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RESEARCH ARTICLE

Assessment of urban ecological conditions using heavy metal accumulation in the leaves of *Paulownia* and *Acer*

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Abstract

Amid intensified urbanisation and industrial expansion, heavy metal (HM) contamination has become a critical challenge for urban ecosystems. Toxic elements such as lead (Pb), cadmium (Cd), iron (Fe), copper (Cu), arsenic (As) and chromium (Cr) threaten both public health and environmental stability. This study evaluates the bioaccumulation capacity of two widespread urban tree species-*Paulownia* and *Acer*-within different districts of Osh city. Leaf samples were collected across multiple seasons and HM concentrations were quantified using inductively coupled plasma optical emission spectrometry (ICP-OES). The findings demonstrate pronounced spatial and seasonal variability, with the highest metal levels recorded in districts under strong anthropogenic pressure. *Paulownia* consistently accumulated more Fe and Cu than *Acer*, particularly during autumn, when atmospheric deposition intensifies. These results highlight the suitability of *Paulownia* not only as an effective bioindicator but also as a promising species for phytoremediation. These findings demonstrate the strong influence of urban structure, seasonality and species-specific traits on patterns of metal accumulation. Overall, the results highlight the value of *Paulownia* as a sensitive bioindicator and a promising species for phytoremediation, providing practical insight for urban ecosystem health assessment and evidence-based planning of sustainable green infrastructure in rapidly developing cities.

Keywords: *Acer*; heavy metals; landscaping; Osh city; *Paulownia*; phytoremediation

Introduction

Urban green plantings play an important role in improving environmental quality by acting as natural biofilters that reduce the concentration of airborne pollutants. However, prolonged exposure to urban pollution can adversely affect vegetation, including reduced photosynthetic activity, impaired growth, cellular damage and accumulation of toxic metals in leaf tissues. This problem has become increasingly relevant as rapid urbanisation is accompanied by elevated concentrations of heavy metals (HMs) in urban air and soils (1).

Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), copper (Cu), iron (Fe) and arsenic (As) are of particular concern due to their high toxicity, persistence and ability to accumulate in plant tissues. Their accumulation can induce physiological stress, inhibit plant growth and negatively affect ecosystem stability and human health. Therefore, regular environmental monitoring based on reliable bioindicators is essential for assessing urban pollution levels.

Leaves of woody plants are especially suitable for biomonitoring purposes because of their large surface area and structural characteristics, which facilitate the interception and retention of atmospheric aerosols and metal-containing particles (2). Numerous studies have demonstrated that tree species differ significantly in their capacity to accumulate HMs, depending on their morphological and physiological traits (3, 4). Consequently, species selection is a critical factor in both environmental monitoring and urban greening strategies.

The city of Osh, located in the southern part of the Kyrgyz Republic, is characterised by intensive urban development, increasing traffic loads and diverse anthropogenic pressures. Urban green spaces in Osh are widely represented by various tree species, among which *Paulownia* and *Acer* are commonly used due to their adaptability and ecological functions. Previous studies suggest that these species differ in their tolerance to pollution and their capacity to accumulate metals, making them suitable candidates for comparative biomonitoring assessments.

The aim of this study was to evaluate spatial and seasonal patterns of HM accumulation in the leaves of *Paulownia* and *Acer* across different urban districts of Osh City and to assess their suitability as bioindicators of urban ecological conditions. The results of this research provide a scientific basis for improving urban environmental monitoring and supporting sustainable greening practices in rapidly developing cities.

Materials and Methods

Sampling and collection

Leaf samples were collected from four representative locations within the city of Osh: the Torobay Kulatov District, the Manas District, the South-Eastern District and the Botanical Garden. These sites were selected to reflect urban areas with different functional characteristics and levels of anthropogenic impact, including residential zones, areas influenced by traffic emissions and relatively low-disturbance green spaces.

Sampling was carried out during three seasons (May, September and November) in order to account for seasonal variability related to plant phenology and environmental conditions. At each site, leaf samples were collected from five mature and visually healthy trees of the studied species during each season. Leaves collected from individual trees were treated as independent biological replicates. Sampling was conducted using a standardised protocol to ensure consistency and comparability among sites and seasons.

Sample preparation

The samples were dried in a drying oven (VWR DRY-line, Germany) at constant temperature for approximately 24–48 hr, or until a constant weight was reached, to ensure complete removal of residual moisture. A 200 mg portion of the dried sample was weighed using an analytical balance (FA220 4N).

Mineralisation

A 200 mg portion of the sample was placed in a mineralisation tube, to which 6 mL of purified nitric acid (HNO_3) and 2 mL of hydrogen peroxide (H_2O_2) were added. The digestion was carried out using a MILESTONE Ethos Easy (Italy) microwave digestion system, in which the mixture was heated to 180 °C for 20 min to ensure complete conversion to a clear solution. After digestion, the resulting solution was transferred into a volumetric flask and diluted with distilled water to a final volume of 25 mL.

Transfer and preparation for analysis

The resulting solution was placed into special tubes in the automatic sampling unit for spectrometric analysis (2).

Inductively Coupled Plasma Optical Emission Spectrometry analysis

The analyses were performed using an Avio 200 ICP–OES spectrometer (Perkin Elmer, USA), which provides high precision and the ability to detect elements at concentrations as low as 10^{-9} g. Samples were analysed to determine the concentrations of key target elements, including HMs such as Pb, Cd, Cr, As, Cu and Fe (2).

Results

Table 1 shows the average levels of key HMs-including Fe, Cu and Pb-in *Paulownia* and *Acer* leaves, grouped by season and sampling location. Seasonal changes have shown that *Paulownia*, as a rule, accumulates higher levels of Fe and Cu than *Acer* and this difference is especially evident in the Manas microdistrict, the area with the greatest anthropogenic load.

For example, in the spring in T. Kulatova microdistrict, the Cu concentration in *Paulownia* was 0.243 mg/ 10 g, while in *Acer* it was almost twice as low - 0.106 mg/10 g. By September, in the same area, the Fe level in *Paulownia* reached a peak of 11.79 mg/10 g, significantly exceeding that of *Acer* (3.93 mg/10 g).

T. Kulatova district

In the spring (May), the leaves of *Paulownia* and *Acer* exhibited relatively low concentrations of the analysed elements. For instance, in *Acer*, the Cu concentration was 0.1055 mg/ 10 g, whereas in *Paulownia* it was notably higher - 0.2426 mg/ 10 g. By September, a substantial increase in Fe concentration was recorded in *Paulownia* leaves, reaching 11.786 mg/ 10 g, which significantly exceeded the corresponding values in *Acer* (3.928 mg/ 10 g). Lead concentrations also rose during this period, reaching 0.028 mg/ 10 g in *Acer* and 0.023 mg/ 10 g in *Paulownia* (Fig. 1).

Thus, in the T. Kulatova district, *Paulownia* shows a greater capacity to accumulate Fe and Cu, suggesting its potential as a bioindicator of environmental contamination.

Manas district

In this area, the element concentrations were the highest among all studied urban zones. In May, the leaves of *Paulownia* contained 0.6335 mg/ 10 g of Cu, which was substantially higher than in *Acer*. By September, the peak Fe concentration was recorded in *Paulownia* leaves - 16.786 mg/ 10 g, while in *Acer* the Fe level reached only 2.088 mg/ 10 g. In November, a general decline in element concentrations was observed; however, *Acer* leaves maintained a comparatively elevated Pb level (0.0615 mg/ 10 g), indicating the presence of localised sources of Pb pollution (Fig. 2).

In general, the Manas district can be described as the area most affected by anthropogenic impact, with a predominance of HMs in the analysed plant material.

South-East district

In spring, *Paulownia* accumulated a comparatively high level of Cu (0.2910 mg/ 10 g). However, by September the situation had changed: in *Acer*, the concentration of Fe reached 10.456 mg/ 10 g, exceeding the corresponding value in *Paulownia* (7.186 mg/ 10 g). By November, *Paulownia* again showed higher Fe levels (10.590 mg/ 10 g) than *Acer* (2.604 mg/ 10 g). The increase in Pb concentration observed in November (0.036 mg/ 10 g in *Paulownia* and 0.024 mg/ 10 g in *Acer*) indicates the influence of atmospheric aerosols and vehicular emissions. Thus, this district is characterised by seasonal variability, with alternating dominance of the two species in terms of metal accumulation (Fig. 3).

Botanical Garden of Osh State University

In this conditionally clean area-used as a baseline reference site characterised by minimal anthropogenic influence-the spring measurements showed the lowest element concentrations. For example, the Cu content in *Paulownia* leaves amounted to 0.1183 mg/ 10 g. By September, however, the concentrations increased: Fe

Table 1. Average levels of heavy metals in *Paulownia* and *Acer* leaves

May (2024)											
Name of plants	**As (mg/ 10 g)**	**Fe (mg/ 10 g)**	**Sn (mg/ 10 g)**	**Cr (mg/ 10 g)**	**Te (mg/ 10 g)**	**Sb (mg/ 10 g)**	**Pb (mg/ 10 g)**	**Ag (mg/ 10 g)**	**Hg (mg/ 10 g)**	**Cd (mg/ 10 g)**	**Cu (mg/ 10 g)**
Acer (Mr. Kulatova)	0,032	0	0	0,02	0	0	0	0	0	0	0,1055
Acer (Mr. Manasa)	0,028			0,0231							0,1618
Paulownia (Mr. Kulatova)	0,014			0,0219							0,2426
Paulownia (Mr. the South-East)				0,0171							0,2910
Paulownia (Mr. Manasa)	0,018			0,0415							0,6335
Paulownia (Botanical Garden)	0,004			0,0195							0,1183
September (2024)											
Name of plants	**As (mg/ 10 g)**	**Fe (mg/ 10 g)**	**Sn (mg/ 10 g)**	**Cr (mg/ 10 g)**	**Te (mg/ 10 g)**	**Sb (mg/ 10 g)**	**Pb (mg/ 10 g)**	**Ag (mg/ 10 g)**	**Hg (mg/ 10 g)**	**Cd (mg/ 10 g)**	**Cu (mg/ 10 g)**
Acer (Botanical Garden)	0,008	2,598	0	0,0241	0	0	0,015	0	0	0,006	0,117
Paulownia (Botanical Garden)	0,010	6,975	0	0,0341	0	0	0,034	0	0	0,002	0,300
Paulownia (Mr. Kulatova)	0,011	11,786	0	0,0423	0	0	0,023	0	0	0,001	0,480
Acer (Mr. Kulatova)	0,011	3,928	0	0,0236	0	0	0,028	0	0	0	0,201
Acer (Mr. of the South-East)	0,008	10,456	0	0,0412	0	0	0,013	0	0	0,002	0,095
Paulownia (Mr. of the South-East)	0,012	7,186	0	0,0317	0	0	0,031	0	0	0,002	0,153
Acer (Mr. Manasa)	0,008	2,088	0	0,0271	0	0	0,010	0	0	0	0,226
Paulownia (Mr. Manasa)	0,009	16,786	0	0,0634	0	0	0,008	0	0	0,001	0,465
November (2024)											
Name of plants	**As (mg/ 10 g)**	**Fe (mg/ 10 g)**	**Sn (mg 10 g)**	**Cr (mg 10 g)**	**Te (mg 10 g)**	**Sb (mg 10 g)**	**Pb (mg 10 g)**	**Ag (mg 10 g)**	**Hg (mg 10 g)**	**Cd (mg 10 g)**	**Cu (mg 10 g)**
Paulownia (Mr. of the South-East)	0,010	10,590	0	0,0368	0	0	0,036	0	0	0,002	0,174
Acer (Mr. of the South-East))	0,011	2,604	0	0,0247	0	0	0,024	0	0	0	0,107

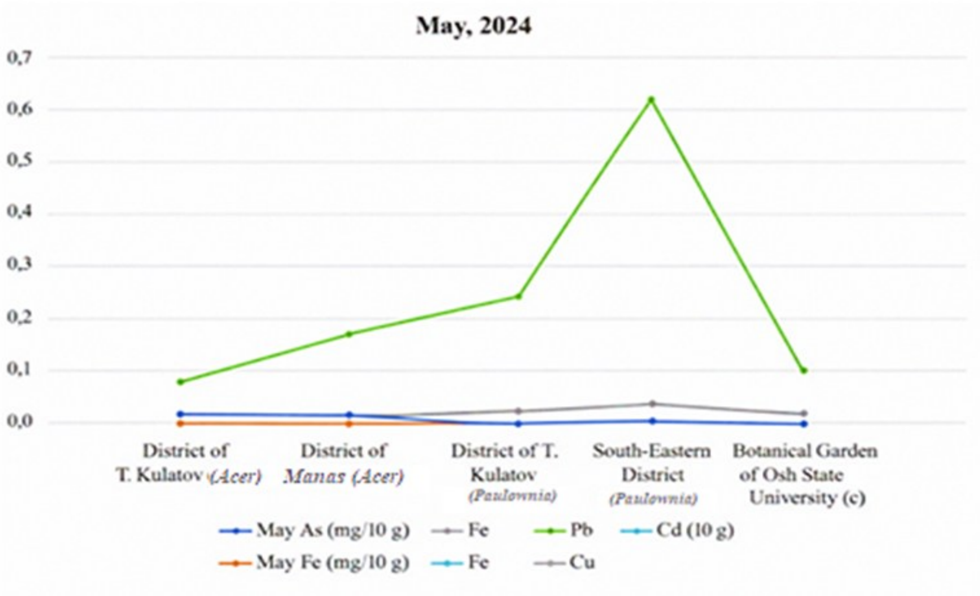

Fig. 1. Metal concentration in samples of *Paulownia* and *Acer* leaf samples for May 2024 by residential districts of Osh city.

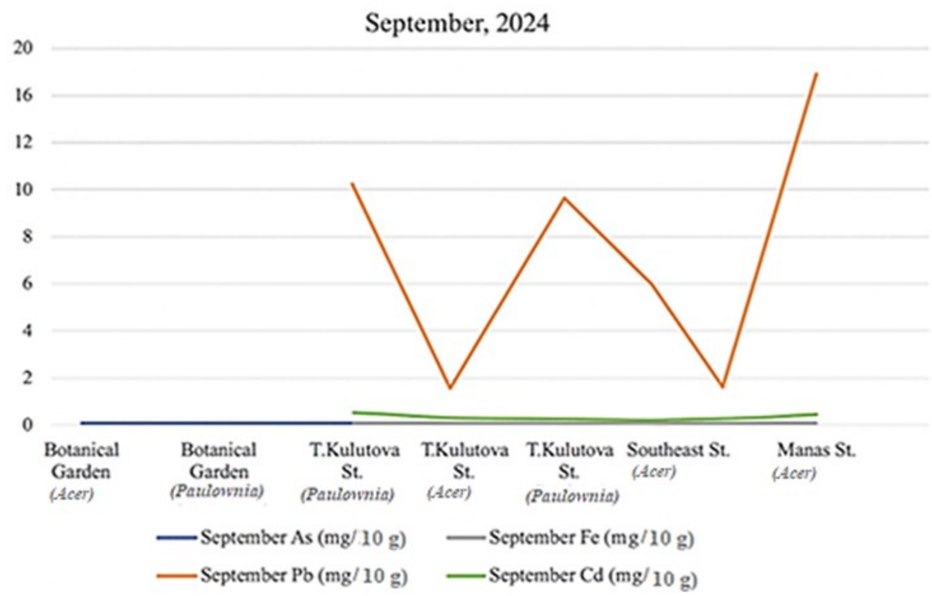

Fig. 2. Metal concentration in *Paulownia* and *Acer* leaf samples for September 2024 in the districts of Osh city.

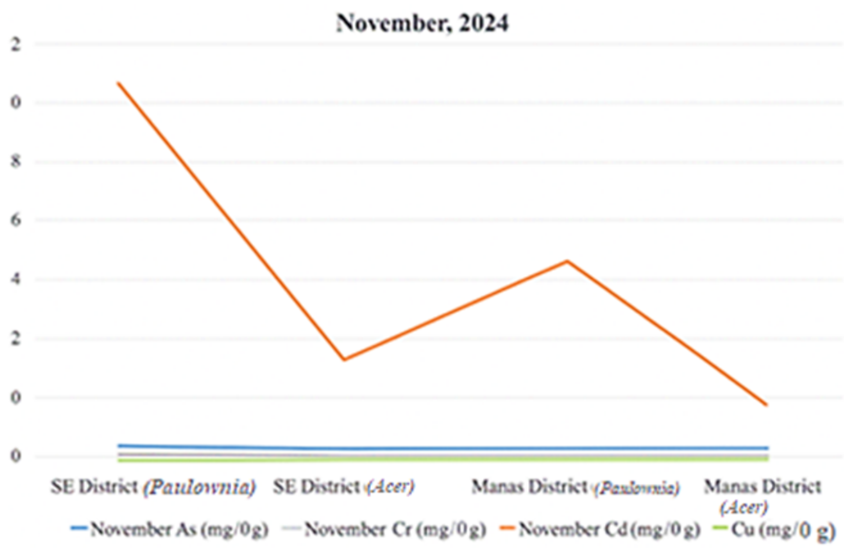

Fig. 3. Metal concentration in samples of *Paulownia* and *Acer* leaf samples for November 2024 by residential districts of Osh city.

levels in *Paulownia* reached 6.975 mg/ 10 g, while in *Acer* they were 2.598 mg/ 10 g. The observed rise in Pb concentration in *Paulownia* (0.034 mg/ 10 g) indicates that even remote green zones with low background pollution are still affected by broader urban environmental impacts.

Influence of meteorological conditions

To better understand how trees accumulate HMs, it is essential to consider weather factors. Temperature, precipitation and sunlight intensity affect plant physiological activity, water evaporation and the degree to which atmospheric aerosols adhere to leaf surfaces. These factors influence the accumulation of toxic elements in plant tissues.

The study analysed meteorological data for the city of Osh over the past 10 years, with special attention to 2024, the year the leaf samples were collected. This analysis revealed seasonal and annual variations, including changes in the number of sunny, cloudy and rainy days - critical parameters for interpreting the dynamics of HM accumulation in vegetation.

Weather conditions

Fig. 4 shows that the number of sunny days per month generally ranged between 30 to 32, although in 2022 this value temporarily declined to approximately 28 before returning to previous levels in the following years. The average number of cloudy days is 14–16, with minor fluctuations. In 2023, there were fewer-about 12-but in 2024, the number rose again to 16. Rainy days are few, ranging from 3 to 5 per year. In 2024, their number increased slightly to about 5. Thus, the weather in Osh is characterised by mostly sunny days, moderate cloudiness and rare rainfall.

The second chart shows a steady upward trend: the average daytime temperature varies annually between 14 and 17 °C. From 2015 to 2024, the temperature gradually increased, especially after 2020, reaching a peak of about 17 °C in 2023. The average nighttime temperature rose even more noticeably-from 10 °C in 2015 to nearly 10.5 °C in 2024. This increase was smoother but consistent.

In the Osh region, there is a clear tendency toward warming, particularly at night. The climate of Osh city over 2015–2024 can be described as follows: mostly clear days, little precipitation, a gradual increase in average temperatures-especially nighttime ones-indicating a shift in climatic conditions toward warming.

Weather characteristics of Osh City

In 2024, clear days increased to approximately 31, confirming the stability of the region's sunny climate, while the number of cloudy days rose to around 16, indicating greater weather variability compared to previous years. Cloudy days were more frequent than in previous years-around 16, indicating increased variability in cloud cover and precipitation patterns compared to 2023. Precipitation also increased to about 5 days, one of the highest values of the decade. The average daytime temperature was about 16 °C, remaining high but slightly lower than in 2023. The average nighttime temperature showed the most significant change, reaching around 10.5 °C, the highest value for the entire observation period (Fig. 5).

The year 2024 was characterised by a high proportion of clear days, increased cloudiness and precipitation and a noticeable rise in nighttime temperatures, suggesting further changes in the climatic regime of the Osh region. The total annual rainfall in 2024 was 676.3 mm and the average annual wind speed was 2 m/s.

Discussion

The comparative analysis of HM accumulation in *Paulownia* and *Acer* leaves across different urban districts of Osh revealed pronounced spatial and seasonal variability driven by both anthropogenic pressure and climatic conditions. Similar spatial patterns of metal enrichment in urban vegetation have been reported in previous biomonitoring studies, where areas with intensive traffic and industrial activity exhibit elevated levels of atmospheric pollutants (3–5). In the present study, the highest concentrations of HMs were consistently recorded in the Manas district, reflecting the strong influence of transport emissions and industrial sources.

Seasonal dynamics indicated that *Paulownia* tended to accumulate higher concentrations of Cu and Fe during spring and autumn, whereas *Acer* showed a more localised increase in Fe, primarily in early autumn. These differences highlight species-specific physiological responses to environmental conditions and temporal variation in atmospheric deposition. The detection of increased metal concentrations even in relatively low-impact areas, such as the Botanical Garden, suggests that airborne pollutants can disperse over considerable distances and affect less urbanised zones.

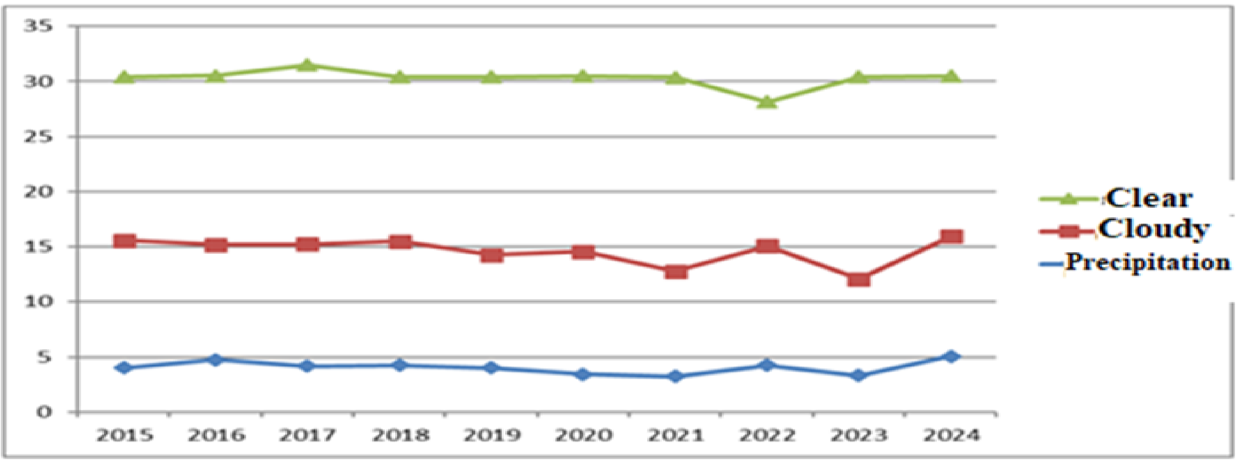

Fig. 4. Average annual number of clear, cloudy days and precipitation (2015-2024).

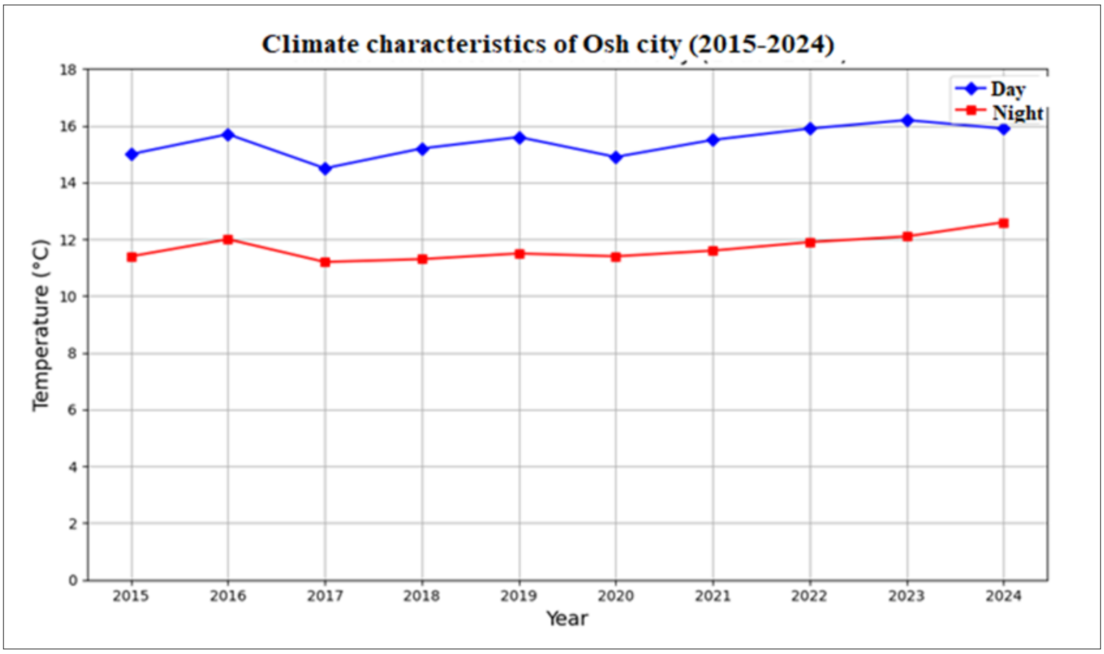

Fig. 5. Climate characteristics of Osh City (2015–2024).

Across all studied districts, *Paulownia* consistently demonstrated a higher capacity to accumulate Fe and Cu than *Acer.* This enhanced accumulation ability can be explained by several physiological and morphological traits characteristic of *Paulownia*. The species is known for its large leaf surface area, high stomatal density and elevated transpiration rates, which collectively promote efficient interception, absorption and internal transport of airborne contaminants. In addition, rapid biomass production and a well-developed vascular system facilitate the translocation and retention of absorbed metals within leaf tissues, as reported in earlier studies (6).

Climatic conditions during the 2024 growing season further support these findings. The predominance of clear days combined with relatively high nighttime temperatures (~10.5 °C) likely maintained sustained physiological activity, reduced respiratory stress and supported continuous transpiration-driven ion transport. Increased cloudiness and precipitation compared to previous years may have additionally influenced metal accumulation by enhancing wet deposition on leaf surfaces and modifying stomatal conductance (7). Since temperature and moisture regulate gas exchange processes, they indirectly affect both metal uptake efficiency and internal redistribution within plant tissues.

Spatial differentiation between high-pollution zones (Manas and Torobay Kulatov districts) and lower-impact areas (Botanical Garden) confirms the decisive role of urban structure and emission sources in shaping environmental contamination levels (8-10). The observed seasonal peak in September is likely associated with the combined effects of intensified anthropogenic activity and heightened plant physiological functioning during the late vegetation period.

Overall, *Paulownia* can be regarded as a promising bioindicator species for monitoring urban air quality and HM pollution. Its pronounced capacity to accumulate Fe and Cu under varying environmental conditions supports its practical application in urban greening programs, environmental monitoring and phytoremediation strategies.

Conclusion

This study demonstrated that HM accumulation in urban vegetation in Osh city varies significantly across plant species, seasonal dynamics and spatial locations. The highest concentrations of metals were consistently recorded in the Manas district, reflecting the strong influence of anthropogenic activities, particularly traffic and industrial emissions. Among the studied species, *Paulownia* showed a greater capacity to accumulate Fe and Cu than *Acer*, confirming its suitability as a bioindicator and potential application in phytoremediation and urban greening programs. Seasonal peaks observed in autumn likely result from a combination of intensified atmospheric deposition and increased plant physiological activity during the late vegetation period. Climatic factors, particularly elevated nighttime temperatures and higher humidity, appear to enhance bioaccumulation processes by sustaining transpiration and metabolic activity, thereby facilitating metal uptake and internal transport. Future research should expand the range of plant species studied and include additional urban functional zones to improve the representativeness of biomonitoring results. Long-term monitoring is recommended to assess interannual variability and the influence of changing climatic conditions on metal accumulation. Further studies integrating soil, air and plant data would allow a more comprehensive assessment of pollution pathways and source attribution. In addition, investigations at the physiological and molecular levels could provide deeper insight into the mechanisms governing metal uptake, translocation and tolerance in *Paulownia*, thereby supporting its optimised use in sustainable urban ecosystem management.

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Authors' contributions

EV conceptualised the study, supervised the research process and contributed to the writing and critical revision of the manuscript. AA carried out field sampling, laboratory analyses and data collection. SB contributed to the design of the methodology, performed statistical analyses and prepared figures and tables. IA assisted in data interpretation, conducted the literature review and edited the manuscript. TS and AZ participated in investigation, sampling, laboratory analyses and visualisation. KK and SR contributed to comparative ecological analyses, linguistic editing and formatting of the final text. TS provided scientific consultation on environmental assessment methodology and strengthened the discussion section for publication readiness. AS contributed to investigation, data curation and manuscript preparation. SI provided financial support, participated in the conceptualisation and design of the study, contributed to data analysis and interpretation and involved in drafting and revising the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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