

Using Aleppo pine (*Pinus halepensis* Mill) growth rings as a
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Using Aleppo pine (*Pinus halepensis* Mill) growth rings as a bioindicator of lead and cadmium air pollution in Al Bayda, Libya

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Abstract

This study estimated lead (Pb) and cadmium (Cd) concentrations in tree-ring wood of Aleppo pine (*Pinus halepensis* Mill.) and evaluated its efficiency as a bioindicator of atmospheric heavy metal pollution. Wood and soil samples were collected from seven trees at sites with varying exposure levels along Al-Bayda City's main streets and from reference sites outside the city. The study covered two decades (2000–2010 and 2011–2021) for temporal comparison. Samples were analyzed using Atomic Absorption Spectroscopy, and the Bioaccumulation Factor (BAF) was calculated. Exploratory statistical analysis was conducted, and the Wilcoxon Signed-Rank Test was used to compare decades within the same trees and to compare BAF-Pb with BAF-Cd. All analyses were performed using SPSS version 23. Results showed a clear upward trend in Pb concentrations, increasing from 0.071 mg/kg in the first decade to 0.075 mg/kg in the second, indicating continued Pb accumulation.

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This was supported by a high mean BAF for Pb (2.57), demonstrating efficient Pb uptake from soil. In contrast, Cd concentrations declined slightly in the second decade (from 0.026 to 0.019 mg/kg), with a low BAF (1.04), indicating limited Cd accumulation. A pronounced spatial variation was observed, with Pb values ranging from 0.012 mg/kg at less polluted sites to 0.12 mg/kg at sites most affected by human activities—a tenfold difference reflecting the influence of traffic density, industrial activities, and proximity to pollution sources. Cd concentrations ranged from 0.009 to 0.041 mg/kg, showing relatively low levels with spatial variation among sites. The study concludes that tree-ring analysis, particularly of Aleppo pine, is an effective and reliable tool for long-term environmental monitoring of heavy elements, provided that qualitative variation among elements and local environmental factors are considered. It recommends enhancing the use of trees, especially Aleppo pine, as bioindicators in national and local monitoring systems, due to their accuracy, ease of sampling, lower cost, and ability to document temporal changes, thus contributing to a historical database for tracking pollution trends.

Keywords: Aleppo pine, tree rings, lead, cadmium, bioindicator, bioaccumulation factor, air pollution, Libya.

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استخدام حلقات نمو الصنوبر الحلبي (*Pinus halepensis* Mill) كمؤشر حيوي لتلوث الهواء بالرصاص والكاديوم في مدينة البيضاء، ليبيا

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الملخص

قُدرت هذه الدراسة تركيزات الرصاص (Pb) والكاديوم (Cd) في حلقات النمو لأشجار الصنوبر الحلبي (*Pinus halepensis* Mill.)، وقيمت كفاءتها كمؤشر حيوي للتلوث بالمعادن الثقيلة في الغلاف الجوي. جُمعت عينات من الخشب والتربة من سبع أشجار في مواقع ذات مستويات تعرض متفاوتة على طول الشوارع الرئيسية لمدينة البيضاء، ومن مواقع مرجعية خارج المدينة. غطت الدراسة عقدين من الزمن (2000-2010 و 2011-2021) لإجراء مقارنة زمنية. حُللت العينات باستخدام تقنية مطيافية الامتصاص الذري (Atomic Absorption Spectroscopy)، وحُسب معامل التراكم الحيوي (BAF). أُجري تحليل إحصائي استكشافي، واستُخدم اختبار "ويلكوكسون" للترتيب الموقعة (Wilcoxon Signed-Rank Test) للمقارنة بين العقدين الزمنيين في الأشجار نفسها، وللمقارنة بين معامل التراكم الحيوي للرصاص (BAF-Pb) ومعامل التراكم الحيوي للكاديوم (BAF-Cd). أُجريت جميع التحليلات باستخدام برنامج SPSS الإصدار 23. أظهرت النتائج اتجاهاً تصاعدياً واضحاً في تركيزات الرصاص، حيث ارتفعت من 0.071 ملغ/كجم في العقد الأول إلى 0.075 ملغ/كجم في العقد الثاني، مما يشير إلى استمرار

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تراكم الرصاص. وقد تعززت هذه النتيجة بمتوسط مرتفع لمعامل التراكم الحيوي للرصاص (2.57)، مما يدل على كفاءة امتصاص الرصاص من التربة. وفي المقابل، انخفضت تركيزات الكاديوم قليلاً في العقد الثاني (من 0.026 إلى 0.019 ملغ/كجم)، مع تسجيل معامل تراكم حيوي منخفض (1.04)، مما يشير إلى محدودية تراكم الكاديوم. لوحظ تباين مكاني ملحوظ؛ إذ تراوحت قيم الرصاص بين 0.012 ملغ/كجم في المواقع الأقل تلوثاً و0.12 ملغ/كجم في المواقع الأكثر تأثراً بالأنشطة البشرية وهو فارق بمقدار عشرة أضعاف يعكس تأثير كثافة حركة المرور، والأنشطة الصناعية، والقرب من مصادر التلوث. أما تركيزات الكاديوم فتراوحت بين 0.009 و0.041 ملغ/كجم، مسجلة مستويات منخفضة نسبياً مع وجود تباين مكاني بين المواقع. تخلص الدراسة إلى أن تحليل حلقات نمو الأشجار، ولا سيما أشجار الصنوبر الحلبي، يعد أداة فعالة وموثوقة للرصد البيئي طويل الأمد للعناصر الثقيلة، شريطة مراعاة التباين النوعي بين العناصر والعوامل البيئية المحلية. توصي الدراسة بتعزيز استخدام الأشجار - ولا سيما الصنوبر الحلبي - كمؤشرات حيوية في نظم الرصد الوطنية والمحلية؛ نظراً لما تتمتع به من دقة وسهولة في أخذ العينات وانخفاض في التكلفة، فضلاً عن قدرتها على توثيق التغيرات الزمنية، مما يسهم في تكوين قاعدة بيانات تاريخية لتتبع اتجاهات التلوث.

الكلمات المفتاحية: الصنوبر الحلبي، حلقات الأشجار، الرصاص، الكاديوم، مؤشر حيوي، معامل التراكم الحيوي، تلوث الهواء، ليبيا.

1. Introduction

Airborne heavy metal contamination has emerged as one of the most critical environmental challenges confronting urban centers globally. Its adverse effects on both environmental quality and public health have been exacerbated by the continuous increase in anthropogenic activities, including vehicular traffic, urban and agricultural waste disposal, and industrial emissions. Accumulating evidence indicates that these pollutants – particularly cadmium and lead – represent a mounting threat to human well-being and ecosystem integrity, owing to their persistent toxicity and bioaccumulative properties (Aksoy *et al.*, 1999; Alzahrán, 2023;



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Cui *et al.*, 2024). Given their sessile nature, plants are entirely dependent on the surrounding air, soil, and water for their vital physiological processes. This inherent immobility renders them primary receptors of environmental contaminants, which can be absorbed either through their above-ground tissues (e.g., leaves and stems) or via their root systems from the soil (Javed *et al.*, 2017; Kabata-Pendias, 2010; Keyster *et al.*, 2020). Lead and cadmium are among the most pervasive toxic elements in the atmosphere, emitted from a variety of anthropogenic sources, including industrial activities, vehicular traffic, agricultural practices, and other human-related sources (Aksoy *et al.*, 1999; Martín *et al.*, 2018). Their widespread distribution and persistence in the environment pose significant risks to both human health and ecosystem integrity.

Research has demonstrated that lead inhibits fundamental metabolic processes, while cadmium contributes to increased tissue desiccation and diminished vegetative growth, underscoring the severity of these metals as environmental toxins that adversely affect both living organisms and plants (Cansaran *et al.*, 2016; Rolfe *et al.*, 1974; Zhang *et al.*, 2015).

Environmental monitoring studies have employed a diverse array of plant materials to assess heavy metal pollution, including fungi, lichens, tree bark, tree rings, and leaves of higher plants. These materials have consistently proven effective in detecting patterns of metal deposition, accumulation, and spatial distribution, thereby serving as sensitive bioindicators for evaluating pollution in urban environments (Cocozza *et al.*, 2016; Sawidis *et al.*, 2011).

Trees constitute a cornerstone of environmental quality enhancement within urban settings, providing a multitude of ecosystem services: they regulate local microclimates, mitigate flood risks by reducing surface runoff, sequester and store carbon, attenuate noise pollution, and purify the air by absorbing and immobilizing various contaminants in their tissues (leaves, stems, and roots). Furthermore, certain tree species possess the additional capability to function as bioindicators or to accumulate pollutants, thereby augmenting their significance in urban environmental planning and management (Alahabadi *et al.*, 2017; Gkini *et al.*, 2026).

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Aleppo pine (*Pinus halepensis*) is considered one of the most important tree species growing in Mediterranean environments (Martín *et al.*, 2018). It represents one of the primary native species in the Al-Jabal Al-Akhdar region of Libya, forming a central component of the vegetation cover in the city of Al-Bayda. This species plays a vital role in improving the local environment through its effective capacity to absorb carbon dioxide from the atmosphere, thereby contributing to improved air quality and mitigating the effects of climate change. Studies indicate that Aleppo pine forests in semi-arid Mediterranean regions possess high carbon sequestration potential (Martín *et al.*, 2018; Samara *et al.*, 2022), making them valuable resources for environmental conservation and climate adaptation strategies (Qubaja, and Moinester, 2026).

These trees can store substantial amounts of organic carbon in both soil and biomass. They also contribute to enhancing environmental stability and reducing land degradation (Martín *et al.*, 2018), making them an essential element in maintaining ecological balance in Al-Bayda city and the surrounding areas of Al-Jabal Al-Akhdar

Al-Bayda city, situated in northeastern Libya, has undergone pronounced demographic and urban transformations over the past two decades, particularly in the post-2011 period. These transformations have been manifested in a doubling of the population driven by internal migration, alongside notable urban expansion, escalating traffic density, and the agglomeration of industrial and service activities within the urban core. These developments have significantly increased the emission of airborne pollutants, notably heavy metals including cadmium and lead (Austruy *et al.*, 2019; Isinkaralar, 2024). Such pollutants are notoriously difficult to monitor temporally using conventional methodologies, especially given the lack of continuous atmospheric monitoring networks. In response to this challenge, the present investigation seeks to capitalize on a distinctive natural environmental archive—the annual growth rings of Aleppo pine (*Pinus halepensis* Mill.), a species recognized for its ability to sequester heavy metals within its xylem tissues (Austruy *et al.*, 2019). The primary objectives are to determine the concentrations of cadmium and lead accumulated in the last twenty growth rings

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and to evaluate the suitability of this species as a bioindicator for
assessing atmospheric heavy metal pollution in urban environments.

2. Materials and Methods

2.1 Study Area

The study was conducted in Al-Bayda city, situated in the Jabal al-Akhdar region of northeastern Libya, at the intersection of 32° 45' 36" N latitude and 21° 26' 24" E longitude, approximately 20 kilometers inland from the Mediterranean coast. The city was chosen owing to its distinctive location atop the Jabal al-Akhdar mountains. Ranking as the third-largest urban agglomeration nationally, Al-Bayda represents the largest urban center within the Jabal al-Akhdar region with respect to social and cultural employment opportunities. The study employed Aleppo pine (*Pinus halepensis* Mill.), a widely distributed Mediterranean species distinguished by its drought tolerance and capacity to adapt to seasonal precipitation variability and diverse soil conditions. This species is known to colonize contaminated substrates, including mining residues and landfill sites, while withstanding elevated concentrations of Zn, Pb, and Cd (Alsanousi *et al.*, 2025; Kharazian, 2023). In addition, pine wood has been established as a reliable bioindicator for evaluating degraded ecosystems and tracing historical patterns of metal deposition (Martín *et al.*, 2018).

2.2 Work Procedures

1. For this study, seven Aleppo pine trees were selected for wood core sampling from diverse locations along the main roadsides of Al-Bayda city, where traffic density is notably high.
2. An off-site control site (Sidi Al-Ahmari Forest) was established as a reference presumed free from pollution and atmospheric contamination sources.
3. Wood core samples were extracted at breast height (approximately 130 cm) using increment borers from each individual pine tree fig (1).
4. The collected samples were placed in sterile plastic bags, labeled with all pertinent data, and transported to the laboratory for subsequent analysis.

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5. A temporal window of approximately 20 years (2000–2021) was defined, subdivided into two 10-year intervals to facilitate comparison. Thereafter, intra-urban samples were compared with those obtained from the control site.

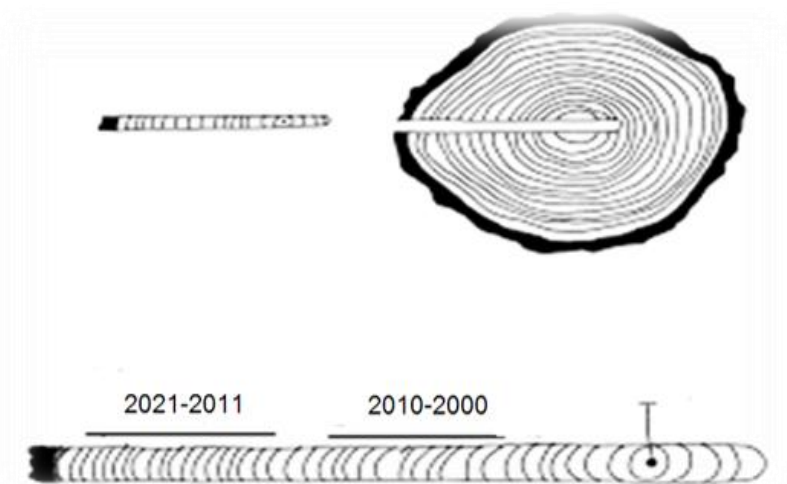


Fig. 1. Schematic representation of wood core extraction and the delineation of the annual rings selected for analysis.

2.3 Wood Sample Processing and Analysis

- Samples were sanded to reveal rings and cleaned to remove dust.
- Rings were counted with a magnifying lens and photographed for verification.
- Samples were dried at 60°C to constant weight and ground.
- 0.05 g samples were digested in 2 mL HNO₃ + 2 mL H₂O₂ at 150°C for 18 h.
- Digests were diluted to 40 mL with 5% HNO₃ and filtered. Reference material and blanks were digested simultaneously (Chen *et al.*, 2021).

2.4 Soil Sample Processing and Analysis

- Soil samples were collected from all study sites to determine the concentrations of lead and cadmium in the soils of the different locations.

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- Sampling was conducted using a random collection method. Soil was extracted from the same sites where wood cores were obtained, at depth intervals of 0–2.5 cm, 2.5–5 cm, 5–10 cm, and >10 cm. Subsamples from each depth were thoroughly mixed to form a composite sample representative of each site, placed in sterile bags labeled with field metadata, and transported to the laboratory for analysis (Al-Zoubi *et al.*, 2013).
- The samples were sieved prior to chemical analysis.
- A 0.5 g aliquot of air-dried soil was weighed and transferred to Teflon digestion vessels. A 6 mL mixture of hydrochloric acid (HCl) and concentrated nitric acid (HNO₃) in a 1:1 ratio was then added.
- The samples were heated on a digestion block at 80–100°C until the solution evaporated nearly to dryness.
- Subsequently, 4 mL of a 1:1 mixture of perchloric acid (HClO₄) and hydrofluoric acid (HF) was added, and the samples were again heated until near dryness.
- The resulting residue was dissolved in dilute hydrochloric acid, and deionized water was added to reach a final volume of 25 mL for each sample (Hantoush and Shukri, 2023).
- Wood and soil samples were analyzed using atomic absorption spectroscopy (AAS) at the Central Research Laboratories, Omar Al-Mukhtar University. The concentrations of lead (Pb) and cadmium (Cd) were determined according to standard analytical procedures.

2.5 Bioaccumulation Factor (BAF)

The bioaccumulation factor (BAF) is used to calculate the transfer of metals from soil to different plant parts (total biomass) using the following equation:

$$BAF = C_{\text{plant}} / C_{\text{soil}}$$

where C_{plant} is the metal concentration in plant tissue (mg/L or mg/kg) and C_{soil} is the metal concentration in soil (mg/L or mg/kg).

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2.6 Statistical Analysis

Initially, an exploratory statistical analysis was conducted to describe the tissue concentrations of lead (Pb) and cadmium (Cd) and to compare the first and second decades within the same trees. The Wilcoxon Signed-Rank Test was deemed the most appropriate test for this purpose, as it determines whether the observed increase in Pb or decrease in Cd is statistically significant. In addition, the Kruskal-Wallis H Test was employed to assess whether the geographical location of the trees significantly influences heavy metal accumulation. Furthermore, the Wilcoxon Signed-Rank Test was applied to compare the bioaccumulation factor for lead (BAF-Pb) and the bioaccumulation factor for cadmium (BAF-Cd). All statistical analyses were performed using SPSS software, version 23.

3. Results and discussion

3.1 Lead and Cadmium Concentrations in Aleppo Pine Wood

The current investigation focuses on the quantification of lead (Pb) and cadmium (Cd) concentrations in wood samples collected from seven distinct sampling sites. To elucidate temporal dynamics in metal deposition, data were obtained from measurements corresponding to two consecutive decadal periods: the first decade (2000–2010) and the second decade (2011–2021). The analysis incorporates several key variables, namely tree age, total metal concentrations in wood, soil metal content, and the bioaccumulation factor (BAF). The BAF serves as an indicator of the efficiency with which metals are translocated from the soil substrate into the tree biomass (Table 1).

Table 1. Descriptive Statistics of the Study Variables

Variable	N	Range	Minimum	Maximum	Mean	SD
Tree age (years)	7	58	42	100	62.71	18.874
Pb first decade (mg/kg)	7	0.105	0.014	0.119	0.071	0.0393
Pb second decade (mg/kg)	7	0.111	0.010	0.121	0.075	0.0438
Total Pb (mg/L)	7	0.216	0.024	0.240	0.146	0.0826

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Variable	N	Range	Minimum	Maximum	Mean	SD
Soil Pb content (mg/kg)	7	0.057	0.031	0.088	0.055	0.0219
BAF (Pb)	7	3.590	0.774	4.364	2.574	1.4315
Cd first decade (mg/kg)	7	0.057	0.010	0.067	0.026	0.0199
Cd second decade (mg/kg)	7	0.020	0.009	0.029	0.019	0.0065
Total Cd (mg/kg)	7	0.064	0.019	0.083	0.0457	0.0221
Soil Cd content (mg/kg)	7	0.092	0.028	0.120	0.053	0.0315
BAF (Cd)	7	1.893	0.350	2.243	1.041	0.707

Descriptive statistics provide a fundamental insight into environmental health and the response of trees to pollution over time. Tree age varied considerably, ranging from 42 to 100 years (mean = 62.7 years), providing a solid basis for assessing long-term accumulation (Table 1). Pb concentrations showed a clear upward trend from the first decade (0.071 mg/kg) to the second decade (0.075 mg/kg), indicating continued Pb accumulation in tree tissues. This is supported by the high BAF for Pb (mean = 2.57), demonstrating efficient Pb uptake from soil. In contrast, Cd concentrations declined slightly in the second decade, with a low BAF (1.04), indicating that Cd accumulation in these trees is considerably less pronounced than that of Pb.

3.2 Lead Concentration in Wood

Figure 2 presents the mean lead concentration recorded in the wood of Aleppo pine trees (*Pinus halepensis*) sampled from different sites inside and outside the city. Lead concentrations in the wood ranged between 0.012 and 0.12 mg/kg.

The results indicate that Pb concentrations in Aleppo pine wood ranged from 0.012 to 0.12 mg/kg, reflecting spatial variation in pollution levels between urban and non-urban sites. This variation is largely attributed to differences in anthropogenic emission sources, particularly vehicle exhaust and industrial activities, which are major contributors to atmospheric Pb release and subsequent deposition on vegetation (Ewen *et al.*, 2009; Rolfe *et al.*, 1974).

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Previous studies have confirmed that human activities are the primary sources of heavy metals such as Pb and Cd in ambient air, with vehicular emissions and industrial operations being major contributors to heavy metals in urban dust and suspended particulate matter (Cui *et al.*, 2024; Ma *et al.*, 2025). These findings underscore the importance of continued monitoring and source apportionment of heavy metal pollution in urban environments.

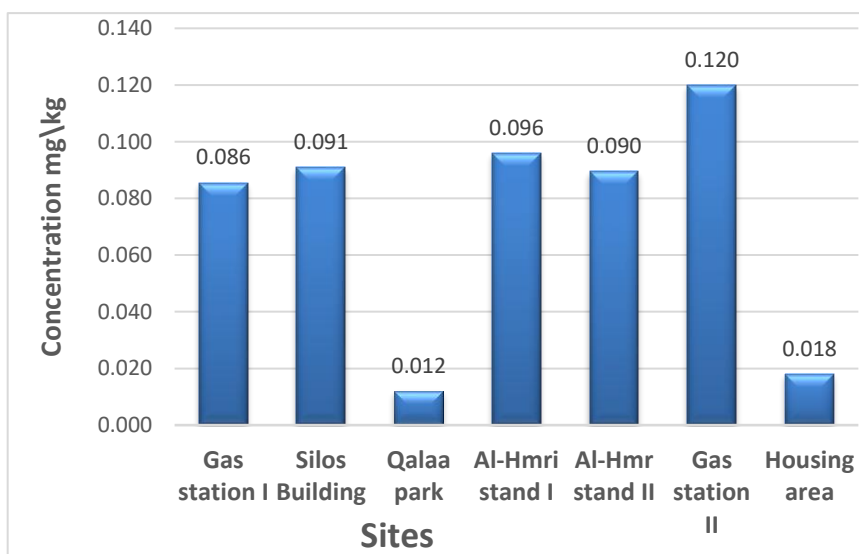


Fig. 2. Mean Lead (Pb) concentration (mg/kg) in Aleppo pine wood at different sites

Studies have demonstrated that trees, particularly conifers, serve as effective bioindicators of heavy metal air pollution, as they absorb elements such as lead through foliage or via soil uptake and subsequently store them in woody growth rings, thereby enabling the tracing of temporal and spatial variations in pollution (Dejoie *et al.*, 2025). Accordingly, the values recorded in the present study reflect not only the current contamination status but also the historical exposure to pollution in the surrounding environment. Furthermore, the elevated lead concentrations observed at certain sites within the city compared to those outside it may be attributed to increased traffic density and urban activities. Previous studies have shown that trees located near high-traffic roads exhibit higher

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lead concentrations than those in more distant or less polluted areas (Al-Alawi and Mandiwana, 2007; Rolfe, 1974). This supports the use of Aleppo pine as a bioindicator of urban air pollution. Similarly, Pantera *et al.* (2007) considered tree rings a promising tool for monitoring changes in soil chemistry and air pollution, having compared elemental concentrations in Aleppo pine rings over a 140-year period in a polluted area near Athens, Greece, and linked variations in concentrations to industrial activities in the region.

Conversely, the lower concentrations recorded at certain sites may indicate either a scarcity of pollution sources or the influence of environmental attenuation processes, such as wind dispersion or distance from emission sources. Some further studies suggest that lead uptake from air is more influential than uptake from soil, as minor changes in atmospheric lead concentrations can lead to noticeable increases in lead content within wood (Eklund *et al.*, 1996; Pantera *et al.*, 2007).

Overall, the concentration range recorded in this study falls within the ranges reported in similar environmental studies (Al-Alawi and Mandiwana, 2007; Elmughrbe *et al.*, 2024), reflecting a relatively moderate to low level of contamination, with a discernible influence of urban factors. These findings further confirm the importance of utilizing tree growth rings as an effective tool for monitoring heavy metal pollution and assessing air quality in urban environments.

3.3 Cadmium Concentration in Wood

Figure (3) shows the mean cadmium (Cd) concentration in Aleppo pine (*Pinus halepensis*) wood collected from various sites within and outside the city, with concentrations ranging from 0.009 to 0.041 mg/kg.

The results of the present study indicate that cadmium concentrations in Aleppo pine wood ranged between 0.009 and 0.041 mg/kg, a range reflecting relatively low levels of this element, with spatial variation between sites inside and outside the city. This variation is attributed to differences in pollution sources, as cadmium is among the heavy metals released into the environment through anthropogenic activities such as fossil fuel combustion,

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metal corrosion, certain industrial processes, and the application of phosphate fertilizers (Alloway, 2013).

These findings are consistent with those of environmental studies indicating that trees, particularly coniferous species, act as effective bioindicators of heavy metal air pollution, absorbing cadmium through foliage (atmospheric deposition) or via roots from the soil, and subsequently storing it in woody tissues, including annual growth rings (Kabata-Pendias, 2010). Atmospheric uptake of cadmium constitutes one of the key pathways, especially in urban areas, where cadmium is associated with fine suspended particulate matter.

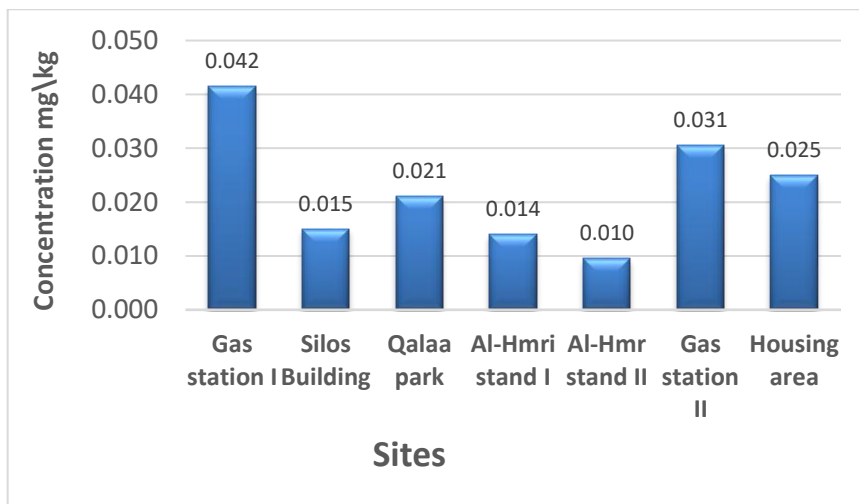


Fig. 3. Mean cadmium (Cd) concentration (mg/kg) in Aleppo pine wood at different sites

Moreover, the relatively higher values recorded within the city compared to outlying areas may be explained by increased traffic density and human activities, as numerous studies have demonstrated that cadmium concentrations rise in urban environments owing to emissions from vehicles and light industrial activities (Ewen *et al.*, 2009; Tomašević *et al.*, 2008). In addition, urban dust may contribute to the transport and deposition of cadmium onto plant surfaces, thereby enhancing its uptake. Conversely, the lower concentrations recorded at certain sites



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outside the city reflect reduced pollution sources, alongside the influence of environmental factors such as wind and rainfall, which act to diminish cadmium accumulation in the atmosphere. Soil characteristics may also play a significant role in governing cadmium availability and its uptake by plants, as its availability is associated with factors such as soil pH and organic matter content (Kabata-Pendias, 2010; Turkyilmaz *et al.*, 2019).

When comparing these results with international studies, the recorded concentration range falls within natural or relatively low levels typical of non-severely polluted environments (Rabab *et al.*, 2025), suggesting that the study area does not suffer from high cadmium contamination, despite a discernible influence of urban activities.

3.4 Comparison of Lead and Cadmium Concentrations Across Time Periods

To compare the two temporal periods (the first and second decades) for the same trees, the Wilcoxon Signed-Rank Test was applied to determine whether the observed increase in lead or decrease in cadmium was statistically significant. The analysis of lead concentrations revealed a slight difference between the two periods; however, this difference was not statistically significant in the mean lead concentration across the different sites, with values in Aleppo pine growth rings ranging from 0.014 to 0.119 mg/kg in the first decade and from 0.010 to 0.120 mg/kg in the second decade, Fig.4. Among the seven tree samples, four exhibited an increase in lead levels (positive ranks), whereas three exhibited a decrease (negative ranks) Table 2. The Wilcoxon Signed-Rank Test yielded $Z = -0.511$ with an asymptotic significance (p) of 0.610, indicating that although a slight increase was observed in the mean concentration in the descriptive data, lead uptake in these trees remained relatively stable over the twenty-year study period.

The accumulated lead concentration in the ring sequence over the past twenty years was variable, with a slight increase recorded in the second decade. Furthermore, the results of the inter-site comparison revealed that the highest lead concentration occurred in samples collected from trees near the Gas station, followed by the Silos

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building. Lead concentration in wood was also elevated in samples collected from the Sidi Al-Hamri area (control site), whereas it was lowest in other samples collected from inside the city at Qalaa Park.

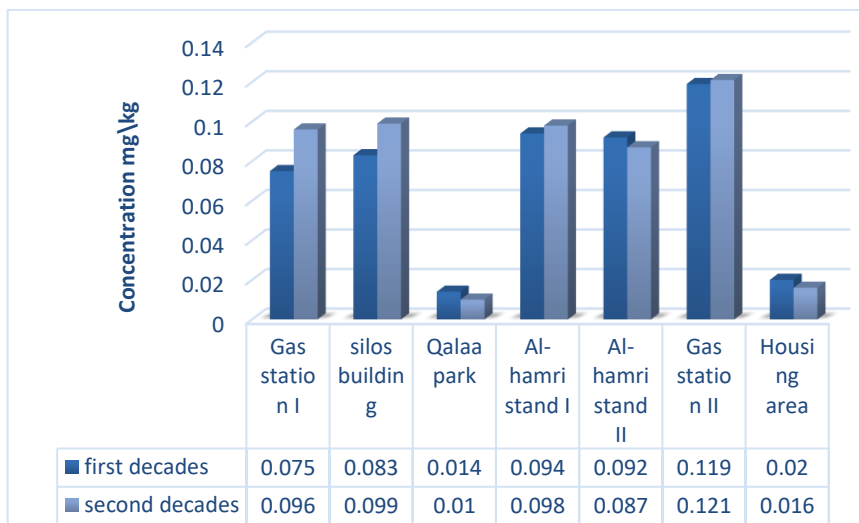


Fig. 4. Lead (Pb) concentrations (mg/kg) in Aleppo pine (*Pinus halepensis* Mill.) wood during the first decade (2000–2010) and the second decade (2011–2021) across the different sampling sites in Al-Bayda City. Bars represent mean Pb concentrations for each site and decade.

Table 2. Wilcoxon Signed-Rank Test Results for Pb and Cd Concentrations Between the First and Second Decades

Group	N	Mean Rank	Sum of Ranks	Z-value	P-value
Negative Ranks (Pb)	3	3.67	11	0.610	-0.511
Positive Ranks (Pb)	4	4.25	17		
Total	7				
Negative Ranks (Cd)	5	3.80	19	0.395	-0.851
Positive Ranks (Cd)	2	4.50	9		
Total	7				

Examination of cadmium in Aleppo pine wood revealed concentrations ranging from 0.01 to 0.067 mg/kg in the first decade and 0.009 to 0.029 mg/kg in the second decade (Fig. 5). The results

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showed a more frequently observed decreasing trend; however, this trend lacked statistical significance. Specifically, five of the seven trees exhibited lower cadmium concentrations in the second decade (negative ranks), whereas only two trees showed an increase. The Wilcoxon Signed-Rank Test yielded $Z = -0.851$ with a p-value of 0.395 (Table 2). Since $p > 0.05$, the observed decreasing trend is not statistically significant, and the null hypothesis cannot be rejected. This variation may be attributed to the physiological conditions of each individual tree (Şahin, 2012). Furthermore, Hagemeyer and Schäfer (1995) demonstrated that the radial distribution of cadmium exhibited increasing concentrations toward the pith.

Despite the descriptive observation indicating an overall decrease in cadmium levels, the statistical evidence suggests that this decline may be attributable to random variation rather than a specific environmental or physiological shift. It is therefore concluded that there is no statistically significant temporal difference in cadmium accumulation between the two decades.

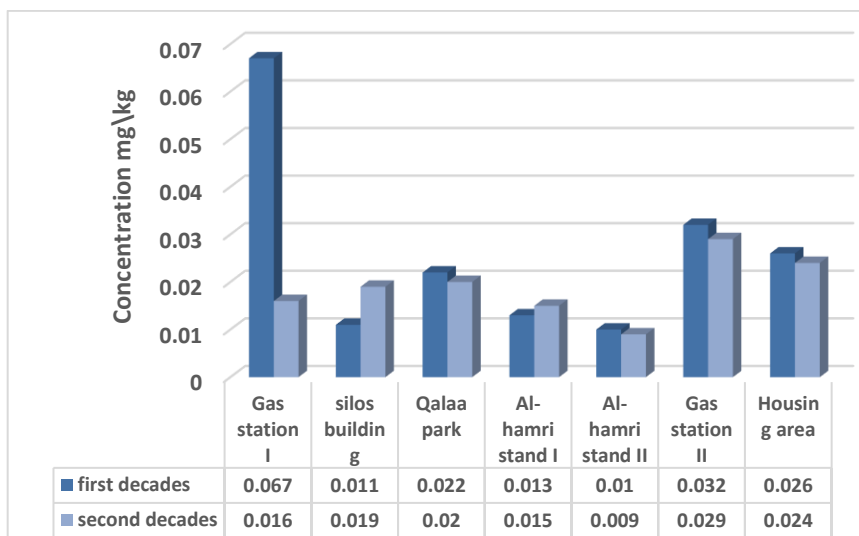


Fig.5. Cadmium (Cd) concentrations (mg/kg) in Aleppo pine (*Pinus halepensis* Mill.) wood during the first decade (2000–2010) and the second decade (2011–2021) across the different sampling sites in Al-Bayda City. Bars represent mean Pb concentrations for each site and decade

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3.5 Soil Lead and Cadmium Content (mg/kg) at the Selected Sites

Soil Pb and Cd contents (mg/kg) at the selected sites are presented in Table 3. Soil Pb content ranged from 0.031 to 0.088 mg/kg, while Cd content ranged from 0.028 to 0.061 mg/kg, indicating clear spatial heterogeneity among sites. This variability is attributed to differences in pollution sources and anthropogenic activity intensity, with urban and service areas (e.g., fuel stations, main roads) being major contributors to soil heavy metal accumulation (Alloway, 2013). The highest Pb concentration was recorded at the Al-Hamri stand site, potentially reflecting localized anthropogenic influences, as Pb is historically associated with vehicular exhaust emissions and other urban sources (Wei and Yang, 2010). Long-term atmospheric deposition is the primary driver of elevated surface soil Pb, as supported by evidence from diverse studies employing multiple methodological approaches (Klaminder *et al.*, 2011; Lv *et al.*, 2025; Nowack *et al.*, 2001).

For cadmium, the highest values were recorded at the Housing area and Qalaa park, potentially linked to sources different from those of lead, such as phosphate fertilizers, waste accumulation, or localized anthropogenic activities. Cadmium exhibits higher mobility in soil than lead, making it more readily translocated and absorbed by plants (Hu *et al.*, 2026; Kabata-Pendias, 2010; Sterckeman *et al.*, 2025).

Table 3. Concentrations of lead (Pb) and cadmium (Cd) in soil at the selected sites (mg/kg)

N	Site	Pb mg/kg	Cd mg/kg
1	Al-hamri stand I	0.088	0.048
2	Al-hamri stand II	0.081	0.040
3	silos building	0.043	0.028
4	Gas station I	0.055	0.035
5	Housing area	0.035	0.061
6	Qalaa park	0.031	0.054
7	Gas station II	0.053	0.037

Figures 6 and 7 demonstrate a relationship between lead and cadmium concentrations in soil and wood, with high-soil sites

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generally showing higher wood concentrations, particularly for lead. This is corroborated by controlled experiments by Eklund *et al.* (1996) and Milošević *et al.* (2025), who found that increased soil Pb leads to statistically significant increases in Pb concentrations in tree compartments, including the stem (wood). This indicates that soil is a key source of metal uptake via roots, followed by translocation and accumulation in woody tissues (Alloway, 2013).

Furthermore, direct atmospheric deposition onto leaf surfaces plays a significant role in introducing heavy metals into plants, especially in urban environments (Kabata-Pendias, 2010). These complexities underscore the need for a multi-factorial approach when interpreting soil–wood metal relationships, as both soil-derived and atmospherically deposited metals may contribute to the total metal burden in tree tissues.

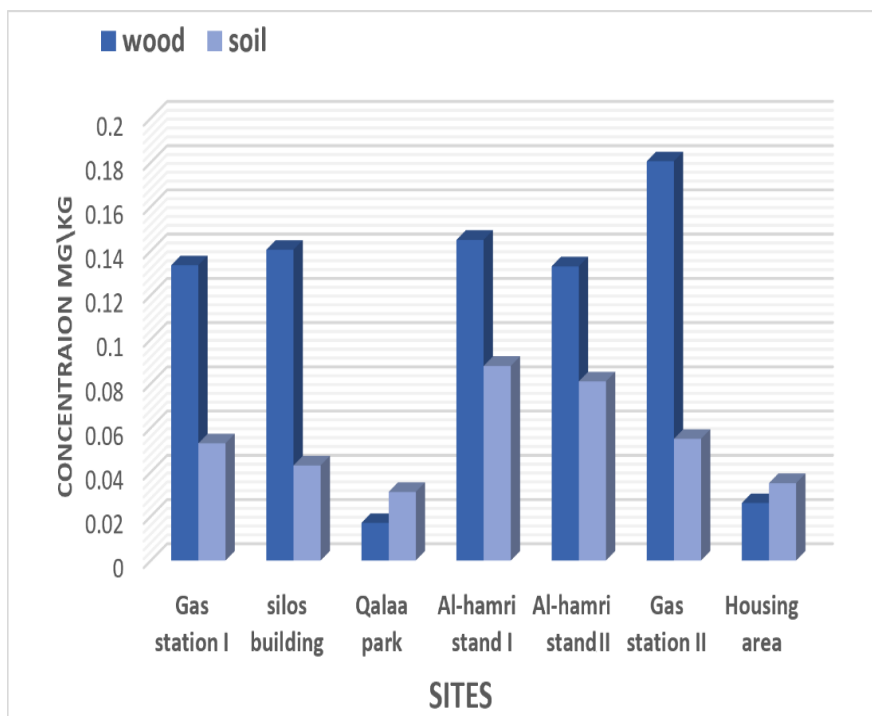


Fig.6. Lead (Pb) concentrations in soil and wood samples collected from the different study sites

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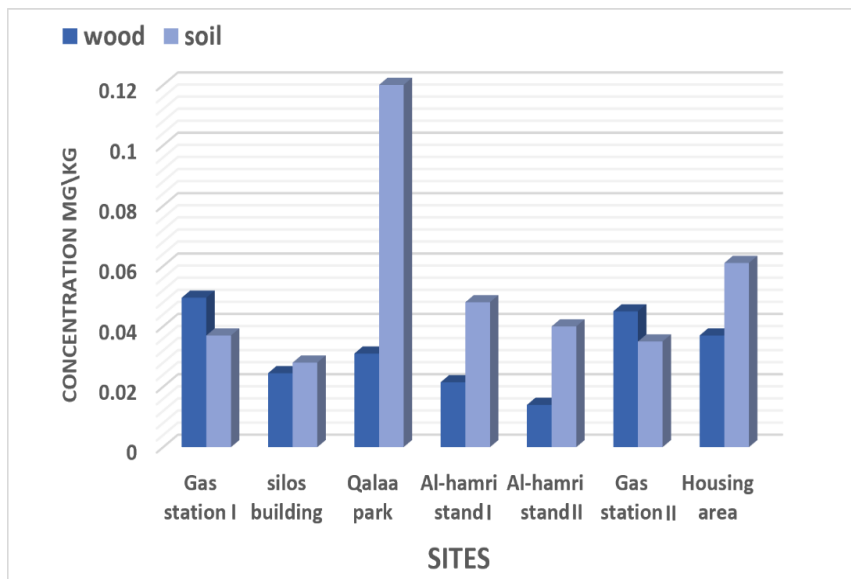


Fig.7. Cadmium (Cd) concentrations in soil and wood samples collected from the different study sites

However, this relationship is not always linear, particularly in the case of cadmium, where its uptake can be influenced by numerous factors, including soil pH, organic matter content, and plant species. Studies indicate that lead tends to accumulate in soil rather than translocate into plant tissues due to its low mobility, whereas cadmium is more readily absorbed and translocated within the plant – a factor that may account for the observed differences between soil and wood concentrations at certain sites (Adriano, 2001). Research consistently demonstrates that lead is highly stable in soil and binds strongly to soil particles, thereby restricting its mobility and translocation to the aerial parts of plants. This limited mobility is attributed to lead's high capacity for adsorption onto clay particles and iron oxides, as well as its ability to form stable complexes with organic matter, resulting in its immobilization within surface soil layers (Sterckeman, 2025). In contrast to lead, cadmium exhibits a considerably higher potential for absorption and internal translocation within plants, posing a greater risk to the food chain. Cadmium is more soluble and bioavailable to plants than lead, a



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characteristic linked to its weaker adsorption affinity for soil particles.

Overall, the concentrations recorded for both lead and cadmium in soil fall within the low to moderate range compared to global studies (Adewumi and Ogundele, 2024; Bouida *et al.*, 2022), indicating that the study area does not suffer from severe contamination. However, the presence of clear differences between sites indicates the influence of local anthropogenic activities. Furthermore, the consistency of results between soil and wood reinforces the use of Aleppo pine trees as an effective bioindicator for monitoring environmental heavy metal pollution. These findings underscore the importance of continued monitoring of soil and vegetation in urban areas, particularly given urban expansion and increasing anthropogenic activities, due to the adverse effects of these metals on ecosystem health and human well-being.

3.6 Assessment of Bioconcentration Factor (BAF)

To enhance the reliability of the environmental assessment, the bioconcentration factor (BAF) was analyzed to determine the efficiency of heavy metal transfer from soil to tree biomass. This analysis is crucial for identifying the role of the tree as a biological sink for environmental pollutants.

3.6.1 Bioconcentration Factor (BAF) of Lead and Cadmium in Aleppo Pine Wood

The results presented in Table 4 indicate that the Bioconcentration Factor (BAF) values for lead in Aleppo pine wood ranged between 0.02 and 5.16; a wide range that reflects a marked variation in the plant's capacity to uptake and accumulate lead from the soil across the different study sites. Similarly, the BAF values for cadmium ranged between 0.26 and 1.34, indicating a clear variation in the capacity of Aleppo pine (*Pinus halepensis*) to uptake and accumulate cadmium in its wood among the study sites.

The Bioconcentration Factor is considered a significant indicator for assessing the efficiency of plants in translocating heavy metals from soil to plant tissues; whereby values exceeding 1 denote the plant's bioconcentration capacity, whereas values below 1 indicate reduced

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uptake efficiency or the presence of barriers limiting elemental
translocation (Clemente, 2025; Yoon *et al.*, 2006).

**Table 4. Bioconcentration Factor (BAF) of Lead and Cadmium in
Aleppo Pine Wood**

Site	Wood		Soil		BAF	
	Pb	Cd	Pb	Cd	Pb	Cd
Gas station I	0.134	0.050	0.053	0.037	3.11	1.34
Silos building	0.141	0.025	0.043	0.028	4.53	0.88
Qalaa park	0.017	0.031	0.031	0.12	0.19	0.26
Al-hamri stand I	0.145	0.022	0.088	0.048	1.79	0.45
Al-hamri stand II	0.133	0.014	0.081	0.04	2.42	0.35
Gas station II	0.181	0.045	0.055	0.035	5.16	1.29
Housing area	0.026	0.037	0.035	0.061	0.02	0.61

3.6.2 Lead Accumulation

Elevated BAF values for lead were recorded at the Gas Station II and Silos Building sites (5.16 and 4.53, respectively), indicating a high accumulation capacity of Aleppo pine for lead in these environments. This may be attributed to the presence of additional contamination sources beyond the soil, most notably direct atmospheric deposition originating from vehicular exhaust and urban activities, whereby lead-bearing particles deposit onto plant surfaces and subsequently translocate to internal tissues (Alloway, 2013). Accordingly, the elevated BAF values do not solely reflect root uptake but also signify the contribution of atmospheric pollution to the accumulation process.

Conversely, markedly low BAF values were recorded at the Housing Area and Qalaa Park sites (0.02 and 0.19, respectively), indicating limited lead translocation from soil to wood. This may be ascribed either to lower contamination levels at these sites or to soil properties that restrict lead bioavailability, such as elevated pH or increased organic matter content, whereby lead is strongly bound to soil particles and becomes less amenable to uptake (Kabata-Pendias, 2010).

Furthermore, intermediate values (1.79–2.42) were recorded at Al-Hamri Stand 1 and 2, suggesting moderate bioconcentration. This is

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presumably the outcome of a balance between soil lead availability and other environmental factors governing its uptake, including soil type, moisture content, and rhizospheric biological activity (Adriano, 2001; Guyette *et al.*, 1991).

Collectively, these findings indicate that Aleppo pine exhibits variable lead accumulation capacity, demonstrating high efficiency in urban environments relative to less contaminated areas. They further confirm that bioconcentration is governed not only by soil elemental concentration but also by multiple environmental factors, in addition to the contribution of atmospheric pollution. This substantiates the use of this species as an effective biomonitor for monitoring airborne lead contamination in urban areas.

3.6.3 Cadmium Accumulation

The highest BAF values for cadmium were recorded at sites such as the Gas station 1,2 (1.34 and 1.29), indicating a relative capacity of Aleppo pine to accumulate cadmium in these environments. This may be explained by increased pollution sources associated with urban activities, such as vehicle emissions and fuel combustion, since cadmium is one of the elements associated with fine particulate matter in the air and can reach the plant through direct atmospheric deposition onto the leaves, in addition to root uptake (Alloway, 2013). Consequently, the elevated values may reflect a dual influence of soil and atmospheric sources.

In contrast, most other sites exhibited BAF values below 1, as in Qalaa Park (0.26) and Al-Hamri Stand 1, 2 (0.35–0.45), indicating reduced bioconcentration efficiency for cadmium at these sites. This may be attributed to the low concentration of bioavailable cadmium in the soil, or to soil properties that limit its uptake, such as elevated pH or increased organic matter, which act to immobilize cadmium and reduce its mobility (Kabata-Pendias, 2010).

The value recorded in the Silos building (0.88) also indicates a moderate accumulation approaching the threshold of 1, which may reflect a moderate urban influence, where pollution sources exist but to a lesser degree compared with fuel stations. Studies indicate that cadmium exhibits higher mobility than lead within the plant; however, its uptake remains influenced by multiple physical and

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chemical factors, such as competition with other elements (e.g., zinc) and soil conditions (Adriano, 2001).

Overall, the results demonstrate that Aleppo pine possesses a limited to moderate capacity to accumulate cadmium, compared with lead, which exhibited higher BAF values in the same study. This is consistent with what has been reported in the scientific literature, namely that plant responses to heavy metals vary according to the type and chemical properties of the element, as well as the plant species and the surrounding environment (Kabata-Pendias, 2010).

3.6.4 Interpretation of Elevated BAF Values: Atmospheric Versus Soil Sources

Our findings differed from those of some studies, which indicated that lead tends to accumulate in soil rather than be translocated to plant tissues due to its low mobility, whereas cadmium is more readily absorbed and translocated within the plant. This may explain the discrepancies observed between soil and wood at some sites. In general, the concentrations recorded for both lead and cadmium in the soil fall within the low to moderate ranges compared with international studies, indicating that the study area does not suffer from severe pollution; however, the presence of clear differences among sites indicates the influence of local human activities. Moreover, the consistency of the results between soil and wood reinforces the use of Aleppo pine trees as an effective bioindicator for monitoring environmental contamination with heavy metals.

Nevertheless, it is important to interpret these elevated BAF values with caution. The vast majority of recent studies indicate quite the opposite pattern for Aleppo pine, classifying it within the category of excluder plants rather than accumulators. This means that it possesses tolerance mechanisms allowing it to grow in contaminated soil, while restricting the uptake of metals and their translocation to its aerial parts. A comprehensive study conducted at contaminated mining sites in Sardinia (Italy) demonstrated that the values of the Bioaccumulation Coefficient (BAC), the Bioconcentration Factor (BCF), and the Translocation Factor (TF) for lead in all tissues of Aleppo pine were less than unity (Kharazian *et al.*, 2022; Kharazian *et al.*, 2023). These values constitute the primary indicator classifying a plant as an excluder, as they confirm

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that it absorbs metals from the soil but stores them mainly in the roots and does not translocate them efficiently to aerial parts such as wood and needles (Kharazian *et al.*, 2023). These findings are consistent with an older study which showed that even when very high concentrations of lead were added to the soil (up to 2000 ppm), only a very small amount was translocated from the roots to Aleppo pine needles, whereas its concentrations in the roots were high and proportional to its concentration in the soil (Nakos, 1979).

Accordingly, the elevated BAF values recorded in the present study — particularly at the Gas Station 2 and Silos Building sites — are more plausibly attributable to direct atmospheric deposition onto plant surfaces rather than to efficient root-to-wood translocation. This interpretation is largely consistent with numerous studies demonstrating that elemental concentrations in tree rings (wood) reflect atmospheric pollution, absorbed through leaves and bark, to a greater extent than they reflect soil contamination. A study on Marula trees near a smelter in Namibia found that lead concentrations in the tree-ring record showed no correlation with its considerably high levels in the surrounding soil; rather, they appeared to reflect direct atmospheric pollution, as documented by Eklund *et al.* (1996) and Mihaljevič *et al.* (2015). These findings collectively underscore the importance of considering atmospheric deposition pathways when interpreting metal accumulation in tree rings, particularly in urban and industrial settings where atmospheric metal loads are elevated.

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