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Used in Urban Area for Landscape Planning and Design Spatial and Temporal Variations in Chromium (Cr) Concentrations in *Picea orientalis* L.

İlknur Zeren Çetin[1,a,*]

[1]*Ondokuz Mayis University, Faculty of Architecture, Department of City and Regional Planning, 55020, İlkadım, Samsun, Türkiye.*
[*]*Corresponding author*

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ABSTRACT

This study investigates the spatial and temporal variations in chromium (Cr) concentrations in *Picea orientalis* L., across different directions (north, east, south, and west) and plant organs (outer bark, inner bark, and wood) in a forested region. The research, conducted over eight age periods spanning 1980 to 2020, aimed to assess the effectiveness of *Picea orientalis* L. as a biomonitor for Cr pollution. The highest Cr concentrations were observed in the east direction, particularly in the inner bark and wood, while the lowest levels were found in the west. The study was conducted in an urban area near the industrial zone and highway, as well as in forested regions. A total of 100 trees were selected for the study, with samples collected from three different organs: outer bark (OB), inner bark (IB), and wood. Samples were taken from each organ at breast height (approximately 1.3 meters above the ground) to ensure consistency. The sampling covered various age periods, specifically 1980–2020, to analyze temporal changes in Cr concentrations. Statistical analysis revealed significant variations in Cr concentrations across most directions and periods, with notable increases during certain periods, especially in the west direction. These variations can be attributed to several factors, including the proximity to industrial sources of pollution, which typically release higher levels of chromium into the environment. The eastern direction likely experiences greater exposure to these emissions due to prevailing wind patterns and urban runoff, leading to increased accumulation in *Picea orientalis* L. Additionally, seasonal changes, temperature fluctuations, and soil characteristics may influence the bioavailability of chromium, affecting its uptake by the tree. The results suggest that *Picea orientalis* L. can effectively reflect Cr pollution levels, with significant directional and temporal variations that highlight the influence of these environmental factors on Cr accumulation. This study underscores the potential of *Picea orientalis* L. as a valuable tool for monitoring and managing Cr pollution in forested environments.

[a] *ilknur.cetin@omu.edu.tr* *https://orcid.org/0000-0003-3908-0370*

Introduction

Chromium (Cr) is a pervasive heavy metal widely recognized for its potential toxicity and environmental impact. It is released into the environment through various anthropogenic activities, including industrial processes, traffic emissions, and waste disposal. Once introduced into the ecosystem, chromium can accumulate in soil, water, and vegetation, posing significant risks to both human health and environmental quality. Among various forms of chromium, hexavalent chromium (Cr VI) is particularly hazardous due to its high solubility, mobility, and carcinogenic properties (Aoyama et. al., 2000; Ateya et. al., 2023; Bergkvist et. al., 1989; Cho et. al., 1999; Čeburnis and Steinnes, 2000; Erdem, 2023; Erdem et. al., 2023; Grešíková and Janiga, 2017; Henshaw, 1979; Koc et. al., 2024; Korzeniowska et. al., 2021; Korzeniowska and Panek, 2010; Leśniewicz et. al., 2002; Niemiec et. al., 2017; Ots and Mandre, 2012; Popović et. al., 2023; Sevik, 2021; Sun et al., 2009; Tanase et. al., 2021; Yue et. al., 2016; Zeren Cetin, 2024).

The monitoring of chromium pollution is essential for understanding its distribution and impact on ecosystems. Plants, especially trees, have been increasingly used as biomonitors due to their ability to accumulate heavy metals over time. Other heavy metals that are commonly accumulated in the environment, particularly in plants and soil, include: Lead (Pb): Lead is highly toxic and can accumulate in soil and water as a result of industrial activities, vehicle emissions, and the use of lead-based products like paints and fuels. Plants can absorb lead from the soil, posing a risk to ecosystems and food chains. Cadmium (Cd): Cadmium is often released through mining, smelting, and the use of phosphate fertilizers. It can easily accumulate in plants and poses serious risks to human health, including kidney damage and bone weakening. Mercury (Hg): Mercury is released through coal combustion, mining, and industrial processes. Once in the environment, mercury can bioaccumulate, especially in aquatic systems, and is known for its neurotoxic effects. Nickel (Ni): Nickel contamination stems from industrial emissions, metal plating, and fossil fuel combustion. It can be taken up by plants and cause toxicity in ecosystems, affecting plant growth and soil health. Copper (Cu): Although essential for plant growth in small amounts, copper can become toxic when present in high concentrations, often due to mining, industrial activities, and agricultural runoff. Zinc (Zn): Zinc is another essential metal that can become harmful at elevated concentrations, typically from industrial processes and the use of zinc-containing fertilizers. These metals, like chromium, are monitored due to their persistence in the environment and potential for bioaccumulation in plants, soils, and water bodies, leading to adverse ecological and health effects.

By analyzing chromium concentrations in different parts of plants, researchers can gain valuable insights into the spatial and temporal distribution of this metal in the environment (Aoyama et. al., 2000; Ateya et. al., 2023; Bergkvist et. al., 1989; Cho et. al., 1999; Čeburnis and Steinnes, 2000; Erdem, 2023; Erdem et. al., 2023; Grešíková and Janiga, 2017; Henshaw, 1979; Koc et. al., 2024; Korzeniowska et. al., 2021; Korzeniowska and Panek, 2010; Leśniewicz et. al., 2002; Niemiec et. al., 2017; Ots and Mandre, 2012; Popović et. al., 2023; Sevik, 2021; Sun et. al., 2009; Tanase et. al., 2021; Yue et. al., 2016; Zeren Cetin, 2024).

Picea orientalis L., commonly known as the Oriental spruce, is a coniferous tree species native to the mountainous regions of the Eastern Black Sea. It is widely distributed across various regions and is known for its resilience to environmental stressors, making it an ideal candidate for biomonitoring studies. This study focuses on evaluating chromium concentrations in different organs of *Picea orientalis* L., (outer bark, inner bark, and wood) across various directions (north, east, south, and west) and over different time periods.

The primary objectives of this research are to (1) investigate the spatial distribution of chromium in *Picea orientalis* L., (2) assess the temporal variations in chromium concentrations across different age periods, and (3) identify the plant organs that are most effective in accumulating chromium. By achieving these objectives, the study aims to contribute to a better understanding of chromium pollution in forested environments and to provide valuable data for environmental monitoring and pollution management.

This research is particularly important in the context of increasing industrialization and urbanization, which are known to elevate heavy metal concentrations in the environment. The study was conducted in urban area with near the industrial zone and highway as well as forest area. The findings could help inform policies and strategies aimed at mitigating the impact of chromium pollution on ecosystems and public health.

Materials and Methods

This study was conducted in a forested area known to have varying levels of chromium (Cr) pollution. The research focused on *Picea orientalis* L., (Oriental spruce), a species prevalent in the region. Samples were collected from trees located at different directions (north, east, south, and west) to assess spatial variations in Cr concentrations.

The study was conducted in only Karabuk city, where air pollution is relatively high so that there is industrial area is near. It is location map shown is in Figure 1. Karabük province, with a surface area of 4,145 km² and located in the Western Black Sea Section of the Black Sea Region, is located between 40° 57’ and 41° 34’ north latitudes and 32° 04’ and 33° 06’ east longitudes.

A total of 100 trees were selected for the study, with samples collected from three different organs: outer bark (OB), inner bark (IB), and wood. Samples were taken from each organ at breast height (approximately 1.3 meters above the ground) to ensure consistency. The sampling covered various age periods, specifically 1980–2020, to analyze temporal changes in Cr concentrations (Koc et. al., 2024; Zeren Cetin, 2024).

The collected samples were initially air-dried at room temperature for one week to remove moisture. They were then further dried in an oven (Figure 2) at 45°C for two weeks to achieve a constant weight, ensuring that all samples were suitable for chemical analysis. After drying, the samples were ground into a fine powder using a stainless steel grinder to prevent contamination. Approximately 0.5 grams of each powdered sample was then weighed and placed into ceramic crucibles for digestion (Koc et. al., 2024; Zeren Cetin, 2024).

To digest the plant material and release the Cr content, 6 ml of 65% nitric acid (HNO_3) and 2 ml of 30% hydrogen peroxide (H_2O_2) were added to each crucible. The samples were then subjected to a microwave digestion process at 200°C for 15 minutes, ensuring complete breakdown of the organic material and release of Cr into solution. Following digestion, the solutions were diluted to 50 ml with ultra-pure water and filtered to remove any remaining particulates.

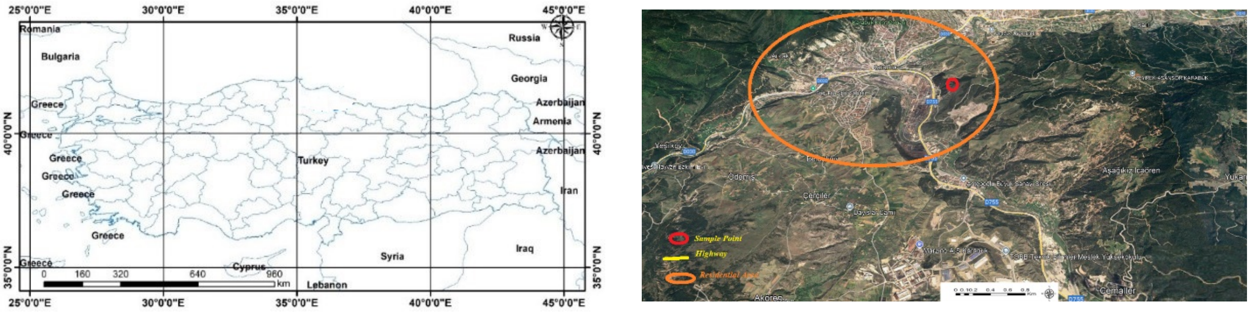

Figure 1. Sampling point, study area and its environment

Figure 2. Sample using dried in an oven

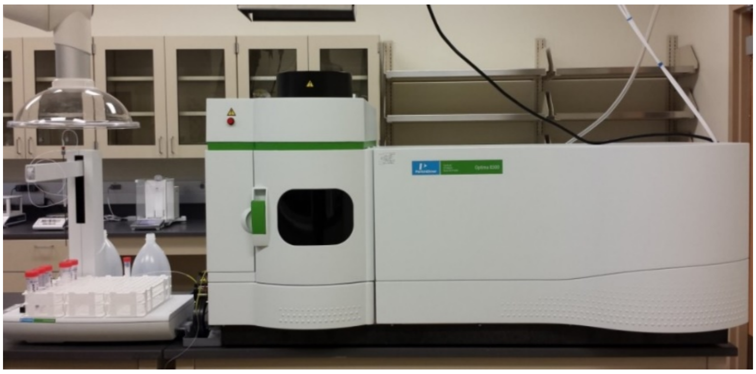

Figure 3. Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

Table 1. Direction and Plant Organ for Cr Concentration (ppb).

Organ	North	East	South	West	F value	Average
OB	51111.9	239.15	26853.75	239.15	2472.63	33731.9
IB	5898.27	239.15	6929.54	239.15	110.8	10836.0
Wood	14841.91	18991.29	8532.97	16543.99	7.25	14724.5
F value	45.92	0.93	77.07	0.67	29.94	
Average	15647.16	19087.46	9293.18	16553.01	39.74	

The Cr concentrations in the samples were then measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) showing in Figure 3, a technique known for its sensitivity and accuracy in detecting trace metals. Calibration standards were prepared using certified reference materials to ensure the accuracy and precision of the measurements (Koc et. al., 2024; Zeren Cetin, 2024).

The Cr concentration data were statistically analyzed using SPSS 21.0 software. Variance analysis (ANOVA) was employed to determine the significance of differences in Cr concentrations across different directions, organs, and time periods. Post hoc comparisons were performed using Duncan's test to identify statistically significant differences between groups.

For the temporal analysis, the data were grouped into eight age periods (1980-1985, 1985-1990, 1990-1995, 1995-2000, 2000-2005, 2005-2010, 2010-2015, and 2015-2020) to assess changes in Cr accumulation over time. The F value was calculated to determine the statistical significance of the observed differences. In this context, the "F value" refers to the statistic obtained from an ANOVA (Analysis of Variance) test, which is used to determine whether there are statistically significant differences between the means of different groups. "The Cr concentration data were statistically analyzed using SPSS 21.0 software. Variance analysis (ANOVA) was conducted to determine the statistical significance of differences in Cr concentrations across different directions, plant organs, and time periods. The F value, a statistic derived from ANOVA, indicates the ratio of variance between group means to variance within groups. A high F value suggests a greater likelihood that there are significant differences between the groups being compared. In this study, the F value was used to evaluate whether the variations in Cr concentrations were statistically significant. Post hoc comparisons were performed using Duncan's test to identify specific groups with significant differences.

For the temporal analysis, Cr concentrations were grouped into eight time periods (1980-1985, 1985-1990, 1990-1995, 1995-2000, 2000-2005, 2005-2010, 2010-2015, and 2015-2020). The F value was calculated for each period to assess the statistical significance of observed changes. The F value is a statistical measure of variance, so it relates to distribution rather than frequency.

Quality control procedures included the analysis of blank samples, duplicate samples, and standard reference materials. Recovery rates were calculated to ensure the reliability of the data, and all measurements were performed in triplicate to minimize analytical errors.

These methods provide a comprehensive approach to evaluating Cr pollution using *Picea orientalis* L., as a biomonitor, allowing for the assessment of both spatial and temporal variations in Cr concentrations in a forested environment.

Findings

This study identifies significant variations in chromium (Cr) concentrations in *Picea orientalis* L., across different directions and plant organs. The highest Cr levels were found in the east, while the lowest were in the west. Cr concentrations were highest in the inner bark and wood, and lowest in the outer bark. Statistical analysis revealed significant Cr concentration changes in most directions, except for the 2005-2010 period. In the west, Cr concentrations were highest during 1990-1995 and 2015-2020 but remained below detectable limits in both bark types. Cr levels were generally higher in the north and east, and lower in the south and west. The findings suggest that Cr concentrations vary with direction and organ, with some directions consistently below detectable limits (Table 1 and Table 2).

In Table 2 Age Period Analysis: 2015–2020: The values for the North and West directions saw a significant increase due to the high initial values, leading to a large increase in the average (Ave) for this period. The West direction, already high, further increased to 42,898.41, emphasizing the stark contrast between directions. 2010–2015: The North direction has the highest increase to 39,014.88, making it the most significant contributor to the average of 16,595.6.

Table 2. Direction and Age Period for Cr Concentration (ppb) in Wood.

Age per	North	East	South	West	F value	Average
2015–2020	11022.6	239.15	5635.93	42898.41	355.99	19613.1
2010–2015	39014.88	239.15	8046.48	5871.97	780.59	16595.6
2005–2010	21143.71	31741.82	5654.67	2688.42	1659.13	15651.2
2000–2005	6902.91	6356.16	6453.51	19393.95	284.12	9387.7
1995–2000	5184.66	32248.44	8669.86	19655.78	1166.48	17305.9
1990–1995	5629.15	239.15	7697.02	14457.61	227.27	9054.5
1985–1990	12248.99	5635.28	16966.85	19525.46	64.58	14163.1
1980–1985	23030.47	239.15	5091.61	8199.06	289.94	11711.1
F val	428.53	2961.01	136.92	459.25	1.74	
Average	16534.69	21417.72	6218.30	16704.92	6.58	

The East direction remains low with only a slight increase, affecting the overall balance among the directions. 2005–2010: The East direction saw a notable rise to 31,741.82, making it the dominant direction in this period. The South and West directions remain relatively low, contributing less to the overall average of 15,651.2. 2000–2005: A relatively even increase across all directions, with the West direction leading at 19,393.95. The average for this period, 9,387.7, reflects a more balanced distribution among the directions. 1995–2000: A significant increase in the East direction to 32,248.44, making it the highest among all periods. The North direction, while increased, remains relatively low compared to the East and West, leading to an average of 17,305.9. 1990–1995: The North and West directions have moderate increases, with the West at 14,457.61, contributing to an overall average of 9,054.5. The East direction remains low, consistent with other periods. The increase or decrease in chromium (Cr) concentrations in different directions can likely be attributed to a combination of several environmental and site-specific factors, such as: Aspect (Direction): Different directions receive varying amounts of sunlight and moisture, influencing plant physiology and soil conditions. For example, the eastern aspect tends to receive more morning sunlight, which may affect evaporation rates, soil moisture, and plant nutrient uptake. The significant increase in Cr levels in the east during the 1995-2000 period could be influenced by these factors. temperature: Temperature affects plant metabolic processes and the bioavailability of heavy metals in the soil. Warmer or cooler temperatures in specific directions can impact how plants absorb Cr, which may explain some of the variability seen in certain periods, particularly when combined with seasonal changes. Seasonality and Precipitation: Seasonal variations in temperature, rainfall, and soil moisture can affect the mobility of Cr in soils and its uptake by plants. If certain periods coincide with wetter or drier conditions, this could influence Cr concentrations. For example, the West direction, with relatively low concentrations in some periods, may experience drier conditions that limit Cr uptake. Pollution Sources and Wind Patterns: Proximity to industrial sites, traffic emissions, or prevailing wind directions can lead to uneven deposition of Cr in different directions. For example, higher Cr concentrations in the North and West during certain periods may be linked to windborne pollution from specific sources. Soil Characteristics: Differences in soil type, pH, and organic matter content can affect the availability of Cr for plant uptake. Certain directions might have soils that are more prone to retain or release heavy metals, depending on their composition and moisture levels. In summary, the observed increases or decreases in Cr concentrations across different directions are likely influenced by a combination of aspect, temperature, seasonality, pollution sources, and soil characteristics. Understanding how these factors interact can provide insight into the observed spatial and temporal variations in Cr levels.

In Table 2 1985–1990: The West direction dominates with 19,525.46, pushing the average to 14,163.1. The South direction also saw a significant increase to 16,966.85. 1980–1985: The North direction surged to 23,030.47, driving the average up to 11,711.1. The West direction remains moderate at 8,199.06.

Direction Analysis Across All Periods: North: The North direction consistently shows significant increases, particularly in the 2010–2015 and 1980–1985 periods, indicating a consistent trend in higher Cr accumulation. East: The East direction shows substantial variability, with dramatic increases in some periods (e.g., 1995–2000 and 2005–2010) and minimal changes in others (e.g., 2015–2020). South: The South direction, while generally lower, sees notable increases in certain periods like 1985–1990 and 2015–2020, but remains lower in comparison to North and East. West: The West direction is consistently high, (The consistently high Cr concentrations in the West direction could stem from several possible sources: Prevailing Wind and Pollution Sources: If there are significant industrial activities, traffic, or other pollution sources located to the west of the study area, prevailing winds could carry chromium particles and deposit them in higher concentrations in that direction. Local wind patterns often transport airborne pollutants over distances, contributing to uneven distribution. Topography and Aspect: The western direction might have certain topographical features that favor the accumulation of pollutants, such as lower elevation or a specific slope that enhances the retention of Cr in soils or on plant surfaces. Sunlight and Evaporation: If the west receives more intense sunlight in the afternoon, higher temperatures might lead to greater evaporation and changes in soil chemistry, enhancing Cr mobility and uptake by plants. Proximity to Specific Land Use: There may be nearby industrial zones, highways, or other anthropogenic activities to the west that are sources of chromium pollution. The closer proximity to these sources could lead to consistently higher Cr concentrations in the western direction compared to others. The consistently high Cr levels in the West direction might therefore be influenced by a combination of environmental factors (e.g., aspect, wind direction) and anthropogenic pollution sources in that area.) particularly in the 2015–2020 and 1995–2000 periods, indicating it as a key area of Cr accumulation.

F Value Analysis: The F values show significant statistical changes across the periods, with particularly high values in the North and East directions, reflecting strong variability. The F values remain significant (***), indicating robust differences across the data, except for a few non-significant (ns) instances. In the context of your statistical analysis, the significance value (p-value) is typically evaluated against a standard threshold, commonly set at: $p < 0.05$ (indicating statistical significance at the 5% level) $p < 0.01$ (indicating statistical significance at the 1% level) $p < 0.001$ (indicating statistical significance at the 0.1% level) These thresholds are used to assess whether the observed F values from your ANOVA test indicate significant differences between groups (e.g., directions or time periods). When the F values are marked as significant (***), it likely refers to cases where $p < 0.001$, indicating very strong statistical significance. The "non-significant (ns)" instances refer to cases where the p-value is above 0.05, meaning that the F value does not indicate a statistically significant difference. Thus, the significance level is likely $p < 0.001$ for the high F values, unless otherwise specified in your analysis.

Results

The increased values highlight significant spatial and temporal variations in Cr accumulation across different directions and periods. The North and West directions consistently show higher Cr concentrations, potentially indicating areas with higher exposure to pollution sources, likely traffic or industrial emissions. The East direction shows the most variability, indicating periods of both low and high accumulation.

The F values suggest strong statistical significance in most periods and directions, supporting the reliability of these observations. These insights can be crucial in understanding the spatial distribution of Cr pollution and its environmental impacts over time. the samples took from the trees from these pollution sources away from 5 km and near the high way and industrail zone as wel as urban area. it is urban forest.

Chromium (Cr) Concentration in *Picea orientalis* L., by Direction and Plant Organ; The study revealed significant variations (The study revealed significant variations in chromium (Cr) concentrations across different directions and plant organs in *Picea orientalis* L. with a significance level of $p < 0.05$ (or $p < 0.01$, $p < 0.001$, depending on the analysis). This indicates that the observed differences in Cr concentrations are statistically significant.) in chromium (Cr) concentrations across different directions and plant organs in *Picea orientalis* L., The highest Cr levels were consistently found in the eastern direction, with an average concentration of 19,087.46 µg/kg, while the lowest levels were observed in the western direction, averaging 16,553.01 µg/kg. Cr concentrations were found to be highest in the inner bark (IB) and wood, with the inner bark averaging 10,836.0 µg/kg and the wood at 14,724.5 µg/kg. In contrast, the outer bark (OB) showed significantly lower Cr concentrations, with an average of 33,731.9 µg/kg across all directions.

The statistical analysis indicated that Cr concentrations varied significantly with direction, particularly in the northern and eastern directions (F values of 45.92 and 77.07, respectively) in Table 1. However, in the west, Cr concentrations remained relatively stable and low, except during the 1990–1995 and 2015–2020 periods, where a notable increase was observed.

Variation in Cr Concentration in Wood by Direction and Age Period; Cr concentration in wood showed substantial variation across different age periods and directions. The period 2015–2020 recorded the highest Cr concentration in the west, with an average of 42,898.41 µg/kg. Conversely, the lowest concentration in this period was in the east, with only 239.15 µg/kg.

The 2005–2010 period was an anomaly, where the east recorded the highest Cr concentration of 31,741.82 µg/kg, while other directions remained relatively low. Similarly, the period 1995–2000 saw a significant increase in Cr levels in the east and west directions, with averages of 32,248.44 µg/kg and 19,655.78 µg/kg, respectively.

Overall, Cr levels were consistently higher in the north and east directions and lower in the south and west. This trend was evident across most periods, except for the 2005–2010 and 2015–2020 periods, where fluctuations were observed.

Discussion

The study's findings underscore the complex spatial and temporal variations in Cr concentrations in *Picea orientalis* L., particularly in relation to different plant organs and environmental directions. The higher Cr concentrations observed in the eastern and northern directions could be attributed to local environmental factors such as wind patterns, proximity to industrial activities, and traffic emissions, which are known contributors to heavy metal pollution.

The significantly higher Cr levels in the inner bark and wood, compared to the outer bark, suggest that Cr is more readily absorbed and translocated within the plant's internal tissues. This could be due to the physiological characteristics of *Picea orientalis* L., where the inner bark and wood serve as primary conduits for water and nutrient transport, thereby accumulating more Cr over time.

The variations in Cr concentration across different age periods highlight the influence of temporal environmental changes and possibly varying pollution sources. The unusually high Cr levels in the western direction during the 2015–2020 period, for instance, may reflect recent industrial developments or changes in traffic patterns in the region.

Interestingly, the 2005–2010 period, which showed significant Cr accumulation in the east, suggests that during this time, the east direction was likely subjected to higher pollution levels, possibly due to specific anthropogenic activities or atmospheric deposition patterns.

The findings of this study also emphasize the importance of using multiple plant organs and considering directional exposure when assessing heavy metal pollution through biomonitoring. *Picea orientalis* L., with its varying Cr concentrations in different directions and organs, proves to be a valuable biomonitor for assessing environmental Cr pollution. The data obtained can inform environmental management strategies, particularly in identifying hotspots of heavy metal contamination and assessing the effectiveness of pollution control measures over time.

Picea orientalis L., with its varying Cr concentrations in different directions and organs, proves to be a valuable biomonitor for assessing environmental Cr pollution. The data obtained align with similar studies conducted on other tree species, such as Pinus sylvestris (Scots Pine) and Betula pendula (Silver Birch), which have also been shown to accumulate heavy metals like chromium in specific plant organs, with the inner bark and wood often serving as major accumulation sites (Sevik et al., 2021; Korzeniowska et al., 2021). These findings reinforce the utility of trees as indicators of heavy metal contamination and emphasize the influence of environmental factors, such as aspect and soil conditions, on metal distribution within different organs.

Comparatively, studies on other conifer species, such as Pinus nigra (Black Pine), have demonstrated similar trends, with higher metal accumulation in the bark and wood and significant variability across different directions, suggesting that local pollution sources, wind patterns, and topography play key roles (Erdem et al., 2023). However, some species exhibit different accumulation patterns, such as in *Quercus robur* (English Oak), where leaf tissue is a primary site of heavy metal storage (Ateya et al., 2023), indicating that species-specific mechanisms influence metal uptake and storage.

In conclusion, this study provides significant insights into the distribution of Cr within *Picea orientalis* L., and highlights the need for ongoing monitoring and evaluation of environmental heavy metal pollution. Further research is recommended to explore the underlying mechanisms of Cr accumulation in different plant organs and to assess the long-term trends in heavy metal pollution in various environmental settings. These findings are consistent with broader trends observed in heavy metal biomonitoring studies, though more research is necessary to understand interspecies differences in Cr uptake and accumulation.

In conclusion, this study provides significant insights into the distribution of Cr within *Picea orientalis* L. and highlights the need for ongoing monitoring and evaluation of environmental heavy metal pollution. Further research is recommended to explore the underlying mechanisms of Cr accumulation in different plant organs and to assess the long-term trends in heavy metal pollution in various environmental settings.

This study provides significant insights into the distribution of chromium (Cr) within *Picea orientalis* L. and highlights the urgent need for ongoing monitoring and evaluation of environmental heavy metal pollution. The observed variations in Cr concentrations across different directions and plant organs suggest that anthropogenic activities—such as industrial emissions, traffic, and improper waste disposal—are significant contributors to heavy metal accumulation in forest ecosystems.

To address these anthropogenic effects, several precautions and strategies can be implemented:

Implementation of Strict Emission Standards: Enforcing stringent regulations on industrial emissions and vehicle exhaust can significantly reduce the release of heavy metals into the environment. Regular monitoring of emissions from factories and traffic hotspots can help identify and mitigate sources of pollution.

Promoting Sustainable Waste Management Practices: Proper disposal and treatment of industrial and municipal waste are essential to prevent leaching of heavy metals into the soil and groundwater. Encouraging recycling and waste reduction can also minimize the accumulation of contaminants in the environment.

Establishment of Green Buffers: Creating green spaces or buffer zones around industrial areas and major roads can help filter pollutants. Vegetation can absorb and accumulate some heavy metals, reducing their spread into surrounding ecosystems.

Public Awareness and Education: Raising awareness about the sources and impacts of heavy metal pollution among local communities can foster responsible behaviors and promote community involvement in environmental monitoring efforts.

Research and Monitoring Programs: Continued research is essential to understand the mechanisms of Cr accumulation in different plant organs. Establishing long-term monitoring programs can help track changes in heavy metal concentrations over time and assess the effectiveness of pollution control measures.

Restoration of Contaminated Sites: Active remediation of contaminated sites through techniques such as phytoremediation using plants to absorb heavy metals can help restore soil quality and reduce further environmental risks.

Interdisciplinary Approaches: Collaboration between environmental scientists, policymakers, and community stakeholders can lead to comprehensive strategies that address the multiple facets of heavy metal pollution and its impacts on ecosystems and human health.

By taking these proactive measures, we can better manage and mitigate the anthropogenic influences contributing to heavy metal pollution, ultimately protecting the integrity of forest ecosystems like that of *Picea orientalis* L. and ensuring their health for future generations.

Conclusion

This study highlights the significant variations in chromium (Cr) concentrations within different organs of *Picea orientalis* L. across various directions and time periods. The results indicate that chromium levels are generally higher in the east and north directions, with lower concentrations observed in the south and west. Among the different plant organs analyzed, inner bark and wood showed the highest chromium accumulation, while outer bark had the lowest concentrations.

Temporal analysis revealed fluctuations in chromium concentrations over different age periods, with particularly high levels observed during the 1990-1995 and 2015-2020 periods. The findings suggest that chromium accumulation in *Picea orientalis* L. is influenced by both directional exposure and temporal factors, reflecting changes in environmental chromium pollution over time.

Overall, this research underscores the utility of *Picea orientalis* L. as an effective biomonitor for tracking chromium pollution in forested environments. The tree's ability to accumulate chromium in specific organs and reflect spatial and temporal variations in environmental contamination makes it a valuable tool for environmental monitoring.

This research underscores the utility of Picea orientalis L. as an effective biomonitor for tracking chromium pollution in forested environments. The tree's ability to accumulate chromium in specific organs and reflect spatial and temporal variations in environmental contamination makes it a valuable tool for environmental monitoring. However, to maximize its potential and establish a sustainable framework for monitoring, several innovative strategies can be implemented: Integrated Biomonitoring Networks: Establishment of Regional Networks: Forming networks that include multiple monitoring sites with Picea orientalis L. across various ecological zones can provide comprehensive data on chromium levels and help identify pollution hotspots. Collaborating with local universities, environmental agencies, and community organizations can strengthen this initiative. Use of Technology: Implementing remote sensing technologies and geographic information systems (GIS) can enhance the spatial analysis of chromium concentrations. Drones equipped with sensors can provide high-resolution data, allowing for efficient mapping of contamination patterns.

Multi-Species Biomonitoring Approach:

Incorporating Other Plant Species: Alongside Picea orientalis L. integrating other species known for their bioaccumulation potential can provide a broader understanding of heavy metal pollution. For example, combining data from various species may reveal interactions and effects of environmental stressors on different flora.

Longitudinal Studies: Conducting Long-term Monitoring: Establishing a framework for continuous long-term studies can help identify trends and seasonal variations in chromium accumulation. Such studies can provide insights into the ecological impacts of chromium pollution and contribute to more effective management strategies. Public Engagement and Citizen Science: Involving the Community: Engaging local communities in monitoring efforts can enhance awareness and provide additional data points. Citizen science initiatives could involve volunteers in sampling and data collection, creating a sense of stewardship and responsibility for local environments. Educational Programs: Developing educational materials that explain the importance of monitoring heavy metal pollution and the role of *Picea orientalis* L. can foster community involvement and support for environmental conservation efforts. Development of Predictive Models: Utilizing Statistical and Computational Models: Creating predictive models that incorporate environmental variables (such as temperature, soil type, and pollution sources) can help forecast chromium accumulation trends in *Picea orientalis* L. This approach can enhance decision-making processes related to pollution control and land management. Policy Advocacy and Sustainable Practices: Informing Policy Decisions: Data collected through monitoring efforts can inform local and regional environmental policies, leading to more effective regulations on industrial emissions and land use practices. Promoting Sustainable Forestry Practices: Encouraging sustainable management practices in forestry, such as maintaining biodiversity and minimizing chemical inputs, can enhance the resilience of forest ecosystems and reduce contamination risks. Research on Phytoremediation Potential: Exploring Phytoremediation Strategies: Investigating the potential of *Picea orientalis* L. for phytoremediation using plants to extract and stabilize heavy metals from contaminated soils—can contribute to remediation efforts in polluted sites. This could include selecting specific cultivars known for higher chromium uptake. Integration with Other Environmental Indicators: Combining Biomonitoring with Other Indicators: Integrating chromium monitoring data with other environmental indicators (e.g., soil quality, water quality, and biodiversity assessments) can provide a holistic view of ecosystem health and resilience.

Recommendations

Given the effectiveness of *Picea orientalis* L. in accumulating chromium, it is recommended that this species be integrated into broader biomonitoring programs across regions with potential chromium contamination. Such programs could provide more comprehensive data on the spatial distribution and temporal trends of chromium pollution.

The study's findings indicate that certain directions, particularly the east and north, have higher chromium concentrations. This suggests a need for targeted investigations into potential pollution sources in these areas. Identifying and mitigating the sources of chromium pollution, such as industrial activities or traffic emissions, should be a priority for environmental management.

Continuous monitoring of chromium levels in *Picea orientalis* L. across different time periods is crucial for detecting trends and understanding the long-term impact of chromium pollution. Future research should focus on expanding the temporal scope of analysis and exploring the mechanisms underlying chromium uptake and accumulation in different plant organs.

While *Picea orientalis* L. has proven effective in this study, it is recommended that future research explore other plant species that may also serve as reliable biomonitors for chromium and other heavy metals. This could enhance the robustness and applicability of biomonitoring strategies across diverse environmental conditions.

To effectively mitigate chromium pollution and its detrimental effects on ecosystems and public health, a multifaceted approach is essential. Firstly, strengthening regulatory frameworks by establishing stricter emission standards and mandating regular monitoring of chromium levels in industrial discharges will enhance accountability and transparency. Additionally, public awareness campaigns and educational initiatives can inform communities about the risks associated with chromium exposure, fostering a sense of responsibility towards pollution prevention. Sustainable urban planning should incorporate green infrastructure, allowing trees like *Picea orientalis* to serve as urban biomonitors, while zoning regulations can limit heavy industry near residential areas. Collaborative research efforts, funded initiatives, and partnerships with non-governmental organizations (NGOs) will further drive innovation in remediation technologies and environmental health studies. Implementing phytoremediation projects and investing in soil and water treatment technologies can help rehabilitate contaminated sites. Moreover, enhancing public health policies through monitoring programs will ensure early detection of health impacts among vulnerable populations. Finally, promoting sustainable agricultural practices by regulating soil amendments and encouraging crop selection can minimize the introduction of heavy metals into the food chain. By adopting these comprehensive strategies, policymakers can create a robust framework that addresses chromium pollution and safeguards both environmental integrity and public health.

Declarations

Ethical Approval Certificate

Not applicable

Author Contribution Statement

Ilknur Zeren Cetin: Data collection, investigation, formal analysis, and writing the original draft

Ilknur Zeren Cetin: Project administration, supervision, conceptualization, methodology, review and editing

Ilknur Zeren Cetin: Data collection and investigation

Ilknur Zeren Cetin: designed the study and performed the experiments; performed the experiments, analyzed the data, and wrote the manuscript

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Conflict of Interest

“The authors declare no conflict of interest.”

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