International Journal of Design & Nature and Ecodynamics
Vol. 19, No. 6, December, 2024, pp. 2197-2204
Journal homepage: http://iieta.org/journals/ijdne

# Assessing Heavy Metal Contamination for Soil Reclamation: Implications for Sustainable Urban Development

Galymzhan Saparov[1,2], Yerlan Dutbayev[3*], Arailym Amanzholkyzy[1,4], Khandakar Rafiq Islam[5], Kanat Tireuov[6], Nazar Hakimov[7], Ekaterina Zudilova[8], Rustem Shichiyakh[9], Olzhas Shoykin[10], Bakhadirjan Ganiyev[11], Ivan Otcheskiy[12], Maxim Trushin[13], Andrey Kozlov[14]

[1] Research Center for Ecology and Environment of Central Asia (Almaty), Almaty 050059, Kazakhstan
[2] U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry, Almaty 010000, Kazakhstan
[3] Kazakh National Agrarian Research University, Almaty 050000, Kazakhstan
[4] Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan
[5] The Ohio State University South Centers, Piketon OH 45661, USA
[6] Saken Seifullin Kazakh Agrotechnical University, Astana 010000, Kazakhstan
[7] Department of Social Humanities and Exact Sciences, Tashkent State University of Economics, Tashkent 100066, Uzbekistan
[8] Moscow Aviation Institute, Moscow 125993, Russia
[9] Department of Management, Kuban State Agrarian University named after I.T. Trubilin, Krasnodar 350044, Russia
[10] P.A. Stolypin Omsk State Agrarian University, Omsk 644008, Russia
[11] Department of Sociology, Fergana State University, Ferghana 712000, Uzbekistan
[12] Department of State and Municipal Administration, University of Tyumen, Tyumen 625003, Russia
[13] Department of Genetics, Kazan Federal University, Kazan 420008, Russian
[14] Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, Moscow 127434, Russian

Corresponding Author Email: yerlan.dutbayev@bk.ru



https://doi.org/10.18280/ijdne.190636

**Received:** 27 September 2024
**Revised:** 21 October 2024
**Accepted:** 1 November 2024
**Available online:** 27 December 2024

***Keywords:***
*ecology, heavy metals, abiotic factors, contamination, correlation, soil remediation, urban development*

**ABSTRACT**

Rapid economic development in Kazakhstan has resulted in numerous environmental challenges, including soil contamination by heavy metals. The largest city of Almaty in Kazakhstan, situated in a foothill basin, grapples with a complex environmental scenario. Heavy metals, particularly in their soluble phase, threaten plants, animals, and human health, impacting metabolism, hindering plant growth, and diminishing soil productivity. To address soil remediation in Almaty, a comprehensive study was conducted to investigate the influence of various factors on the concentrations of heavy metals Cd, Pb, Cu, Zn, and Cr in soil across different city areas from 2004-2021. The results show a significant temporal decrease in the concentrations of lead, mobile copper, chromium, and mobile zinc, indicating the effectiveness of pollution reduction measures implemented over the years. These findings are important for soil remediation, as decreasing contamination levels contribute to improved soil quality and reduced risks to plant, animal, and human health. Additionally, the sampling locations influenced these indicators. At the same time, moderate associations were observed between mobile copper and zinc, mobile zinc and total lead, total lead and mobile copper, total lead and Cd. Weak correlations were identified between Cd and mobile copper, total Cd, and mobile zinc, total lead and mobile chromium, as well as between mobile copper and total lead. In Almaty, variations in mobile chromium, cadmium, and copper contents across districts highlight diverse pollution sources. Additionally, the correlations between total copper and mobile chromium, as well as moderate associations between other metals, suggest interconnected contamination patterns. The results of this study will help to develop more efficient multi-metal remediation strategies, minimizing resources and time required for soil rehabilitation for advancing sustainable urban development.

## 1. INTRODUCTION

Rapid economic growth has always been portrayed as two ways. The evident positives, characterized by industrialization, urbanization, development of technology and infrastructure, and the attraction of foreign expats, are usually followed by negatives if handled carelessly. This growth impacts the environment, leading to widespread contamination of soil and water bodies by heavy metals, as observed in most countries, such as China and South Korea [1].

This is also the case in Kazakhstan, where the growing economy has led to an exponential rise in human activity and emissions from machinery, subsequently increasing soil pollution problems [2-4]. Almaty, the largest economic city in

Kazakhstan, is strongly affected by its geographical location in a foothill basin, which allows for the accumulation of pollutants. Research has also detected trace amounts of heavy metals in the bottom sediments of the Kapshagay Reservoir and large amounts in the riverbeds of the Kaskelen and Turgen Rivers [5].

The exponential rise in human activity primarily contributes to exacerbating soil pollution problems [6, 7]. Heavy metals cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr) have been identified as significant contaminants. High concentrations of these metals can pose severe threats to the environment, hinder plant growth when absorbed, and pose health risks when contaminated plants or animals are consumed [6, 8]. Therefore, identifying the sources of this pollution has become a pressing issue for ecologists [9].

Research efforts have focused on recognizing the contributions of various natural and anthropogenic processes through quantitative assessment methods [10]. Some studies utilize geographic data and machine learning techniques to pinpoint potentially polluting industries, whereas others propose methods involving principal component analysis and geographic detector models. Tian et al. [11] studied the potential risk and sources of heavy metal contamination in farmlands via an integrated method of concentration-oriented risk assessment (CORA) and a source-oriented risk assessment (SORA) approach coupled with a high-precision X-ray fluorescence (HDXRF) spectrometer. Senoro et al. [12] conducted quantitative analysis on the soil in the capital town of Romblon Province, Philippines, via spatial analysis and a handheld portable Olympus Vanta X-ray fluorescence analyzer (pXRF). Felegari et al. [13] used Sentinel-2 data, linear and step-by-step regression, and GIS to estimate the concentrations of lead, copper, and zinc caused by industrial activities in Ust-Kamenogorsk, Northeast Kazakhstan.

In the context of Almaty, which has a challenging environmental situation due to its location in a foothill basin, understanding the levels of heavy metal pollution (Cd, Pb, Cu, Zn, and Cr) in soil from 2004-2021 is crucial [14]. The city was among the most polluted places in 2010, with road transport and industrial enterprises identified as primary sources of heavy metal emissions into the atmosphere and soil. Baubekova et al. [15] identified the Karasai landfill as a major hotspot for cadmium (Cd) contamination in 2019. Additionally, slightly elevated nickel (Ni) concentrations of approximately 60 mg kg-1 were found in Almaty in 2012. Several samples of lightly contaminated surface water were reported in the Kapshagay reservoir north of Almaty in 2013. Additionally, cobalt sediments were reported at the mouth of the River Topar. Understanding these factors will provide insights into the patterns and sources of these contaminants, enabling the development of precise and effective remediation strategies [16-19].

This study aims to analyze the factors influencing heavy metal concentrations in Almaty, such as location, season, and industry, to identify contamination patterns and sources.

## 2. MATERIALS AND METHODS

Measurements of the concentrations of heavy metals (Cd, Pb, Cu, Zn, and Cr) in the soils of various parts of Almaty from 2004-2021 were carried out in the spring and autumn periods. The influence of various factors, such as year, time of year, and sampling location, was assessed as part of the study. The selection of sampling points was based on factors such as the intensity of industrial activities, traffic density, and historical data on known pollution hotspots, ensuring that a representative range of contamination levels could be captured.

### 2.1 Soil sampling and processing

Composite soil samples were collected from 0 to 30 cm depth at 7.5 cm intervals. The samples were collected from different zones of Almaty city (43.238949, 76.889709), from the "Dorozhnik" microdistrict (55.743284, 38.115580), Baum Grove (43.1822, 76.5652), Kazakh National University territory (43.225, 76.921111), Airport territory (43.3520700, 77.0405100), AXBK (43.239685 76.850757), "Mercur" (43.298684, 76.949973), Sairan (43.246964, 76.867222), VAZ areas (43.338264, 76.983741). The collected field-moist soils were air-dried under shade at room temperature (25℃) for 15 days, ground with a porcelain mortar and pestle, and passed through a 2mm sieve prior to analysis [1]. These pre-treatment steps were taken to standardize the samples and reduce variability caused by moisture content and particle size.

### 2.2 Quantitative determination of heavy metals

The concentrations of heavy metals (Cd, Pb, Cu, Zn, and Cr) in the soils of various parts of Almaty were identified via AAS (atomic absorption flame emission spectrophotometer Shimadzu AA-6200). Instrument parameters were optimized for maximum sensitivity and accuracy, with detection limits for each metal as follows: Cd (0.02 mg/L), Pb (0.05 mg/L), Cu (0.02 mg/L), Zn (0.01 mg/L), and Cr (0.03 mg/L).

### 2.3 Statistical analysis

The Kruskal-Wallis test, a nonparametric alternative to one-way analysis of variance (ANOVA), was used to assess differences in metal concentrations across different sampling locations and time periods. Before applying this test, the data were checked for normality and homogeneity of variances using the Shapiro-Wilk and Levene's tests, respectively. Due to violations of normality assumptions in several datasets, the Kruskal-Wallis test was deemed appropriate for the analysis. The significance level was set at $P < 0.05$, considered statistically significant. This value was used to determine the critical significance level and interpret the statistical significance of the results [20-22].

## 3. RESULTS

### 3.1 Cadmium: Distribution and asymmetry

The distribution of cadmium in the population exhibited right-sided asymmetry. To analyze this asymmetry and identify significant differences, the Kruskal–Wallis test was used as a nonparametric alternative to intergroup analysis of variance. Figure 1 presents a diagram illustrating the results of the analysis via the Kruskal–Wallis test, which enables visual assessment of cadmium distribution differences and identification of their statistical significance.

Figure 2 shows the fluctuations in the average cadmium content in Almaty's soil from 2004-2021. Analysis of the data revealed notable variations in cadmium contamination levels over time. In 2005, a peak level of cadmium (0.5mg/L) was recorded, followed by a gradual decrease in subsequent years. From 2009–2019, cadmium levels remained relatively low (0.2mg/L), suggesting the effectiveness of pollution reduction measures. However, in 2013, there was a sharp spike in cadmium levels to 0.6mg/L, indicating potential temporary anomalies or environmental degradation. Further research is necessary to elucidate the causes behind this increase. The overall trend highlights the importance of systematic soil quality monitoring and the implementation of measures to maintain cadmium levels within safe limits.

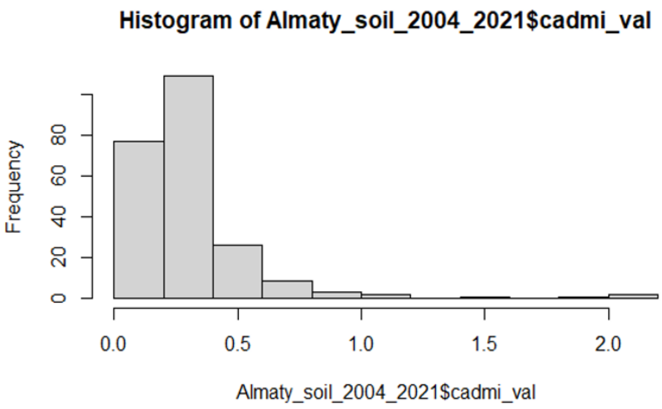



**Figure 1.** Temporal distribution of cadmium concentration (mg/L) in the Almaty variable cadmium (shaft) (2004-2021)

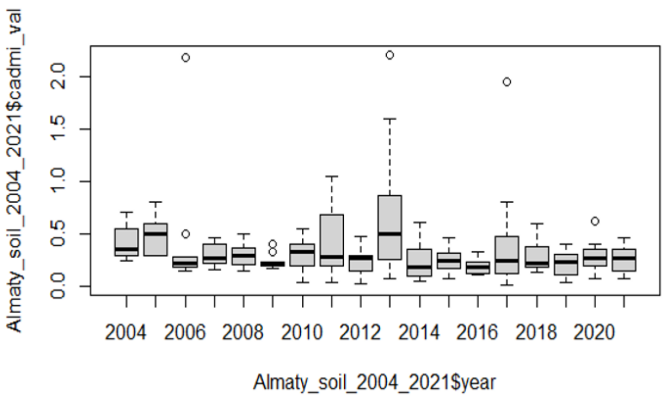



**Figure 2.** Average annual cadmium concentration (mg/L) (P<0.01) in soils from different territories of Almaty

The observational results revealed disparities in cadmium content across various territories within the city of Almaty. Notably, no gross cadmium was detected in the Dorozhnik area, suggesting the absence of significant contamination sources in that vicinity. Conversely, areas such as Baum Grove, Kazakh National University, the airport, Almaty Cotton Mill, and the Mercur Auto Center presented average annual soil cadmium levels ranging from 0.2 to 0.3mg/L, indicating relatively low contamination levels. In contrast, the VAZ area and city streets presented relatively high average annual cadmium concentrations in the soil, ranging from 0.4 to 0.5mg/L. Further research and ongoing monitoring efforts are imperative to gain a deeper understanding of the underlying causes and ramifications of variances in cadmium levels across different city areas.

### 3.2 Lead

The distribution of the population variable for gross lead is right skewed, indicating that the mean (38.2) surpasses both the median (30.7) and the first quartile (22.7). The majority of values cluster toward the lower end of the distribution, with a few larger values (maximum 240). Therefore, the Kruskal-Wallis test, a nonparametric alternative to intergroup analysis of variance, was employed for the analysis (Figure 3).

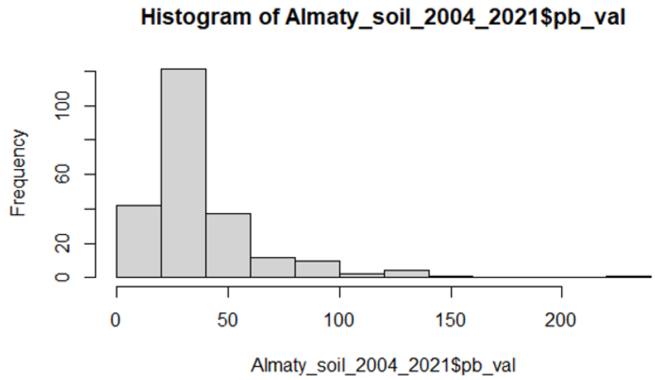



**Figure 3.** Gross lead concentration (mg/L) in the Almaty variable gross lead (2004-2021)

Figure 4 shows the trend in lead content in Almaty's soil from 2004-2021. During this period, lead levels noticeably decreased. From 2010-2013, the lead content ranged relatively high, between 45.1 and 56.8mg/L. However, since 2014, there has been a consistent decline in lead levels. From 2014-2021, the lead content in the soil ranged between 24.6 and 30.5mg/L. This reduction may have implications for soil contamination with this metal. Further monitoring and research are essential to fully understand the causes and consequences of this decline. It is imperative to implement necessary measures to maintain safe levels of lead in the soil.

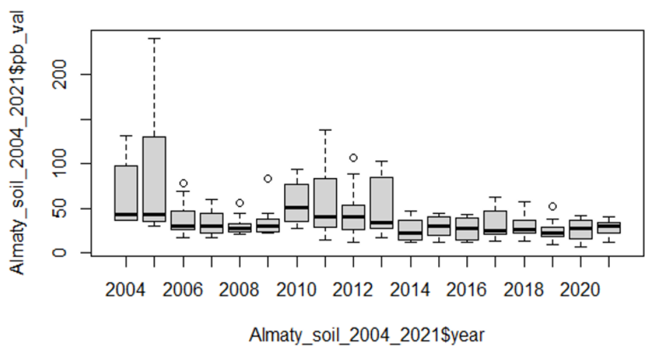



**Figure 4.** Temporal trend of lead concentration (mg/L) in Almaty soils (P<0.0001)

### 3.3 Mobile copper

During the periods of 2004-2005 and 2011-2021, no gross copper was detected in the samples. However, from 2006-2007 and 2009, the average copper concentration in Almaty's soil ranged from 29.8 to 32.4mg/L. In 2008-2009, the average copper content subsequently decreased to 1.8-3.2mg/L (Figures 5, 6).

Figure 7 depicts the variation in the mobile copper content in Almaty's soil from 2004-2021. Significant fluctuations in mobile copper levels across different periods are evident. Specifically, in 2006, 2007, and 2009, the average mobile copper content in the soil ranged between 29.8 and 32.4mg/L. However, from 2008-2009, this level decreased to 1.8-

3.2mg/L. Notably, from 2010-2021, mobile copper was not detected in the soil.

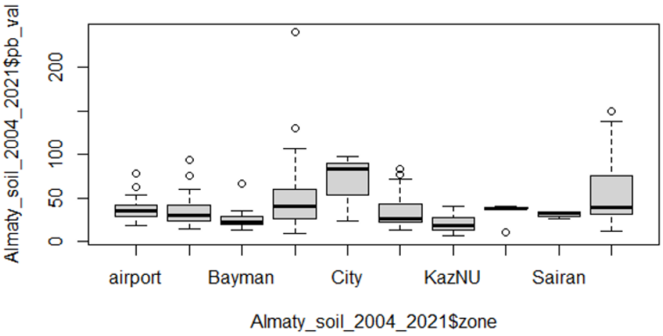



**Figure 5.** Influence (P<0.0001) of sampling location on average mobile copper concentration (mg/L) in Almaty

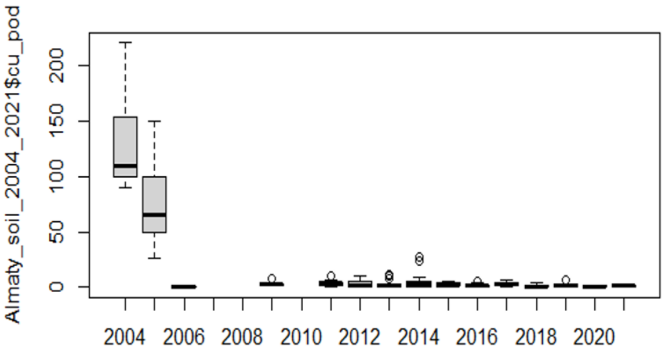



**Figure 6.** Influence (P<0.0001) of the year factor in mobile copper concentration (mg/L) in Almaty soils

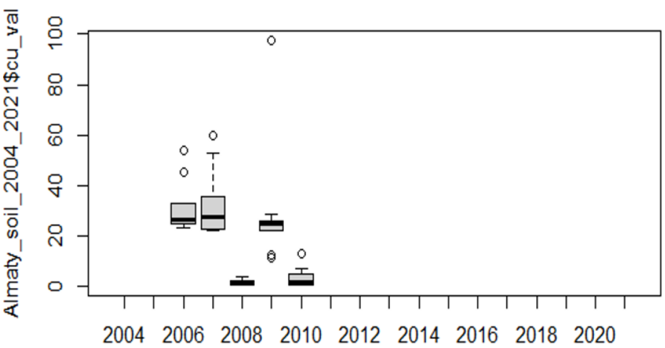



**Figure 7.** Influence (P<0.0001) of the sampling location factor on the mobile copper concentration (mg/L)

### 3.4 Lead variations

Figure 8 illustrates the fluctuations in the mobile copper content in Almaty's soil across various parts of the city from 2004-2021. These findings enable the identification of primary trends and disparities in copper levels among different areas. From 2006-2009, the total mobile copper content ranged from 29.8-32.4mg/L, decreased to 1.8-3.2mg/L from 2008-2009, and was undetected from 2011-2021. Variations in copper levels exist among different parts of the city: the VAZ area has the highest values, reaching up to 18mg/L, whereas urban areas such as KazNU, the airport, and the AXBK districts show values ranging from 8.2 to 14.8mg/L. In regions such as Baum Grove, Mercur Auto Center, and Sairan bus station, the mobile copper content ranges from 1.3 to 1.4mg/L. Conversely, no copper was found in the Dorozhnik microdistrict. These data underscore the heterogeneous nature of copper soil pollution across Almaty's districts, providing valuable insights for developing targeted measures to manage and mitigate pollution levels in specific areas.

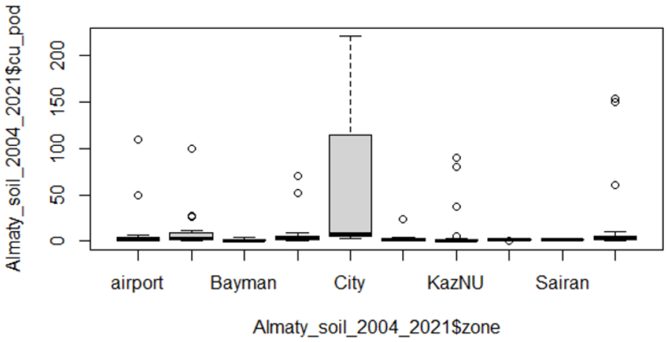



**Figure 8.** Influence (P<0.01) of the sampling site factor on mobile copper concentration (mg/L)

### 3.5 Chromium

Figure 9 shows the fluctuations in the mobile chromium concentration in Almaty's soil from 2004-2021. The results demonstrate a consistent downward trend in chromium concentrations during this period. In 2004, a high concentration of 71.1mg/L was recorded, which decreased to 8mg/L in 2007. Subsequently, between 2005 and 2009, the chromium concentration ranged from 2.6 to 4.6mg/L. Furthermore, from 2008-2009, the chromium concentration continued to decrease. These findings suggest a positive trend toward reducing the mobile chromium content in Almaty's soil, possibly because of various environmental safety and pollution management measures.

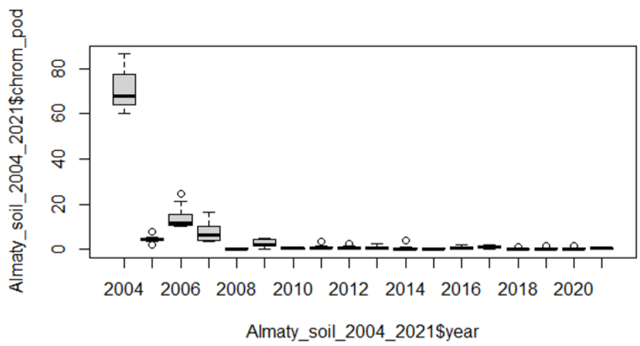



**Figure 9.** Effect (P<0.0001) of the year factor on the mobile chromium concentration (mg/L)

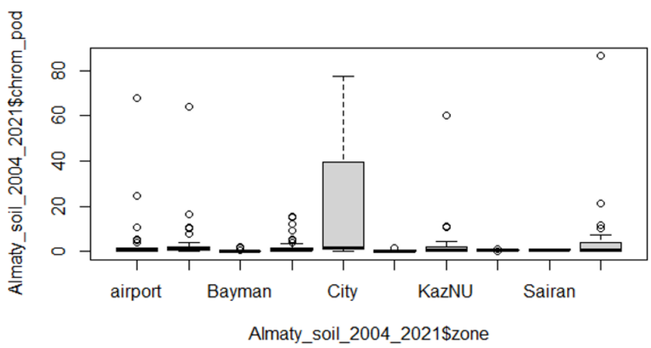



**Figure 10.** Influence (P<0.0001) of the sampling location factor on the mobile chromium concentration (mg/L)

In the soils adjacent to the airport, Almaty Cotton Mill, city streets, and the premises of Kazakh National University, the mobile chromium content ranged from 3.9 to 5.3mg/L. Conversely, in the vicinity of Baum Grove, Dorozhnik microdistrict, Mercur Auto Center, and Sairan bus station, these indicators fluctuated within 0.3–0.7mg/L in the soil (Figure 10).

### 3.6 Zinc

Over time, the concentration of mobile zinc in the soil of Almaty decreased. In 2005, the average content of mobile zinc in the soil was 44.6mg/L; in 2007-2017, it decreased to 17.9-23.5mg/L. In 2006: 6.9-11.5mg/L (Figure 11).

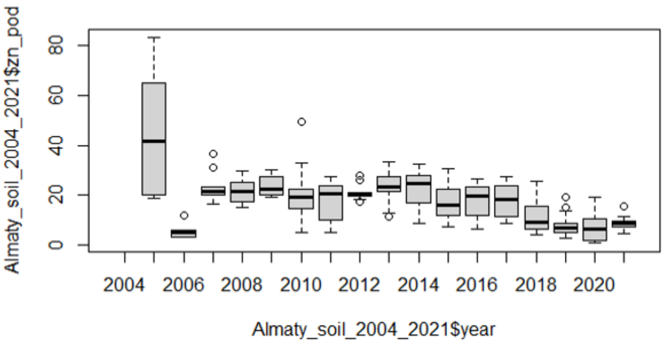



**Figure 11.** Effect (P<0.0001) of year on the mobile zinc concentration (mg/L)

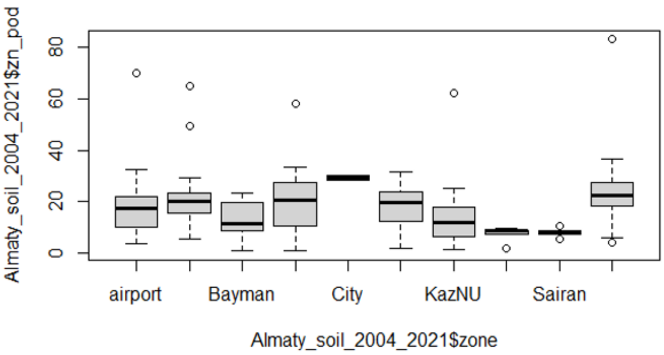



**Figure 12.** Effect (P<0.0001) of the sampling site on the mobile zinc concentration (mg/kg)

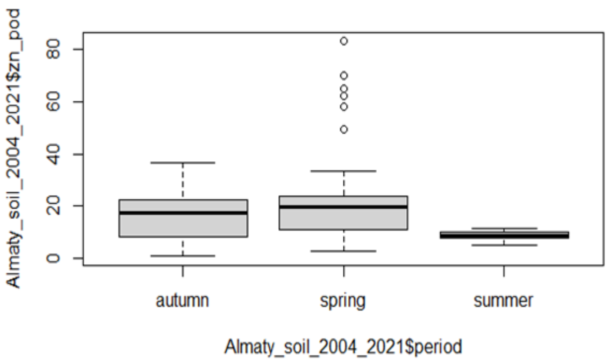
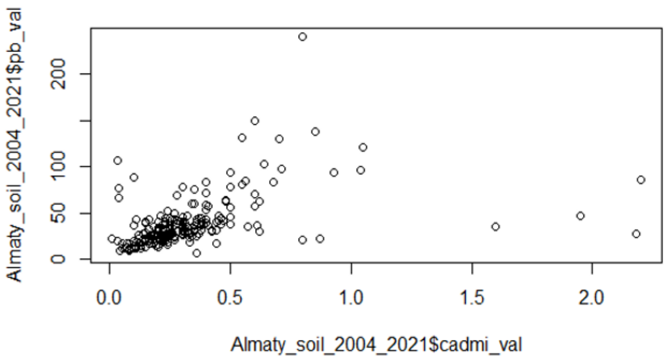



**Figure 13.** Effect of the seasons factor on the variable zinc under

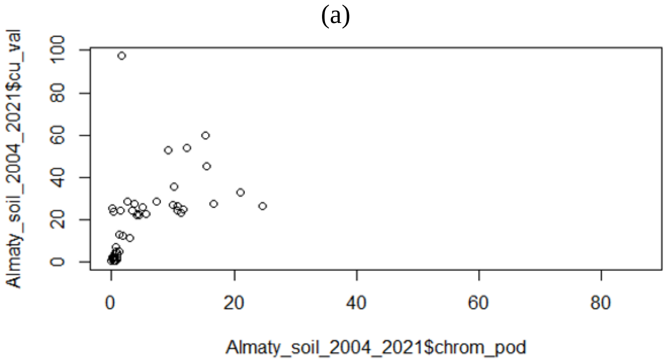
Figure 12 shows the concentration of mobile zinc concentration (mg/kg) in soils in different regions of Almaty. As can be seen from the figure, in the vicinity of airports, cotton mills, city streets and AvtoVAZ, the soluble chromium concentration is between 17.9 and 23.1 mg/kg; In Dorozhnik and Baum Grove, the concentration of soluble chromium was low, ranging from 13.0 mg/kg to 13.4 mg/kg, indicating that there were significant differences in the degree of chromium pollution in different functional zones.

The timing of sample collection plays a significant role in determining mobile zinc indicators in the soil. On average, during spring sampling, the content was 20mg/L, whereas during fall sampling, it averaged 15.9mg/L (Figure 13).

On the basis of the analysis, different levels of correlation between various variables in the soil of Almaty were identified. A strong positive correlation (0.8) was observed between bulk copper and mobile chromium. Moderate positive correlations (0.5-0.6) were found between mobile copper and mobile zinc, mobile zinc and gross lead, as well as between gross lead and mobile copper. Weak positive correlations (0.3-0.4) were noted for several pairs of variables, including cadmium gross and mobile copper, cadmium gross and mobile zinc, gross lead and mobile chromium, and mobile copper and gross lead (Figure 14(a) and (b)).




(a)




(b)

**Figure 14.** (a) Scatter plot of the correlation between the dependent variables lead shaft and cadmium shaft (moderate positive relationship - 0.6**); (b) Scatter plot of the correlation between the dependent variables copper shaft and chromium_pod (strong positive relationship - 0.8***)

## 4. DISCUSSION

Based on the analysis, different levels of correlation between various variables in the soil of Almaty were identified. A strong positive correlation (0.8) was observed between bulk copper and mobile chromium, which suggests that these metals may originate from similar industrial sources or share similar pathways in the soil, possibly due to overlapping pollution processes or co-deposition from industrial emissions. Moderate positive correlations (0.5–0.6) were found between mobile copper and mobile zinc, mobile zinc, and gross lead, as well as between gross lead and mobile copper. These moderate correlations imply that certain sources, such as transportation or industrial activities, may simultaneously release multiple metals into the environment, leading to their joint presence in the soil. The data we obtained are consistent with the results obtained by Madibekov et al. [23], who reported a (r =0.62) strong positive correlation between copper and lead in the snow cover of Almaty. This alignment reinforces the hypothesis that emissions from industrial and vehicular sources play a major role in heavy metal contamination across various environmental media in the city.

Weak positive correlations (0.3-0.4) were noted for several pairs of variables, including cadmium gross and mobile copper, cadmium gross and mobile zinc, gross lead and mobile chromium, and mobile copper and gross lead (Figure 14(a), (b)). These findings are consistent with previous studies, such as Liu et al. [24], who demonstrated complex interactions between heavy metals in urban soils irrespective of location. The correlation between heavy metals and the high correlation of lead in Almaty suggests that industrial activities and transportation may significantly contribute to heavy metal contamination.

We obtained data that revealed an increase in cadmium levels in 2013, supported by the research of Amirgaliev et al. [25], who reported cadmium concentrations between 0.7 and 1.75mg/kg in the Ural River. This calls for more research at the national level to determine the possible reason behind this spike.

Identifying sources of heavy metal pollution in soil necessitates applying efficient data analysis techniques. Notably, the studies by Jia et al. [26] and Yang et al. [27] introduce novel methodologies for the precise identification and classification of potentially polluting enterprises. Jia et al. [26] proposed a method to study the interaction between anthropogenic pollution and natural sources of heavy metals in soil, achieving high accuracy (87%) and a kappa coefficient (0.82) through various machine learning approaches, including multiple naïve Bayesian classification methods, in the Yangtze Delta, China. Similarly, Yang et al. [27] and Nasiyev et al. [28] utilized a multiple linear regression model to identify four land plots associated with mining and metallurgical activities as actual sources of soil heavy metal pollution, analyzing their respective contributions to the total accumulated concentration of heavy metals in the study area. Both methodologies underscore the importance of modern data analysis techniques in effectively identifying sources of pollution and devising control measures. Nazariani et al. [29] applied remote sensing to measure and evaluate the concentrations of heavy metals in the aerial parts and soil of tree species in Bandar Abbas city and identified the species that has the highest potential for absorbing heavy metals.

Moreover, Luo et al. [30] applied principal component analysis (PCA) to identify sources of heavy metals in surface sediments, whereas Zeng et al. [31] combined PCA with geodetectors and multiple linear regression to apportion and locate heavy metal sources in soil and dust. In our Almaty studies, we employed the Kruskal–Wallis test and correlation analysis to evaluate the influence of factors (year, sampling location, season) on heavy metal contents (e.g., Cd, Pb, Cu, Zn, and Chr) in soil, revealing various correlations among different heavy metal variables. Zhou and Wang [32] assessed the impact of industrial activities on heavy metal concentrations in urban agglomerations in China, highlighting the substantial contribution of industrial activities to heavy metal concentrations in soils.

Additionally, studies by Hu et al. [33] confirm the importance of proximity to industrial plants in determining heavy metal concentrations in soil, particularly emphasizing the elevated risks associated with heavy metal exposure to children in polluted regions. Research conducted by Madibekov et al. [23] in Almaty revealed that high concentrations of lead are correlated with the widespread use of tetraethyl lead as an additive to gasoline, i.e., emissions of motor vehicles, the use of low-quality gasoline, emissions of thermal power stations (ThPSs), etc. This finding is also confirmed by Faurat et al. [34], who reported that lead contamination is highest in industrial areas and in populated areas with highways.

Moreover, Ryskeldieva et al. [35] analyzed heavy metal concentrations in the surface waters of the transboundary Ertis River, which is crucial for assessing water quality and identifying pollution sources. Furthermore, Madibekov et al. [36] conducted a spectrometric analysis of heavy metals in the soils of the Ili River delta and the Ili-Balkhash State Nature Reserve, identifying concentrations exceeding permissible levels. A study by Faurat et al. [34] revealed that the distribution of heavy metals was high near the oil refinery and decreased at a distance of 700 m, whereas Zhyrgalova et al. [37] reported that the ash dumps at the Troitskaya regional power station and the tailings dumps at the Sokolovsko-Sarbaisky mining and processing plant were major contributors to heavy metal conatmination, as toxic waste is still stored and accumulated without compliance with environmental standards.

In Almaty, significant differences in mobile chromium content are observed across various districts, suggesting diverse pollution sources. Similarly, variations in cadmium content are noted among different areas of the city, indicating disparate pollution levels. High copper values are detected in certain areas, emphasizing the heterogeneous nature of heavy metal pollution in Almaty's soil. The variance in the distributions of cadmium and copper agreed with the research of Kalimoldina et al. [38], who observed three sample sites in Almaty (Tashkentskaya st., Botanical garden and Altyn Orda) and recorded high copper concentrations and inconsistent cadmium concentrations. Overall, the application of diverse data analysis techniques enables the effective identification and assessment of different sources of heavy metal pollution in soil, facilitating the formulation of pollution management strategies.

## 5. CONCLUSIONS

The concentration dynamics of heavy metals in the soil revealed a general trend toward decreased levels of lead, mobile and gross copper, chromium, and mobile zinc across various parts of Almaty from 2004-2021. An analysis of the sampling site factors revealed their influence on the heavy metal content in the soil. Specifically, the season of sampling, whether in spring or autumn, has a notable effect on mobile zinc levels. Furthermore, the presence of plants within a 2–3km radius from sampling locations significantly impacts mobile chromium and copper contamination, with areas near industrial enterprises exhibiting 3–5 times higher contamination levels than those without such establishments. A strong positive correlation between bulk copper and mobile chromium was identified, along with moderate and weak relationships among various heavy metal variables, suggesting interconnections between their concentrations in soil. These findings provide vital insights into the heavy metal contamination status of different areas in Almaty, offering valuable guidance for implementing pollution control measures and safeguarding the environment.

However, the study's limited spatial scope and reliance on specific time points highlight the need for more comprehensive, long-term monitoring to capture seasonal and industrial variations in greater detail. Future research should focus on the continuous monitoring of soil contamination across broader regions and incorporate advanced modeling to predict contamination trends under varying environmental conditions.

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