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Assessment of 40-year Al Deposition in some Exotic Conifer Species in the Urban Air of Düzce, Türkiye

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Abstract Heavy metal (HM) pollution in urban air, a global dilemma, has increased drastically in the last century. Aluminum (Al) is one of the HMs and a neurotoxic element that can be absorbed into human tissues through digestion, breathing, and skin. Al accumulation in humans can cause diseases and even cause death. Due to the risks it poses to human and environmental health, it is vital to track the Al contamination shifts in the airborne and decrease them. In this study, 40-year Al concentration differences in *Pseudotsuga menziesii*, *Cedrus atlantica*, *Picea orientalis*, *Cupressus arizonica*, and *Pinus pinaster* grown in Düzce, Türkiye, the fifth most polluted European town, in terms of direction, tree species, and tissue type were assessed. As a result, Al accumulation in the tissues generally varies as outer bark > inner bark > wood. Whole species can accumulate Al significantly, and Al transfer between adjacent cells in the wood part is limited. In conclusion, all species can be used as biomonitors to track temporal Al pollution changes. However, the highest concentrations, especially in the wood part, were observed in *Cedrus atlantica*, *Picea orientalis*, and *Cupressus arizonica*, and these species were chosen to be the most suitable species to be used in phytoremediation studies.

Keywords Aluminum · Biomonitor · Düzce · Pollution · Wood

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1 Introduction

In the last century, advancements in technology and industry have brought troubles such as urbanization, global warming, and environmental pollution to the world agenda and have made them the most critical crises on a global scale today (Dogan et al., 2023; Tekin et al., 2022). Since fossil fuels essentially provided the energy demands throughout this process, the burning of fossil fuels became a primary source of pollution. Therefore, fossil fuel use is considered one of the leading reasons for global warming and environmental problems, especially air pollution (Yayla et al., 2022; Zeren Cetin et al., 2023).

Road transportation is one of the areas where fossil fuels are used the most, and therefore, road traffic is considered one of the most important sources of pollution in the atmosphere (Cobanoglu et al., 2023; Istanbullu et al., 2023). However, moving vehicles in main road transportation accounts for a large share of fossil fuel combustion, which releases gaseous and particulate contaminants into the air in most countries (Al-Thani et al., 2020). The road transport sector makes a significant contribution in terms of carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), methane (CH_4), non-methane hydrocarbon (NMHC), hydrofluorocarbon, and particulate matter (PM) [PM 2.5 and PM 10] emissions (Hooftman et al., 2018; Teixeira et al., 2018; Alasfarn & Isaifan, 2021).

Studies show that both PM and HM pollution in the atmosphere are predominantly caused by traffic in urban areas (Ou et al., 2022). It is stated that PM contaminated with HMs induces severe health problems (Guo et al., 2021). Air pollution worldwide causes roughly 4 million premature births and 7 million deaths annually (WHO, 2022). Studies show that the most critical and deadly apparatuses of atmospheric pollution are HMs, which are much more destructive when taken into the human body via the respiratory tract (Jadaa and Mohammed, 2023).

Aluminum (Al), one of the most used HMs in industry, is Earth's third most abundant element (Martin, 1990). It is environmentally ubiquitous and accounts for about 8% of the Earth's crust (Niu, 2018). Due to its reactive nature, it is usually not found in a metallic state but in compounds with oxygen, silicon, fluorine, and other elements (Alfrey, 1983). The most common primary and secondary minerals are aluminosilicates, which include clay minerals, micas, and feldspars (McLean et al., 1965). Concentrations of Al in water and ambient air are continuously rising due to human activities (Alasfarn & Isaifan, 2021). Air emissions from the Al production process, mining, waste incineration, coal combustion, and automobile exhaust contribute to greater atmospheric Al concentrations (Alasfarn & Isaifan, 2021).

Aluminum can be absorbed via breathing, digestion, and skin (Niu, 2018). Aluminum is a well-known neurotoxicant. It can be absorbed from the gastrointestinal tract and lungs. Occupational Al dust exposure drives pulmonary fibrosis, aluminum sulfate, aluminum fluoride, and potassium aluminum tetrafluoride inhalation, and electrolytic aluminum production cause asthma (Yokel & Sjögren, 2022). It can also damage the central nervous system (Niu, 2018) and cause diseases such as osteomalacia, dialysis encephalopathy, and microcytic anemia (Becaria et al., 2002). In addition, Al accumulated in brain tissue is considered to play a role in the development of neurological disorders (Osińska et al., 2004), cognitive disorders, neurodegenerative disorders, and the occurrence of Alzheimer's disease have been determined to be associated with Al (Klotz et al., 2017; Niu, 2018). It is known that the presence of elevated Al content in the brain tissue and the inflammatory cells within the tissue, and the high amount of Al in the body is carried to the brain through the vascular system, causing brain inflammation and death (Mold et al., 2019).

It is stated that Al accumulation in the liver causes cholestasis and disrupts the maturation of erythroblast series cells and heme biosynthesis, causing normo- or microcytic anemia (Osińska et al., 2004). It is also known that it reduces the osmotic resistance of red blood cells, inhibits the defense mechanisms associated with white blood cells and macrophages, and is responsible for several hematological changes such as hemolytic activity, shortened lifespan of blood cells or impaired erythropoiesis process (Osińska et al., 2004).

Many studies have shown that PM in different urban regions contains notable amounts of Al from natural and human-related activities (Kalugina et al., 2017; Liu et al., 2020; Alasfarn & Isaifan, 2021). The sector's contribution to PM is of a specific dilemma in metropolises, as many residents are directly exposed (Hooftman et al., 2018; Teixeira et al., 2018; Alasfarn & Isaifan, 2021). Therefore, determining the change in Al pollution in the atmosphere is essential in identifying urban areas threatening health and guiding the precautions to be taken.

Düzce city, Türkiye, is preferred as a study site because the population started to increase due to immigration, especially after the earthquake that caused great destruction in 1999, with the establishment of new industrial zones and residential areas. The rate of this increase accelerated in the last decade, as a result of which the province was shown to be among the most polluted provinces. In addition, the fact that the province is a connecting route between Ankara and Istanbul, and countless vehicles travel on this route every year contributes to the increase in the province's air pollution level.

Düzce, in the Western Black Sea territory of the Republic of Türkiye, is among Europe's five most unclean cities (annual mean PM2.5 = 44.4 μg/m^3), according to the 2021 World Air Pollution Report (IQAir, 2021). Düzce province is located on a plain with an altitude of 140 m (a.s.l.) and is surrounded by mountain ranges. The average temperature of the province, which is affected by three climate types (mild winters, hot summers, and rainy in all seasons), for the last 30 years (1991–2021) is 12.6 °C, and the mean rainfall during the growing period (March to October) is approximately 39.2 mm (MGM, 2023). Throughout the province, rainfall occurs mainly in autumn and winter. Although it varies according to months and seasons, the dominant wind velocity is in the NE-SW axis, and the mean wind velocity in the province is 0.7 m/s (Düzce Meteorology Provincial Directorate, 2013). The topographic structure of the province (bowl-shaped) reduces the wind speed; therefore, fog and pollution remain in the city for a long time, especially during winter.

In 1999, the 7.2 magnitude earthquake caused considerable damage to house and industrial facilities throughout the province. In the following years, it has increased and diversified thanks to both the incentives provided by the state and individual investments, and today, there are many industrial facilities in the study area. The province has five big-scale industrial zones hosting numerous small-scale industrial businesses. The sectors with the massive quantity of facilities and work in Düzce are metal-machinery, textile, food, furniture, forest, rubber-tire-plastic, construction, chemical and pharmaceutical, automotive, and mining sectors (Düzce Valiliği, 2023). It has been claimed that in Düzce, one of the most polluted European cities, PM2.5 and PM10 in the airborne elevated up to a maximum 244.83 and 386.31 μg/m^3, respectively (Çevre, 2023).

This study aimed to define the biomonitors that can be used to track Al pollution shifts in the airborne and the species that can be used to decrease this pollution. For this purpose, five 40-year-old species [*Pseudotsuga menziesii* (Mirb.) Franco, *Cedrus atlantica* (Endl.) Maanetti ex Carriere, *Picea orientalis* L., *Cupressus arizonica* Greene, and *Pinus pinaster* Aiton.] growing in a park (surrounded by a 1–1.5 m high stone wall), in Düzce province, Türkiye were selected. These trees are not native to the Düzce region but have high aesthetic value, are well adapted to this region in terms of growth and development, and are the most preferred in urban landscaping works (road and park area afforestation) due to some features (evergreen, low maintenance cost, durability and other traits, such as screening and shading).

The study's primary objective is to determine the change in Al concentration in tree species grown in similar soil conditions in the same site and exposed to air pollution at similar rates depending on the species, species tissue, direction, and age range. Therefore, the study's hypotheses are as follows: a) There is a difference between the Al accumulation potentials of the species in the area. b) The Al accumulation potentials of the species in the area vary depending on the tree tissue. c) The Al accumulation potentials of the species in the area vary depending on the direction. d) The Al accumulation potentials of the species in the area vary based on a period.

2 Materials and Method

The study was conducted in Düzce province (40°49′36.97″ N–31°10′31.40″ E), Türkiye, where atmospheric pollution is elevated (Fig. 1). The study was carried out on samples taken from exotic plant species planted by human hands approximately 40 years ago in a park surrounded by a 1.2–1.5 m high stone wall in Düzce province. This park is located in the east-southeast part of the city center and is surrounded by the D-100 highway from the north (running from east to west direction and 650–700 m away), and from the south, there are agricultural areas. However, the city has been expanding west to east for the last ten years, and construction has increased recently.

During the maintenance and arrangement work carried out by the municipality, among the trees planned to be cut down, those that were healthy and approximately the same height (approx. 15 m) and at equal distance (approx. 10–30 m) were determined. In the study, directions were marked on the trunks of the trees [*Pseudotsuga menziesii* (Pm), *Cedrus atlantica* (Cda), *Picea orientalis*

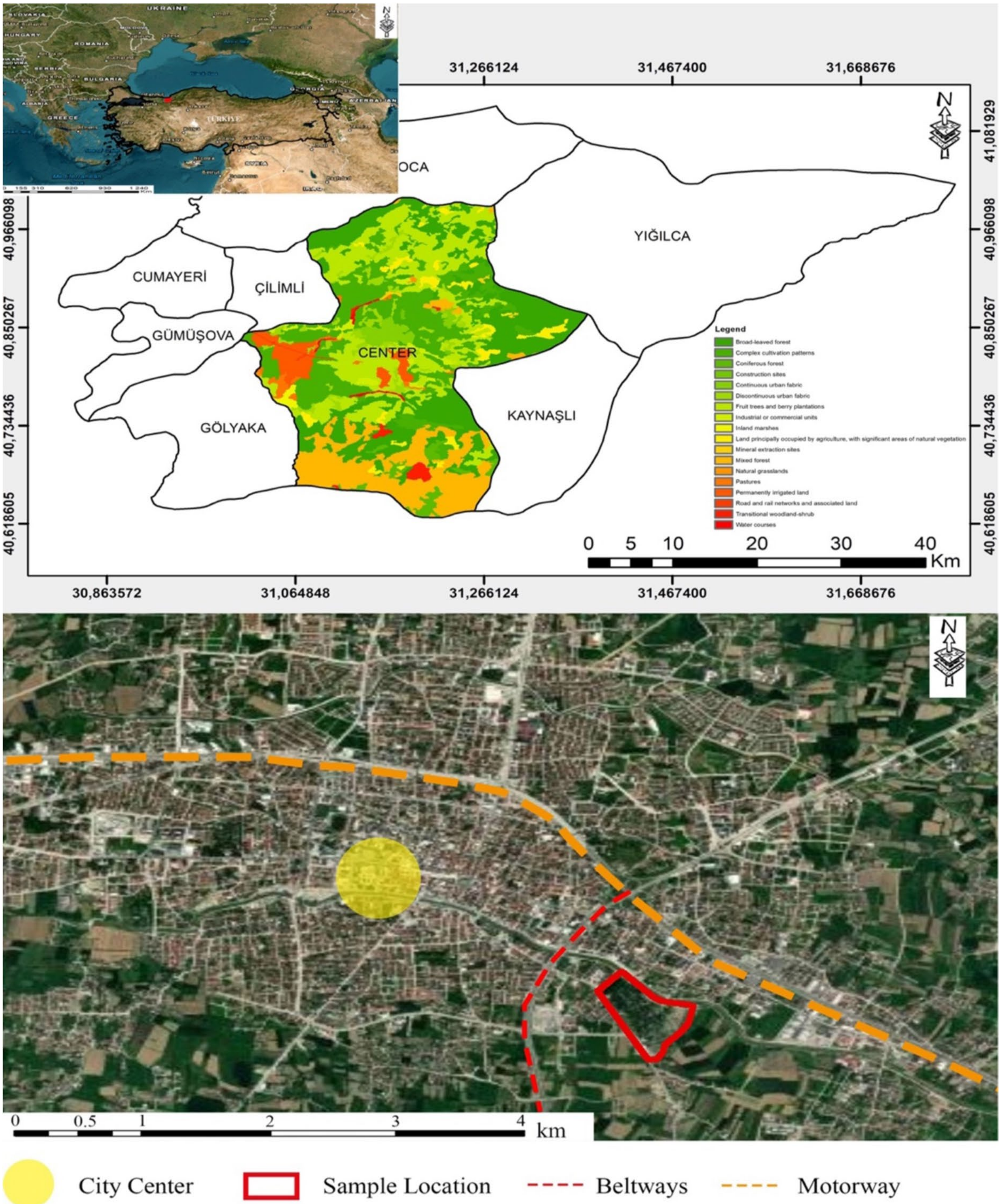


Fig. 1 Location of sample area in Düzce, Türkiye

(Po), *Cupressus arizonica* (Cpa) and *Pinus pinaster* (Pp)] that were cut in the late autumn period of 2022. Ten cm thick log samples were obtained from the cut trees, approximately 40–60 cm above the soil level. The annual rings on the log samples were made visible by planing, and it was determined in the laboratory that the trees were 40 years old. Five-year age classes were determined based on annual ring widths, and samples were taken from each age class and the outer bark and inner bark in three replicates with the help of a steel-tipped drill. The samples obtained as sawdust were kept in glass petri dishes with open lids for 15 days and allowed to air dry. These sawdust samples were then oven-dried (45 °C) for a week. 0.5 g of dried samples were taken, 6 ml HNO_3 (65%) and 2 ml H_2O_2 (30%) were added and placed in the microwave oven, and then the resulting solution was placed in flasks and completed with ultrapure water up to 50 ml. The samples' solutions were analyzed using the ICP-OES instrument [GBC Scientific Equipment Pty Ltd., Melbourne, Australia]. The Al element concentrations were estimated by multiplying the acquired values by the dilution factor. This procedure has often been used in recent research (Canturk, 2023; Koc et al., 2024).

Sampling was performed in 5 replicates within the study's scope. Since the study area is a park, trees were planted at equal planting intervals, and there was approximately a 20-m distance between the trees. This distance ensures at least one tree crown diameter between the branches of the trees and does not prevent air circulation. Therefore, the trees are thought to be equally exposed to airborne pollution. Forest trees' trunks swell at the root collar level. To avoid the effects of this swelling, log samples were taken 40–60 cm above the ground at the root collar level. The distribution of the selected trees in the area is random. The north compass direction was marked before the trees were cut. Samples were taken from different directions of the same log in the cut logs. In order to prevent possible contamination during the analytical process, drying was done in closed areas without air pollution during the pre-treatments, and equipment made of Al was not used at any stage of the study. The experts performed the analyses in an accredited laboratory. The method used in the study is a proven method used in articles published in some journals with high impact factors in recent years (Yaşar İsmail et al., 2024; Canturk et al., 2024; Ozturk Pulatoglu et al., 2025). Statistical analyses were performed after checking the normality and homoscedasticity of the Duncan test and ANOVA distributions.

3 Statistical Analysis

The SPSS 22.0 package program was used to assess Al element concentration. Initially, analysis of variance (ANOVA) was used on the data, and the Duncan test was applied for the parameters with statistically substantial dissimilarities at alpha = 0.05. Last, the Al concentration variation based on tree species, tissue, direction, and age class was estimated separately.

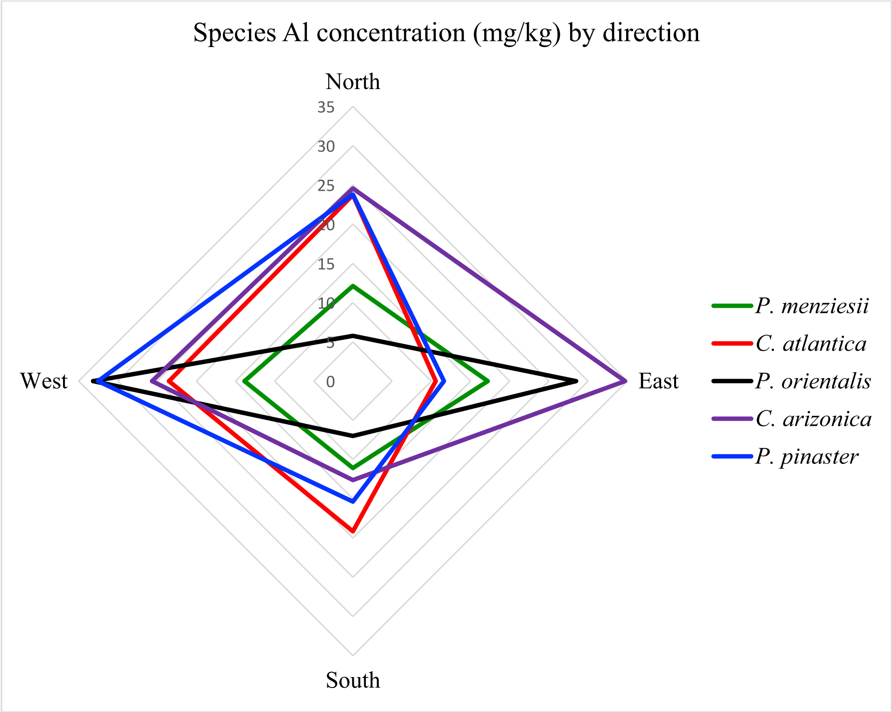
4 Results

The Al concentration variation based on direction and species was specified independently, and the averages are displayed in Fig. 2. It was determined that the Al concentration change in all directions except the east was not statistically significant ($P > 0.05$). In the eastern direction, the most considerable value was obtained in the Cpa, while the smallest value was in the Cda and Pp species. The Al concentration in Cda, where the highest value is obtained, is more than three times that in Cpa, where the lowest value is obtained. The total Al concentration values also obtained the highest concentration in Cpa, while the lowest was in Pm.

The variation of Al concentration by tree species and tissue is given in Fig. 3. The difference of Al concentration based on a tree species is momentous in all tissues ($P \leq 0.05$). The maximum value was obtained in the outer bark in the Pp, while the lowest was in the Cda. The peak value in the inner bark was in the Cpa, while the lowest was in the Po. In wood, the values formed two groups: Cda, Cpa, and Po are in the same group with the highest values, while Pm and Pp are in the other one with the lowest values. According to the average values, Al concentration is ordered as outer bark > inner bark > wood.

The change of Al concentration in wood based on period and direction is displayed in Fig. 4. According to the ANOVA results, Al concentration changes based on a period are significant ($P \leq 0.05$) in directions other than north and east and compared to the average values. Notably, the highest values in the southern and western directions were obtained after 2015. Similarly, according to averages, the highest Al concentration was obtained after 2015. Apart from this,

Fig. 2 Variation of species Al concentration based on direction



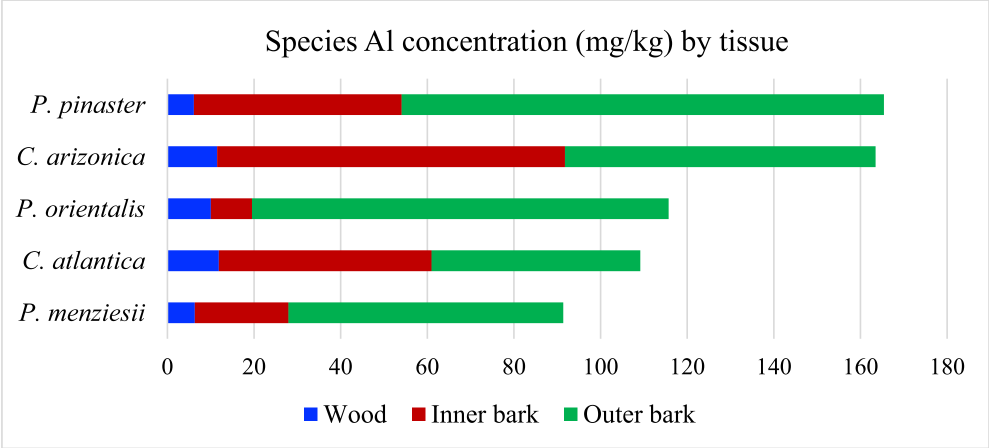


Fig. 3 Variation of species Al concentration (mg/kg) by tissue

Al concentration change based on direction was significant $P \leq 0.05$) in all periods except the 2003–2007 period, and generally, the minimum values were obtained in the south and the peak values in the west direction.

The Al concentration change based on tissue and direction is displayed in Fig. 5. According to the average values, Al concentration change based on tissue is significant in all directions ($P \leq 0.05$) (data not shown). The maximum Al concentrations were in the west direction and the lowest in the north and south. It was observed that the Al concentration change based on the direction in tissue other than wood was not significant ($P > 0.05$). The maximum Al concentrations in wood were in the west and the minimum in the north and south.

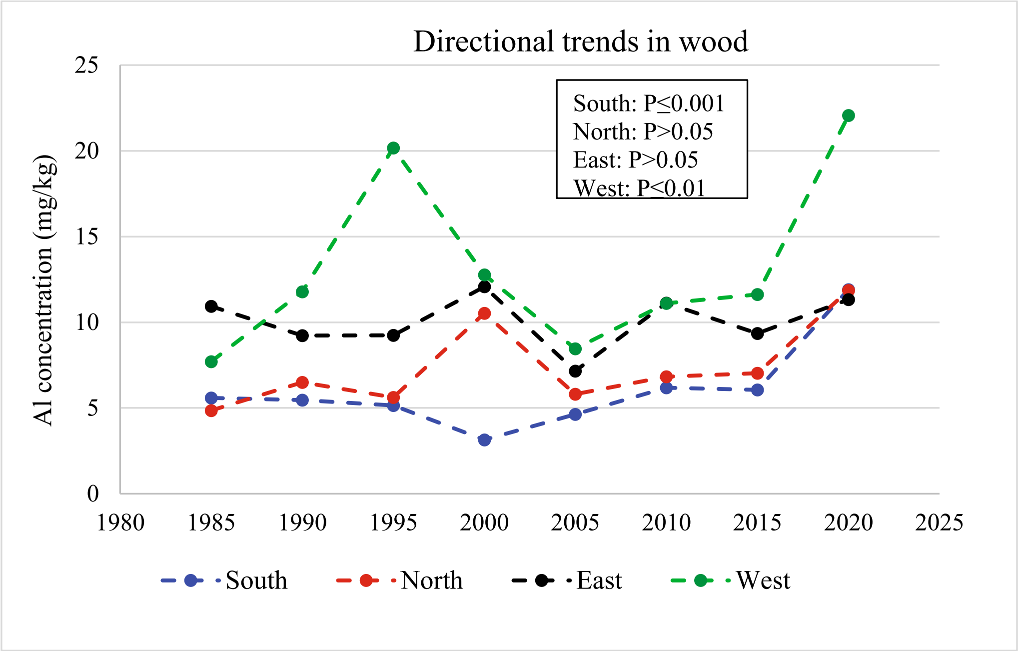


Fig. 4 Al concentration changes in wood based on period and direction

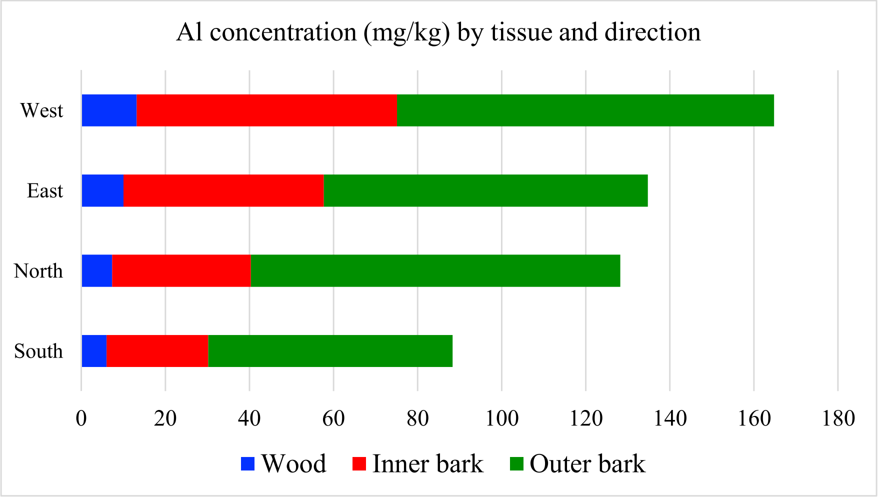


Fig. 5 Al concentration (mg/kg) change based on tissue and direction

The Al concentration variation by period and tree species is displayed in Fig. 6. It is seen that the Al concentration decreased until 2010 and then boosted through 2000–2020 in Cda, Cpa, Pm, and Po. Nevertheless, the Al element concentration in Pp boosted until 2000, then declined until 2020.

The concentration variation in the species' wood used in this study based on tissue and direction is presented in Table 1. As a result of ANOVA, the Al concentration variation in all species used in the study is significant in all tissues based on direction (except outer bark in Cpa) and in all directions based on tissues.

According to Duncan's analysis, concentrations followed by the different letters (A, B, C, or a, b, c) are statistically different at $P \leq 0.05$. Uppercase

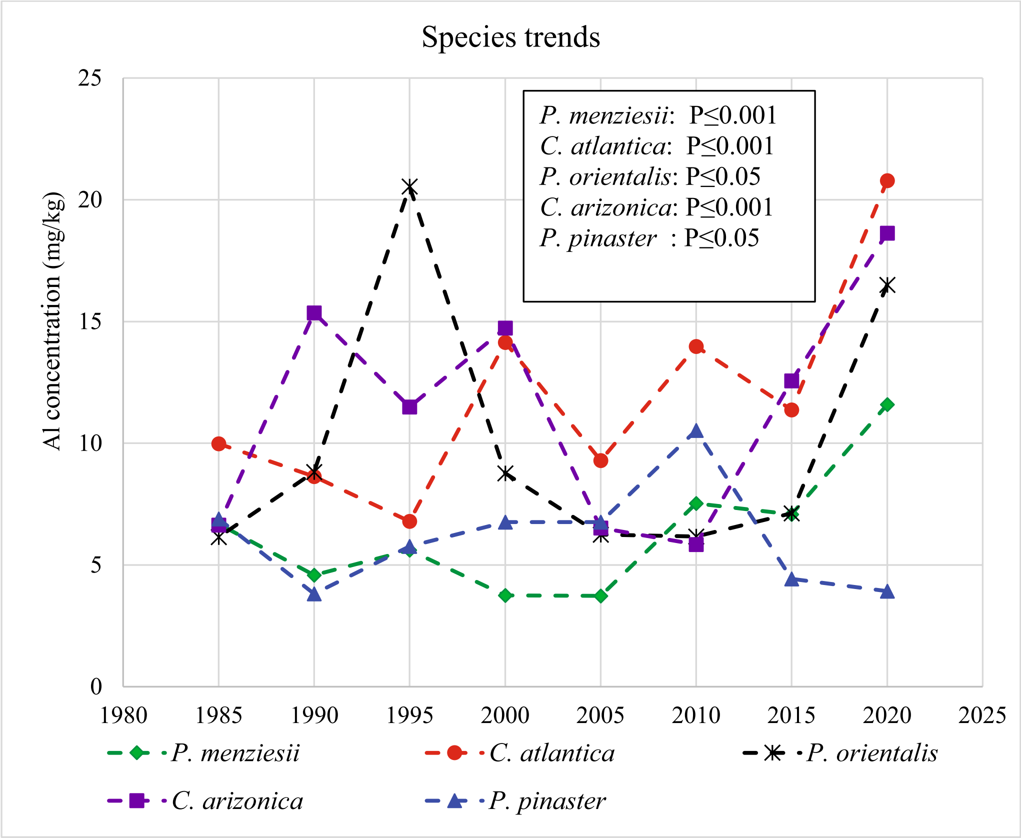


Fig. 6 Variation of Al concentration in wood by species and period

letters show horizontal directions, while lowercase letters show vertical directions.

Regarding the tissues, the lowest Al was acquired in the Pm wood, while the maximum value was in the outer bark. In terms of direction, the peak values were in the east, while the lowest Al amounts were in the south for Pm. While the lowest Al concentration change based on tissue was in the Cda wood, the highest concentrations were in the outer and inner bark. The lowest Al concentration variation was in the east, while the maximum Al values for Cda were in the west and north. The Al concentration variation in Po based on tissue was ordered as outer bark > inner bark > wood. For direction, it was listed as east > west > north > south.

As a result of ANOVA, the Al concentration variation in Cpa wood based on direction was significant in tissues other than the outer bark. While the smallest Al concentration based on tissues was in the Cpa wood, the highest were in the outer and inner bark. There was no substantial alteration between the directions ($P > 0.05$). At the same time, the highest Al concentration was found in the outer bark from the north and south and the inner bark from the east and west. The Al concentration variation in Pp based on tissue was significant in all directions, and the Al concentration in all directions was sorted as wood < inner bark < outer bark. While the maximum Al concentration in the north, east, and south was in the outer bark, in the west direction, it was in the inner bark for Pp.

5 Discussion

Study results show that Al concentration varies considerably by species and tissue. In our study, the highest Al concentrations were obtained in

Table 1 Change of aluminum concentration (mg/kg) (±Std. dev.) in 5 species' wood based on tissue and direction

Pseudotsuga menziesii				
Tissue	West	East	North	South
Wood	6.88±4.80 Ba	10.31±5.64 Ca	3.77±1.52 Aa	4.33±1.47 Aa
Inner Bark	15.93±0.13 Bb	36.48±0.50 Db	6.48±0.03 Ab	27.54±1.22 Cb
Outer Bark	67.44±1.10 Cc	53.13±0.35 Bc	84.51±0.30 Dc	48.69±0.40 Ac
Cedrus atlantica				
Wood	16.67±8.45 Ca	7.15±4.91 Aa	12.40±5.21 Ba	11.27±8.60 Bc
Inner Bark	40.45±0.36 Bb	31.05±0.29 Ac	80.64±0.33 Dc	44.31±0.09 Cb
Outer Bark	60.91±0.19 Cc	17.44±0.62 Ab	57.40±0.49 Bb	57.04±0.36 Ba
Picea orientalis				
Wood	20.93±19.48 Ca	11.02±3.71 Bb	3.49±1.67 Aa	4.72±2.82 Aa
Inner Bark	19.45±0.08 Da	2.07±0.02 Aa	3.58±0.06 Ba	12.86±0.18 Cb
Outer Bark	144.61±0.33 Cb	194.61±2.47 Dc	26.12±0.68 Bb	19.34±0.06 Ac
Cupressus arizonica				
Wood	13.51±4.64 Ba	11.74±5.92 Ba	14.97±11.65 Ba	5.67±2.78 Aa
Inner Bark	89.55±0.27 Cc	155.37±2.18 Dc	46.72±0.26 Bab	29.52±0.13 Ab
Outer Bark	58.65±0.10 b	97.94±1.92 b	79.00±1.84 b	51.29±0.08 c
Pinus pinaster				
Wood	8.04±1.31 Ba	10.07±7.07 Ba	2.25±0.69 Aa	4.09±1.48 Aa
Inner Bark	144.12±1.01 Dc	13.40±0.11 Bab	27.58±0.20 Cb	6.72±0.13 Ab
Outer Bark	116.85±0.40 Cb	22.22±0.02 Ab	192.10±0.56 Dc	114.25±0.80 Bc

Pp, Po, and Cpa in the outer bark and Cda, Po, and Cpa in the wood. It is thought that the difference in Al concentrations, especially in the outer bark, is related to the branching structure rather than the roughness of the bark. Species with lower Al concentrations in the outer bark are those that branch intensively from the bottom, and therefore, particulate matter is probably held by the branches before it reaches the trunk. This result is generally consistent with the literature. Studies conducted to date have revealed that many HMs vary significantly in biomonitors, both based on species (Isinkaralar et al., 2022; Karacocuk et al., 2022) and tissue (Savas et al., 2022; Key et al., 2022). In the region where the study was conducted, air pollution measurements only include the recent past. In measurements made between 2011 and 2018, it was determined that the amount of PM10 in the air varied between 54 and 107 (Düzce, 2024). However, no data was found on Al pollution in the air. Therefore, the study's results could not be compared with the Al pollution in the region where the study was conducted. However, studies conducted in different regions have shown that Al accumulates in the tissues of plants due to airborne sources and that there is a correlation between this accumulation and Al pollution in the air (Erdem et al., 2023; Kuzmina et al., 2023). In studies conducted on the subject, it was determined that Al concentration in wood was 2550–12700 mg/kg in *Robinia pseudoacacia*, 90.4–27,400 mg/kg in *Platanus orientalis*, 10,000–23900 mg/kg in *Acer negundo*, 4768–70,200 mg/kg in *Ulmus minor*, 10,500–11600 mg/kg in *Nerium oleander* (Kuzmina et al., 2023), 9.4 mg/kg on average in Quercus species (Turkyilmaz et al., 2019), and 3.7–8.8 mg/kg in different directions in *Corylus colurna* (Key et al., 2022).

Our study found the highest average Al values in the outer bark and the minimum in the wood. The high Al concentrations in the outer bark are thought to be related to the shell structure and Al-contaminated PM. It has been stated that HMs in the air stick to PM and contaminate them. Therefore, this PM settling on plant organs increases the HM concentrations in plant tissues (Cesur et al., 2022). The coarse surface structure of the outer bark makes it easier for PM to adhere there (Koç, 2021; Cesur et al., 2022).

HMs have three pathways to enter the plant body: from the ground via root hairs and from the atmosphere via stem and plant leaves (Isinkaralar et al., 2022). However, the knowledge regarding the speciation of HMs within the plant and their shift between tissues after access to the plant is minimal (Savas et al., 2021). Wani et al., (2018) stated that cell structure and cell wall are primary factors for element transportation in wood. The flexible structure of the cell wall-plasma membrane (CWPM) acts as a barrier (apoplastic mechanics) and senses and transmits metal and metalloid stress (Wani et al., 2018). CWPMs, which serve as a response mechanism against environmental strain factors (drought, cold, heat, etc.), have been recognized and characterized in detail for many field crops. Under different environmental stress conditions, major CWPMs may include C-repeat binding factor, salt hypersensitive kinases (SOS), phospholipases, transcription factors, mitogen-activated protein kinases and phosphatases, dehydration-sensitive element binding proteins, and abscisic acid. The interface of CWPM is a possible source of HM tolerance as it collects significant fractions of HMs (Wani et al., 2018).

Studies have shown that Al enters the sensitive plants' root tips and accumulates in the epidermal and cortical layers just below the epidermis (Delhaize et al., 1993). The cell wall has been determined to be the primary location of Al accumulation. However, membrane transport occurs within minutes of Al exposure. This situation is supported by sequestration in the vacuole. It also suggests that rapid transfer of Al to the protoplasm may cause intracellular lesions (Taylor et al., 2000). Ranjan et al. (2021) stated that Al accumulates in the cell wall and the upper layer of the plasma membrane, which subsequently results in secondary cell wall lignification. It has been stated that in the second stage, Al, with the assist of plasma membrane transporters (e.g., NIP, HmPALT1, Nrat1), triggers the formation of ROS (reactive oxygen species) and lipid peroxidation by incorporating Al^{3+} ions into the plasma membrane. Then, with the beginning of the next stage in which Al^{3+} is present, its accumulation in the cell begins and stimulates the formation of ROS. They stated that ROS prevents the entry of Al^{3+} into root cells by activating membrane transporters to chelate Al^{3+} in the soil and expel phenolic compounds and organic acids. Shetty et al. (2021) reported that Al ions translocate to the upper parts of the plant very slowly. Alternatively, Al restriction is reasonable in root cells, especially in vacuolar organelles, thus leading to a low Al translocation rate in leaf tissues (Shetty et al., 2021).

Generally, there was a significant difference between the Al concentrations determined in the woods formed in diverse directions in the same period or successive periods in the same direction in the species in this study. For example, in 2003–2007, the Al concentration in Pp wood in the north was 1.73 mg/kg, while it was 14.28 mg/kg in the east. Similar results have been received in other plants.

In many studies conducted to date, it has been stated that particulate matter is an important factor in the entry of heavy metals into the stem part of the plant and that heavy metals can enter the plant body from the stem parts (Erdem et al., 2024; Şevik et al., 2024). In these studies, it has been determined that heavy metals accumulate at different levels in different directions in the plant's main stem, and it has been emphasized that two factors are effective in this result. The first of these factors is that particulate matter contaminated with heavy metals adheres to the outer bark and enters the wood part from there. The second factor is that the transfer of heavy metals within the wood is limited. For these reasons, heavy metal concentrations are high in tree tissues where pollution is elevated, and there are large differences between heavy metal concentrations in neighboring wood cells (Key et al., 2023; Sevik et al., 2024; Sulhan et al., 2023).

This study found the highest values in the western and eastern directions. The closest highways to the study's area pass through these directions. Therefore, these results can be interpreted as Al concentration increasing due to traffic. Studies have emphasized that traffic is one of the primary sources of various HMs (Aricak et al., 2019; Isinkaralar et al., 2023). Similar results were obtained for Al. For example, a study conducted on *Robinia pseudoacacia* determined that the Al concentration in washed leaves was 27.8 mg/kg in areas with no traffic, 57.7 mg/kg in areas with low traffic, and 229 mg/kg in areas with high traffic. In the same trees, the Al concentration in wood was determined to be 2550 mg/kg in areas with no traffic, 7700 mg/kg in areas with low traffic, and 12,700 mg/kg in areas with high traffic (Kuzmina et al., 2023). However, activities producing mineral dust (such as mines, construction, agriculture, and forestry) may affect these concentration values. A study conducted in three cities in China found that dust contributes approximately 10% overall to deteriorating air quality. This rate can reach even higher values (50%) in different seasons. However, the absence of mine areas very close to the study area, the concentration of urbanization in the western direction of the area where the samples were taken, and the fact that the primary wind direction is northeast and southwest reveal that the accumulated concentrations may be due to traffic.

When the Al concentration variation based on a period basis is examined, it is noteworthy that while there was generally at low levels until 2000, the Al concentration elevated after that and reached the highest levels in 2020. This condition is estimated to be related to the number of vehicles and the fuel used. In Türkiye, the total number of vehicles was approximately below 2 million in 1980, but it has been constantly increasing and exceeded 26 million in 2023 (Çevre, 2024). It is estimated that this increased rate is much higher in Düzce province. The main reason for this is that Düzce became a province after the earthquake in 1999, and its population increased rapidly. Also, the Ankara-Istanbul highway, which passes through the province and is one of the busiest roads in Türkiye, has become operational. Although the use of electric vehicles in Türkiye is very limited, this number has increased in recent years. During the study's period, the number of electric vehicles was almost non-existent in Düzce. Although the number of vehicles in traffic has boosted remarkably in recent years, the widespread use of hybrid and electric automobiles in recent years may cause a proportional reduction in the use of fossil fuels and, in this case, will help diminish Al pollution in the air.

According to the average values in the study, the highest Al concentrations in wood were obtained in Cda, Po, and Cpa. This situation is thought to be largely due to the species' branching structure. Among the species in the study, Cda, Po, and Cpa branch more densely from the bottom compared to the other species. It is estimated that they hold PM more densely due to their dense branch and leaf structure, and therefore, the Al concentration in their wood is more dense. Studies conducted in recent years have sought ways to reduce HM pollution as well as monitor it, and the usability of plants in reducing HM pollution is among the most critical research subjects (Kuzmina et al., 2023; Liu et al., 2022; Pouresmaieli et al., 2022). The element concentration in woody plants is much more critical than in other tissues in reducing atmospheric HM pollution. The most enormous tree mass is wood in terms of mass, and it does not separate from the tree and re-enter the ecosystem, unlike other tissues. Therefore, HMs in the wood are stored and kept away from the ecosystem. Thus, trees with a high potential to accumulate HMs in their wood can be used effectively to decrease HM contamination in the airborne. As a result, it was decided that the most proper species to diminish Al pollution were Cda, Po, and Cpa.

6 Conclusion and Suggestion

The study acquired substantial details about monitoring and diminishing atmospheric Al pollution in urban neighborhoods. This study concluded that Al could be accumulated significantly in all trees, and Al transfer between adjacent cells in the wood was restricted. According to this conclusion, all the species used in the study can be used as biomonitors to observe the Al pollution change throughout the years.

In conclusion, the Al accumulation potential of the species was at different levels, and the most elevated concentrations, especially in the woody part, were obtained in the *Cedrus atlantica*, Picea orientalis, and *Cupressus arizonica* species. Therefore, these species are the most proper species within selected species for phytoremediation studies. These species should be preferred, especially in landscape works in urban neighborhoods where air pollution is elevated. Among these species, *Cedrus atlantica* and *Cupressus arizonica*, which are especially slow-growing and therefore have a long biological life, can be especially recommended because they will trap Al in their trunks for many years and remove it from nature. However, due to the diversity and multifaceted nature of the subject, studies on this subject still need to be increased. It is recommended that studies on the topic be continued by diversifying and expanding.

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sample preparation, data analysis, and editing. Hatice Cobanoglu: sample preparation, data analysis, and editing. Semsettin Kulac: data analysis, writing, and editing. Kubra Key: sample preparation and editing. Hakan Sevik: supervision, reviewing and editing. All authors read and approved the final manuscript.

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

Declarations

Ethical Approval "Not applicable."

Consent to Participate "Not applicable."

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