa* may have potential as a biomonitor of long-term atmospheric trace metal deposition. Nevertheless, further research incorporating broader spatial coverage and biological replication is necessary to confirm its suitability for environmental monitoring applications.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

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