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Assessing Tree Species for Monitoring and Mitigating Strontium Pollution in Urban Environments

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Abstract Air pollution, particularly heavy metal contamination, has emerged as a critical global issue, posing significant human and environmental health risks over the past century. Strontium (Sr), a highly hazardous heavy metal, even at small concentrations, is classified as a priority contaminant by international organizations due to its potential adverse effects. This study aimed to specify the most appropriate plant species for observing and mitigating Sr contamination. Samples were collected from *Pseudotsuga menziesii* (Douglas fir), *Tilia tomentosa* (Silver linden), and *Fraxinus excelsior* (European ash or common ash) growing in Düzce, Türkiye, one of the five most unclean towns in European countries according to the 2021 World Air Pollution Report. Variations in Sr concentrations over the past 60 years were analyzed based on tree species, tree organs, direction, and age group. The findings reveal that these species are unsuitable as biomonitors for tracking Sr pollution trends. However, all three species demonstrated the ability to accumulate significant levels of Sr in their wood, making them viable candidates for phytoremediation efforts. Among the species studied, European ash trees were the most effective in reducing Sr contamination, with the highest Sr accumulation in wood (11.36 mg/kg).

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1 Introduction

Around 6 million premature births, 3 million low-birth-weight newborns, and 7 million premature deaths occur globally as a result of air pollution (Isinkaralar et al., 2022; WHO, 2023; Şevik et al., 2024). Epidemiological studies indicate that approximately 12.5% of global mortality can be attributed to air pollution exposure (WHO, 2023). This public health burden is particularly concerning in Europe, with an estimated 2.5 million residential areas currently affected by pollution (WHO, 2024). According to data from the WHO (World Health Organization), approximately all individuals on the planet (99%) inhale air that comprises high levels of toxins that are higher than the WHO's established limits, and the highest exposure occurs in low- and middle-income nations (WHO, 2024).

Studies on air pollution show that this threat can affect humans, all living things, and ecosystems. For example, studies have shown that nanoparticle pollution can affect even the most remote ecosystems (Sevik et al., 2025), heavy metal pollution can be carried hundreds of kilometers away from its source (Cetin et al., 2025), and these pollution agents are effective not only in open areas but also in indoors (Cetin & Abo Aisha, 2023).

For this reason, air pollution is considered one of the most pressing global glitches, along with global climate change and urbanization, which are considered irreversible worldwide (Cantürk et al., 2024; Isinkaralar et al., 2025; Sevik et al., 2025). However, unlike the other two problems, it is also known that air pollution can be reduced locally. For this purpose, determining the level of air pollution, especially in urban areas where more people live per unit area, determining the factors affecting air pollution, and taking precautions are among the priority research topics. Therefore, many studies are being conducted on the subject.

Among the components of air pollution, the ones that threaten human health the most are heavy metals. The increasing need for raw materials, parallel with industrial activities and technological developments in the last century, is primarily met by mining activities (Ergül & Kravkaz Kuşçu, 2024). Heavy metals extracted from mineral deposits and processed and used in industrial products are released into nature due to various processes. Mining, industrial activities, vehicles and traffic, agricultural activities, and anthropogenic sources in urban areas play a prominent role in the release of heavy metals into nature (Bayraktar et al., 2024; Isinkaralar et al., 2024; Istanbullu et al., 2023; Kuzmina et al., 2023). Heavy metals seriously threaten all living things and ecosystems after they are released into nature. Because they do not easily disappear and break down in nature, they tend to bioaccumulate in living things, and some can be carcinogenic, venomous, poisonous, and even fatal to living things, even at small concentrations (Abd Elnabi et al., 2023; Ejaz et al., 2023; Yayla et al., 2022). Several heavy metals have been included on the primacy contaminant list by international agencies such as EPA (United States Environmental Protection Agency) and ATSDR (Agency for Toxic Substances and Disease Registry) due to their potential harm (Şevik et al., 2024; Xie et al., 2024).

Strontium (Sr) is one of the most hazardous heavy metals for human health and the environment. Because of its possible impact, Sr is one of the elements on the ATSDR's priority pollutant list. Lung cancer and other serious issues that can build up in the body over time and even cause abrupt death are caused by Sr compounds, which are dangerous to human health, even in small doses. Additionally, research indicates that Sr may give out radiation (Bu et al., 2018; Erdem, 2023; Khan et al., 2022; Ru et al., 2024). Therefore, human health needs to monitor and lower the amounts of these metal elements in the airborne. Unlike soil, water, and living organisms, heavy metal concentrations in the airborne are unstable and fluctuate, making monitoring changes in airborne heavy metal pollution difficult. Monitoring directly airborne heavy metal contamination is rather costly, and interpreting the findings is considerably more difficult.

Furthermore, the measurement results cannot explain the consequences of heavy metal pollution on the ecosystem. Thus, biomonitors are the most appropriate instruments for measuring airborne heavy metal contamination (Ateya et al., 2023; Koç, 2025; Lv et al., 2023; Sulhan et al., 2023). In areas with four distinct seasons, like Türkiye, the annual rings of trees with a long lifespan can serve as excellent biomonitors. Therefore, they are the approach most commonly employed to track changes in airborne heavy metal pollution over time (Cobanoglu et al., 2023; Isinkaralar et al., 2024; Xie et al., 2024; Ozturk Pulatoglu et al., 2025).

Another advantageous strategy for lowering airborne heavy metal pollution is plants, particularly tall trees. Since the tree's wood is its largest organ, it can store a lot of heavy metals and keep them out of the environment for decades or even hundreds of years. Therefore, trees grown in regions with elevated heavy metal contamination are very effective in phytoremediation studies (Koç, 2025).

However, studies have shown that each plant can accumulate heavy metals in different amounts in different organs. Therefore, it is vital to specify the appropriate plant species for biomonitoring and phytoremediation studies for each heavy metal separately. This study aimed to determine the variation in Sr concentration in the air of some high-structure trees frequently grown in urban areas and their usability for reducing contamination.

2 Materials and Method

The study was performed on trees growing in the city center of Düzce, Türkiye. Düzce region, where the samples were collected, is the province with Europe's 5th highest contamination level, according to the World Air Pollution Report 2021. The geography (bowl or concave shape surrounded by high mountain ranges) and meteorological features of the Düzce region (rainy throughout the year and fog mixed with air pollution, especially in the winter period), located in the Western Black Sea region of Türkiye, increase airborne contamination. The primary contaminants causing air contamination in Düzce are largely natural resources (natural gases and coal for heating buildings), vehicle traffic load, and industrial facilities (Koc et al., 2024).

The log samples used in this research were taken from the *Fraxinus excelsior* (European ash or common ash), *Pseudotsuga menziesii* (Douglas fir), and *Tilia tomentosa* (Silver linden) trees' trunk, which are extensively selected in landscaping throughout the Düzce region. The log samples were taken from a height of approximately 50 cm from the ground in 2022 after the growing period (early winter), with a thickness of 10 cm. Three plant species'log samples were taken with the logs marked with the North and South orientations. In order to make the annual rings easier to view, sections from trunk logs were first sanded in the lab to polish the top surface. Considering their widths and the tree's age, annual rings were grouped.

Consequently, trees around 60 years of age were separated into 5-year age groups. Then, samples were extracted from the wood, inner bark, and outside bark of each age range using a stainless-steel drill and put on glass Petri dishes. The tree samples were converted into sawdust without using instruments from the metal elements analyzed in the study. The sawdust specimens were put in glass containers without the lids on, left in the lab for 15 days until they were entirely dry, then allowed to air dry before being dried for an additional week at 45 °C in an oven. The combination was then put in the microwave oven after extracting 0.5 g of dried samples, 6 ml of 65% HNO_3, and 2 ml of 30% H_2O_2. The microwave oven was programmed to reach and stay at 200 °C for 15 min. Following the burning process, the collected samples were put into graduated vials, and ultrapure water was added until the final volume reached 50 ml. Sr concentrations were calculated by multiplying the results by the appropriate dilution factor after the samples were examined using the ICP-OES instrument (GBC Scientific Equipment Pty Ltd., Melbourne, Australia). Numerous earlier investigations have extensively used this technique (Erdem, 2023; Koç, 2025; Ozturk Pulatoglu et al., 2025).

The SPSS 22.0 package software used variance analysis (ANOVA) to analyze the data of the Sr element. Furthermore, factors exhibiting statistically significant differences at a minimum 95% confidence level ($p < 0.05$) were subjected to the Duncan test. Following the data's presentation in a table, analyses and interpretations were conducted by considering the Duncan test result.

3 Results

The changes in Sr concentration in Silver linden based on plant organ and compass orientation are illustrated in Table 1. It is seen that Sr concentration is very high in Silver linden barks, and Sr concentrations determined in barks can exceed 10 times those in wood. Sr concentrations determined in inner barks are slightly lower than those in outer barks. It was determined that only the values obtained in barks were statistically significant in terms of direction. The maximum Sr concentrations were acquired in the outer bark's south and east orientations and the inner bark's north and east directions.

The changes in Sr concentration in Silver linden wood based on direction and period are given in Table 2. When the change in Sr concentration in Silver linden woods is analyzed in terms of direction and period, a statistically significant change is observed in all directions in terms of period and all periods in terms of direction. When the change is examined based on a period, the Sr concentration generally

Table 1 Changes in Sr concentration (mg/kg) in Silver linden based on organ and compass orientation

Organ	North	East	South	West	F-value	Average
Outer bark	76.84cB	82.20aC	92.27cD	71.71cA	611.6***	80.76c
Inner bark	71.31bD	64.88bC	59.10bA	60.96bB	272.1***	64.06b
Wood	7.00a	7.53a	7.22a	7.23a	1.10ns	7.24a
F-value	7134.9***	10437.5***	15230.3***	7683.4***		6187.1***
Average	16.58	16.96	17.00	15.67	0.00ns	

A different letter indicates that the average concentrations are statistically different. Lowercase letters (a, b, c, etc.) show vertical courses, while capital letters (A, B, C, etc.) show horizontal courses. ***: $p \leq 0.001$; ns: not significant. These justifications are true for every table

Table 2 Changes in Sr concentration (mg/kg) in Silver linden wood based on compass direction and age period

Period	North	East	South	West	F-value	Average
2018–2022	9.11iD	6.19aB	6.78eC	5.23aA	3664.3***	6.83ab
2013–2017	5.37bA	7.27eB	8.25jC	5.37bA	27,850.2***	6.56ab
2008–2012	5.04aA	7.99gD	7.49hC	6.04cB	11,592.4***	6.64ab
2003–2007	6.55dD	6.30bB	6.45cC	6.08cA	101.9***	6.35a
1998–2002	6.24cA	6.30bB	6.36bB	6.90dC	169.7***	6.45a
1993–1997	6.53dB	6.79cC	6.22aA	7.54eD	2171.9***	6.77ab
1988–1992	6.62eA	7.63fC	6.93fB	7.84fD	387.7***	7.26bcd
1983–1987	7.17gC	8.24hD	6.69dA	6.90dB	676.8***	7.25bcd
1978–1982	6.84fA	8.37iD	7.05gB	8.29gC	1953.8***	7.64cd
1973–1977	7.22gC	7.02dB	6.78eA	7.28deC	66.1***	7.07abc
1968–1972	7.45hA	8.19hC	7.91iB	8.16gC	295.0***	7.93d
1963–1967	9.84jB	10.06jC	9.66kA	11.111hD	361.4***	10.17e
F-value	4745.8***	2897.5***	2140.2***	2321.3		20.7***
Average	7.00a	7.53a	7.22a	7.23 a	1.1ns	

A different letter indicates that the average concentrations are statistically different. Lowercase letters (a, b, c, etc.) show vertical courses, while capital letters (A, B, C, etc.) show horizontal courses. ***: $p \leq 0.001$; ns: not significant. These justifications are true for every table

increases with the age of the wood, especially according to the average values. Notably, there is no significant change on a direction basis; the values obtained are pretty close to each other, and the difference between the lowest and highest values is only a few times. According to the average concentrations, the difference in the Sr concentration on a compass direction basis is statistically negligible.

The change in the Sr concentration in Douglas fir in terms of organ and compass direction is illustrated in Table 3. It is seen that the Sr concentration is also very high in the barks in Douglas fir, and the Sr concentrations determined in the barks can be 7–8 times higher than in the woods. The Sr concentrations determined in the inner barks are much lower than in the outer barks. It was determined that only the values obtained in the barks were statistically noteworthy in terms of direction. The inner bark in the west and south directions and the outer bark in the north and west directions had the highest Sr concentrations.

The change in the Sr concentration in Douglas fir woods in terms of period and compass orientation is illustrated in Table 4. When the alterations in Sr element concentration in Douglas fir woods in terms of direction and period are scanned, Sr concentration changes in all directions in terms of period, and all periods in terms of direction are statistically notable. However, when the values are assessed, Sr concentration changes in a limited range. Indeed, this situation is also reflected in the average values , and as a result of the

Table 3 Change in the Sr concentration (mg/kg) in Douglas fir in terms of organ and compass orientation

Organ	North	East	South	West	F-value	Average
Outer bark	38.52cD	31.30cB	30.79cA	37.79bC	795.8***	34.60c
Inner bark	21.60bB	19.52bA	22.33bC	32.99bD	4854.0***	24.11b
Wood	4.27a	4.24a	4.10a	4.29a	1.4ns	4.95a
F-value	4549.9***	4611.6***	4093.7***	5224.2***		260.9***
Average	7.95a	7.27a	7.31a	8.73a	2.3ns	

A different letter indicates that the average concentrations are statistically different. Lowercase letters (a, b, c, etc.) show vertical courses, while capital letters (A, B, C, etc.) show horizontal courses. ***: $p \leq 0.001$; ns: not significant. These justifications are true for every table

Table 4 Changes in Sr concentration (mg/kg) in Douglas fir woods in terms of period and compass direction

Period	North	East	South	West	F-value	Average
2018–2022	3.19aC	2.96aA	3.01aB	4.26eD	3091.7***	3.36a
2013–2017	3.44bA	5.11iD	3.84dB	4.56fC	1767.0***	4.23a
2008–2012	4.06eB	4.27eC	4.38fD	2.61aA	5616.5***	3.83a
2003–2007	3.87dA	4.72hB	5.02hC	5.47iD	3122.6***	4.77a
1998–2002	4.33gB	4.51gC	4.14eA	5.99jD	3663.9***	4.74a
1993–1997	4.25fC	4.37fD	4.12eB	4.03dA	59.3***	4.19a
1988–1992	5.27iD	4.25eA	4.61gB	5.03hC	2239.5***	4.79a
1983–1987	5.44jC	4.03dA	4.59gB	4.08deA	721.1***	4.53a
1978–1982	4.25fA	4.71hB	4.34fAB	3.89kC	22,420.5***	4.30a
1973–1977	3.74cC	4.41fD	3.47cB	3.13bA	1304.8***	3.69a
1968–1972	4.24fD	3.97cC	3.15bA	3.60cB	1620.1***	3.74a
1963–1967	5.12hD	3.61bA	4.57gB	4.78gC	2649.9***	4.52a
F-value	1909.7***	1097.8***	1821.8***	22,423.2***		1.2ns
Average	4.27a	4.24a	4.10a	4.29a	1.4ns	

A different letter indicates that the average concentrations are statistically different. Lowercase letters (a, b, c, etc.) show vertical courses, while capital letters (A, B, C, etc.) show horizontal courses. ***: $p \leq 0.001$; ns: not significant. These justifications are true for every table

ANOVA, the change in Sr concentration in both periods and directions was found to be statistically insignificant.

The Sr concentration variation in European ash trees in terms of organs and directions is given in Table 5. As in other species, it was revealed that Sr concentration is very high in the barks of European ash trees and that the Sr concentrations acquired in the barks are many times higher than in the woods. The Sr element concentrations determined in the inner barks are greater than in the outer barks in directions other than the west. Regarding direction, it was determined that only the values obtained in the barks are statistically significant. The maximum Sr concentrations in bark were acquired in the south and east.

The Sr concentration variation in European ash woods in terms of compass orientation and period is illustrated in Table 6. According to Table 6, Sr element concentration change in all directions in terms of period and all periods in terms of direction are statistically significant. It was determined that two groups were formed because of the Duncan test according to the averages on a period basis, and the values obtained in the last period woods were statistically higher than those in all other periods. It is noteworthy that there is no significant change in terms of direction. Only the values obtained in the last period in the south and west directions are very high. Other than that, the values obtained are pretty close, and the difference between the lowest and highest values is only a few times. According to the averages, the Sr concentration changes in direction are statistically insignificant.

Table 5 Variations in Sr concentration (mg/kg) in European ash trees in terms of organs and directions

Organ	North	East	South	West	F-value	Average
Outer bark	64.04bA	71.28bC	80.18bD	70.13bB	616.9***	71.41B
Inner bark	82.50cB	83.51cC	86.06bD	2.86aA	107439.3***	63.73B
Wood	10.11a	7.43a	14.88a	13.03a	2.5ns	11.36A
F-value	148.4***	23984.4***	33.0**	41.6***		142.4***
Average	19.13a	17.42a	24.63a	16.39a	0.9ns	

A different letter indicates that the average concentrations are statistically different. Lowercase letters (a, b, c, etc.) show vertical courses, while capital letters (A, B, C, etc.) show horizontal courses. ***: $p \leq 0.001$; ns: not significant. These justifications are true for every table

Table 6 Changes in Sr concentration (mg/kg) in European ash woods in terms of period and compass orientation

Period	North	East	South	West	F-value	Average
2018–2022	39.07gB	9.25hA	80.29hD	49.86iC	18.877.5***	44.62b
2013–2017	8.36fB	6.44aA	10.86fD	10.28gC	2875.2***	8.93a
2008–2012	8.49fB	6.50aA	9.22eC	9.25eC	1850.9***	8.37a
2003–2007	7.88eC	7.13cA	7.57bB	9.82fD	2338.3***	8.10a
1998–2002	8.31fC	7.84fB	7.18aA	10.24gD	1782.6***	8.39a
1993–1997	7.66deA	8.08gB	8.10dB	10.11gC	1269.5***	8.49a
1988–1992	7.48dB	7.29 dA	7.56bC	9.21deD	2663.9***	7.88a
1983–1987	6.73bA	7.80 fB	8.19dC	8.51bD	426.8***	7.81a
1978–1982	6.45aA	7.48 eB	9.29eD	8.72bcC	2169.6***	7.98a
1973–1977	6.48aA	7.47 eB	7.79cC	8.97cdD	2811.0***	7.68a
1968–1972	7.21cA	7.25 dA	7.53bB	8.11aC	284.6***	7.53a
1963–1967	7.19cB	6.64 bA	15.00gD	13.35hC	21075.0***	10.55a
F-value	12040.7***	571.6***	150758.4***	18459.0***		21.7***
Average	10.11	7.43	14.88	13.03	2.5ns	

A different letter indicates that the average concentrations are statistically different. Lowercase letters (a, b, c, etc.) show vertical courses, while capital letters (A, B, C, etc.) show horizontal courses. ***: $p \leq 0.001$; ns: not significant. These justifications are true for every table

4 Discussion

Numerous studies claimed that heavy metal concentrations are much higher than expected values in urban neighborhoods (Cebi Kilicoglu & Zeren Cetin, 2024; Gültekin et al., 2025), areas with heavy traffic (Cetin et al., 2022a, 2022b), industrial sites (Istanbullu et al., 2023), mining regions (Ergül & Kravkaz Kuşçu, 2024), agricultural regions (Kravkaz Kuşçu et al., 2022) and even wetlands and lakes (Mutlu, 2021; Mutlu et al., 2024; Tokatli et al., 2024). This situation causes plants growing in areas with high heavy metal pollution to accumulate heavy metals in various organs (Zeren Cetin, 2024a, 2024b; Yucedag et al., 2025). The potential of plants to accumulate heavy metals makes them practical tools both in observing the change of heavy metal pollution and in lessening this pollution (Cetin & Jawed, 2024; Cetin et al., 2023). The current study was designed with two main objectives. The first is to specify the potential of the trees in question to be used as biomonitors to monitor the Sr concentration change in the air. As an outcome of the current research, it was specified that Sr concentrations in wood generally varied within a narrow range, the difference between the highest and lowest values did not generally exceed a few times, and the Sr concentrations determined between neighboring cell groups were quite close to each other. This result can be interpreted as the Sr element can be exchanged in wood.

As it is known, for a plant species to be used as a biomonitor in determining the change in heavy metal contamination in the air, it must be able to accumulate heavy metals in its body and not die under the effect of heavy metals. However, it must be able to continue its life. The trees in question meet this criterion. Another feature sought in biomonitor species is that heavy metal transfer between wood tissues is limited (Cobanoglu et al., 2023; Koç, 2025). Since the trees in question do not meet this criterion, they are not proper biomonitors that can be used to track the change in Sr concentration in the air. According to studies, only certain species may be appropriate biomonitors for certain metal elements, including heavy metals.

Research indicates that only specific tree species are suitable as biomonitors for particular heavy metals. As shown in Table 7, not every species effectively monitors all types of heavy metal contamination. This variation is largely due to differences in how elements are transported and retained within the wood of different species. While some elements may accumulate consistently in the wood of certain trees—making them reliable biomonitors—they may be more mobile or inconsistently distributed in others, reducing their suitability for monitoring purposes.

The current study's second aim is to determine which species are suitable for lessening the environment's Sr pollution. For this purpose, woody species with high metal accumulation capacity are particularly valuable, given that stems constitute the largest biomass component in plants. Plants that accumulate exceptionally high metal concentrations—exceeding 1000 µg per gram (1 mg/kg or 1 ppm) of dry biomass—are classified as *hyperaccumulators* (Visoottiviseth et al., 2002).

In the current research, the average Sr concentrations in wood were 4.95 mg/kg in Douglas fir, 7.24 mg/kg in Silver linden, and 11.36 mg/kg in European ash. According to these results, all three species in the study are hyperaccumulator species for Sr. The values acquired in the current study are generally higher than those found in other studies. For instance, Erdem (2023) compared the trees grown in the region where the research was conducted and determined the average Sr concentrations in *P. orientalis*, *C. arizonica*, *C.*

Table 7 Suitability of metal elements for use as biomonitors in the woody parts of certain tree species

Suitability	Element(s)	Species	Author(s)
Suitable biomonitor	Cu	*Cedrus deodora*	Zhang, 2019
	Ba	*Fagus orientalis, Carpinus orientalis, Quercus petraea*	Oztürk Pulatoğlu, 2024
	Sr, Pd	*Pinus pinaster*	Erdem, 2023; Sevik et al., 2024
	Cr, Sr, Pd	*Pseudotsuga menziesii*	Koc et al., 2024; Erdem, 2023; Sevik et al., 2024
	Pd, Tl, Sr	*Picea orientalis*	Canturk, 2023; Erdem, 2023; Sevik et al., 2024
	Cr, Mn, Ni, Pd, Sr,	*Cedrus atlantica*	Erdem, 2023; Koç, 2021; Savas et al., 2021; Sevik et al., 2024
	Cr, Ni, Cd, Zn, Co, Pb, Mn	*Corylus colurna*	Key et al., 2023; Key & Kulaç, 2022; Key et al., 2022
	Zn, Cd, Tl, Cr, Ni, Fe, Sr, Pd	*Cupressus arizonica*	Canturk, 2023; Cesur et al., 2021; Cesur et al., 2022; Cobanoglu et al., 2023; Erdem, 2023; Koç et al., 2024 Sevik et al., 2024
Unsuitable biomonitor	Cr	*Fraxinus excelsior, Robinia pseudoacacia, Fraxinus excelsior, Tilia tomentosa*	Ozturk Pulatoglu et al., 2025
	Co	*Cedrus atlantica*	Koç, 2021
	Pb, Zn	*Cedrus deodora*	Zhang, 2019
	Bi, Cr, Li	*Cupressus arizonica*	Cesur et al., 2021; Cesur et al., 2022; Zhang, 2019; Cobanoglu et al., 2023
	Sb, Ag, Se, Tl	*Pinus nigra*	Şevik et al., 2024

atlantica, *P. pinaster*, and *P. menziesii* woods 5.32, 3.21, 2.34, 1.88, and 1.20 mg/kg, respectively. Yiğit (2024) also compared the Sr concentrations in the woods of 16 species growing in the same region and stated that the Sr concentration in the woods of many species remained below the detectable limits. As an outcome of that research, the uppermost Sr concentrations in woods were found in *Platanus orientalis* (33.60 mg/kg), *Populus alba* (14.70 mg/kg), and *Prunus avium* (10.10 mg/kg) species (Yiğit, 2024).

According to these results, Sr concentrations accumulate in higher concentrations in the wood of broad-leaved trees and lower concentrations in coniferous trees. The main entry points for heavy metals into the plant body are the leaves, roots, and stems (Chen et al., 2021). No statistically significant correlation was observed between the amount of Sr transferred to the stem wood (heartwood, sapwood) and its vertical distribution in soil profiles (Golyaka et al., 2020). It was stated that the Sr element was comparatively constant throughout the trunk, except for the oldest growth rings, which showed a rapid expansion and most likely indicated active radioactive transfer to senescing tissues (Holiaka et al., 2023).

The primary method for Sr (II) ion adsorption on carboxymethyl groups of carboxymethylcellulose is ion exchange. The extra H^+ ions compete with the Sr (II) ions to bind with the carboxylate ion (^-COO) at low pH (< 2.0). Because of increased polymer hydrolysis, carboxylate spots can interchange with strontium ions (II) when the medium's pH rises. As KCl concentration increases, the solution's ionic power increases, but Sr (II) adsorption in carboxymethylcellulose decreases. It suggests that the medium's ionic force also influences ions' adsorption (Jain et al., 2022).

The cell assembly, particularly the cell wall (apoplastic route), has a significant role in the movement of components throughout the wood portion of plants. The apoplast is a flexible assembly that senses and produces signals in metalloid/metal strain. It is situated between plants' cell wall and plasma membrane (CWPM). Numerous plant species have had their cell wall proteins (CWPs) implicated in abiotic stressors thoroughly discovered and described (Wani et al., 2018). Abiotic stressors are common throughout the life cycle of plants. Climate stressors like cold and drought are the most frequent pressures on plants (Ertürk et al., 2024; Aricak et al., 2024). Because environmental factors (Özdikmenli et al., 2024; Özel et al., 2022) and genetic structure interact to determine plant development (Westerband et al., 2021; Tandoğan et al., 2023; Mackay & Anholt, 2024). Therefore, the plant growth environment and the stress factors it is exposed to in this environment affect the entry and accumulation of heavy metals into the plant body (Şevik et al., 2024; Ozturk Pulatoglu et al., 2025).

The study results reveal that the organ's Sr concentration is generally ranked as wood < inner bark < outer bark. Studies have shown that the outer bark contains substantial quantities of heavy metals (Guney et al., 2023; Key et al., 2023). This condition is typically caused by the bark's structure and heavy metal-contaminated particulate matter to attachment it. Such high levels of Sr concentrations in the outer bark indicate that Sr pollution in the region is relatively high. Studies in the area have found that heavy metal concentrations like Cr, Sb, Pd, and Tl—which can be detrimental to human health even in small amounts—are also relatively high (Canturk et al., 2024; Sevik et al., 2024; Ozturk Pulatoglu et al., 2025). This is in addition to the fact that the Düzce province, where the study was conducted, is Europe's fifth most polluted city (Koc et al., 2024).

The physical characteristics of outer bark, particularly its rough texture and natural crevices, enable effective deposition and retention of airborne heavy metal particles (Cobanoglu et al., 2023; Yayla et al., 2022). The element concentrations in the inner bark, which is not in touch with airborne, are lower than in the outer bark but higher than in the wood because it is thought that Sr penetrates the inner bark from the trunk sections (Key et al., 2023; Sevik et al., 2024). According to Kudzin et al. (2020), in pine plantations, the potential of tree tissues and organs to accumulate Sr is ranked as follows: bark > roots > wood. Similarly, many studies obtained the lowest concentrations in wood (Erdem et al., 2023; Yaşar İsmail et al., 2025). However, the entry and accumulation of heavy metals into the plant body is still the result of a complex mechanism in which many factors interact, and there are still significant knowledge gaps on this subject.

5 Conclusion

This study examined the suitability of *Tilia tomentosa*, *Pseudotsuga menziesii*, and *Fraxinus excelsior* for biomonitoring and mitigating Sr pollution in one of the dirty areas of Europe, Düzce, Türkiye. While none of these tree species revealed the characteristics required for effective biomonitors due to the potential for Sr relocation within the wood, all three were hyperaccumulators of Sr.

Among three tree species, European ash proved to be the most effective species for phytoremediation, with the highest average Sr concentration in wood (11.36 mg/kg). This outcome makes it a promising candidate for use in urban afforestation programs to reduce heavy metal pollution. Additionally, the high Sr concentrations observed in the bark emphasize the importance of this tree organ in capturing and sequestering airborne particulates.

These findings emphasize the significance of selecting appropriate tree species tailored to specific heavy metal contaminants for urban pollution management. Future studies should search other tree species and their Sr accumulation and retention mechanisms, explicitly focusing on the interactions between environmental stress factors, soil composition, and the cellular pathways involved in heavy metal sequestration.

Authors' Contribution Semsettin Kulac: designed the study, raw material collection, and wrote and reviewed the original manuscript. Ayse Ozturk Pulatoglu: designed the study, raw material collection and edited the original manuscript. İsmail Koç: designed the study, analyzed the data, wrote and edited the original manuscript. Hakan Sevik: sample preparation, analyzed the data and edited the original manuscript. Halil Baris Ozel: designed the study and edited the original manuscript. All authors read and approved the final manuscript.

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Declarations

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