

An Environmental Assessment of the Heavy Metal Impact on the Soil Cover: The Case Study of Shymkent

Zhaksylyk Pernebayev

Limited Liability Company "Centre for Scientific Research and Ecological Expertise KazEcoHolding",
Shymkent, Kazakhstan
pernebaev.zh.d@mail.ru

Gulmira Kenzhibayeva

Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan
sovetovna.g7272@gmail.com (corresponding author)

Akmaral Issayeva

Limited Liability Company "Centre for Scientific Research and Ecological Expertise KazEcoHolding",
Shymkent, Kazakhstan
akissayeva@mail.ru

Ayaulym Tileuberdi

Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan
17tile@gmail.com

Sabyr Balybek

Mukhtar Auezov South Kazakhstan University, Shymkent, Kazakhstan
ecology_uko@mail.ru

Kural Nurseit

Limited Liability Company "Centre for Scientific Research and Ecological Expertise KazEcoHolding",
Shymkent, Kazakhstan
kuralnurik15@gmail.com

Received: 4 April 2026 | Revised: 27 April 2026 | Accepted: 15 May 2026

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.19108>

ABSTRACT

Soil contamination by heavy metals is a significant environmental problem that adversely affects soil systems and human health. However, integrated assessments that combine spatial distribution analysis, microstructural characterization, and economic damage evaluation remain limited for industrial cities such as Shymkent. This study aims to provide a comprehensive environmental assessment of heavy metal contamination in urban soils through a combined geochemical, microscopic, and economic approach. Soil and slag samples were collected along a transect at distances of 0–1000 m from a metallurgical waste source and analyzed using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Atomic Absorption Spectroscopy (AAS). The results revealed elevated concentrations of Pb, Zn, Cu, and Fe exceeding regulatory limits, with a clear decrease in concentration with increasing distance from the pollution source. Strong positive correlations among heavy metal concentrations indicate a common anthropogenic origin and synchronous migration within the soil profile. The economic assessment, based on a standardized national methodology, showed that the total environmental damage exceeds 750 million KZT per year, with iron and lead contributing most significantly to the overall impact. The novelty of this study lies in the integration of spatial analysis, microstructural investigation, and economic evaluation, providing new insights into the relationship among contamination distribution, migration processes, and

economic consequences. The results provide a scientific basis for environmental risk assessment, soil remediation planning, and sustainable urban land management in industrial regions.

Keywords-soil cover; sustainable development; heavy metals; environmental assessment; soil pollution; economic damage assessment

I. INTRODUCTION

Soil contamination from anthropogenic waste has a significant negative impact on the environment, leading to soil quality degradation and reduced biological productivity [1]. In this study, soil cover refers to the upper layer of the Earth's crust composed of mineral particles, organic matter, water, and air, which functions as a dynamic system supporting ecosystems and regulating pollutant migration. Long-term exposure to industrial activities, particularly metallurgical operations, results in the accumulation of heavy metals in soils, suppressing vegetation growth and increasing the risk of secondary contamination through leaching and pollutant transport processes [2]. Previous studies have reported average heavy metal concentrations reaching 27.9 ± 0.7 times the Maximum Permissible Concentration (MPC), mainly due to the historically intensive development of lead–zinc metallurgy and the use of outdated industrial technologies [3]. Rapid expansion of metallurgical production in the region occurred during periods when environmental regulations were limited or absent, contributing substantially to present-day contamination levels [4]. Heavy metals such as cadmium (Cd) and lead (Pb) are of environmental concern because of their toxicity, persistence, and ability to accumulate in soils and food chains [5, 6]. Continuous accumulation of metallurgical waste further increases the environmental burden on soil systems and intensifies the risk of secondary pollution through alkalization and migration of contaminants [7]. Among the most hazardous pollutants are Pb, Cd, Zn, and Cu due to their high mobility and ecological toxicity. Mineralogical investigations have shown that metallurgical slags mainly consist of fayalite (Fe_2SiO_4), magnetite (Fe_3O_4), olivine-group minerals, zinc ferrite (ZnFe_2O_4), sulfides, and Pb- and Zn-bearing phases, together with both crystalline and amorphous components [8].

X-Ray Diffraction (XRD) research has indicated that the amorphous phase content in slag materials ranges from 20% to 40% [9, 10]. In pyrometallurgical lead production, slag generated during concentrate smelting typically contains 0.3%–3% Pb, 3%–12% Zn, 25%–45% Fe, and 20%–35% SiO_2 , with formation temperatures ranging between 1200°C and 1400°C [11]. Gas-cleaning systems associated with metallurgical operations also produce dust-rich wastes containing volatile Pb and Zn compounds, with Zn concentrations ranging from 20%–60% and Pb concentrations from 5%–25% [12]. In hydrometallurgical processes, zinc slag leaching with sulfuric acid produces residues enriched with insoluble Pb, Ag, and Fe compounds, typically containing 8%–15% Pb and 1%–5% Zn. Additional by-products, such as gypsum cake, are formed during zinc solution purification and contain calcium sulfate mixed with heavy metal impurities [13]. Globally, metallurgical industries generate approximately 2–2.5 billion tons of waste annually. Ferrous metallurgy contributes around 1.8 billion tons per year, while non-ferrous metallurgy accounts for approximately 0.2–0.3 billion tons [14]. Asia is responsible

for nearly 60% of global metallurgical waste production, followed by Europe (20%) and North America (15%). China alone contributes approximately 40% of global metallurgical waste generation due to the rapid expansion of its metallurgical industry [15].

Despite the extensive body of research on heavy metal contamination, previous studies have primarily focused either on assessing pollutant concentrations or on developing remediation techniques. However, integrated approaches that combine spatial distribution analysis, microstructural characterization, and economic damage assessment remain limited, particularly for industrial cities such as Shymkent. Therefore, this study aims to provide a comprehensive environmental assessment of heavy metal contamination in the soil cover of Shymkent by integrating geochemical analysis, microstructural characterization, and economic evaluation. Specifically, the study investigates heavy metal concentrations at different distances from a metallurgical waste source, examines their spatial distribution and migration patterns, analyzes the microstructural properties of slag and soil samples, evaluates relationships among heavy metal concentrations, and estimates the associated environmental and economic damage. The novelty of this work lies in the application of an integrated methodological framework that combines field observations, laboratory analyses, and economic assessment to achieve a holistic understanding of heavy metal pollution in an industrial urban environment. The findings contribute to the development of scientifically grounded strategies for soil remediation, environmental monitoring, and sustainable urban land management.

II. MATERIALS AND METHODS

The study was conducted in the industrial zone of Shymkent, which is historically associated with lead–zinc metallurgical activities (Figure 1). Sampling was carried out in May–June 2024 in the zone affected by metallurgical waste (slag dumps).



Fig. 1. Map of the study area with sampling locations (adapted from Google Maps).

TABLE I. CHARACTERISTICS OF SAMPLES

Sample code	Sampling places from sources	DMS coordinates		Sampling size	pH
		N	E		
A 1	0 m	42°18'43"	69°31'29"	50 mm-150 mm	7.5-8
A 2	50 m	42°18'40"	69°31'39"	50-150 mm	7.6-8.1
A 3	100 m	42°18'39"	69°31'41"	10 mm-30 mm	7.6-8.2
A 4	200 m	42°18'37"	69°31'47"	10 mm-30 mm	7.7-8.3
A 5	500 m	42°18'35"	69°31'51"	5 mm-20 mm	7.7-8.4
A 6	1000 m	42°18'33"	69°31'59"	5 mm-20 mm	7.8-8.5

Sample preparation was carried out in accordance with [16]. The samples were pre-dried in drying cabinets at 105°C and then ground to a size of 0.1 mm in a grinding mill. Measurements were carried out at element-specific wavelengths (e.g., Pb: 217 nm; Zn: 213.9 nm; Cu: 324.8 nm). The Limits of Detection (LOD) for the analyzed elements ranged from 0.001 to 0.01 mg/kg, depending on the element. The concentrations of heavy metals (Pb, Zn, Cu, Fe) were determined using AAS (ContrAA 300). Measurements were carried out at element-specific wavelengths (Pb: 217 nm; Zn: 213.9 nm; Cu: 324.8 nm). The LOD ranged from 0.001 to 0.01 mg/kg depending on the element. Microstructural analysis of slag and soil samples was performed using SEM (JSM-6490LV, JEOL, Japan). The analysis was conducted at an accelerating voltage of 15 kV–20 kV in Backscattered Electron (BSE) mode. The obtained images were used to evaluate the morphology, porosity, and phase distribution of the samples. Quality control procedures included the analysis of Certified Reference Materials (CRM), procedural blanks, and duplicate samples. All measurements were performed in five replicates. The recovery rates for heavy metals ranged from 92% to 105%, indicating acceptable analytical accuracy. The Relative Standard Deviation (RSD) did not exceed 5%, confirming good precision of the measurements. Statistical processing of the data was performed using descriptive statistics (mean and standard deviation) and Pearson correlation analysis to assess the relationships between heavy metal concentrations. The significance of the correlations was evaluated at a confidence level of $p < 0.05$. In addition, the obtained concentrations were compared with MPC to assess the level of soil contamination.

The economic damage caused by environmental pollution is estimated using a standardized calculation method that combines pollutant emissions and regulatory coefficients. The calculation is performed in accordance with the methodology approved by the Government of the Republic of Kazakhstan for environmental damage assessment [17]. The model incorporates parameters such as pollutant mass, regulatory limits, emission duration, and environmental risk coefficients. All variables used in the calculation are defined in:

$$U = (C_{fact} - C_{norm}) \cdot 3600/1000000 \cdot A_i \cdot T \cdot 2.2MCI \cdot 10 \cdot K_1 \cdot K_2 \quad (1)$$

where U is the economic damage indicator, C_{fact} is the actual emission rate of pollutants, C_{norm} is the regulatory emission rate, A_i is the hazard coefficient of pollutant i (1/

MPC), T is the operating time (h/year), MCI is the monthly calculation index (KZT), 10 is the increasing coefficient, K_1 is the coefficient accounting for environmental conditions, and K_2 is the coefficient of possibility of environmental consequences. All parameters were selected in accordance with national regulatory guidelines, ensuring the consistency and comparability of the obtained results.

III. RESULTS AND DISCUSSION

The chemical compositions of the samples are outlined in Table II.

TABLE II. CHEMICAL COMPOSITION OF THE SAMPLES

Average amount of slag components		Average content of oxide and sulfide compounds in slag	
Formula	%	Formula	%
Na	2.28±0.11	Na ₂ O	2.58±0.18
Mg	1.88±0.02	MgO	3.45±0.085
Al	2.89±0.02	Al ₂ O ₃	5.56±0.13
Si	0.85±0.0002	SiO ₂	25.12±1.21
K	0.89±0.001	K ₂ O	1.17±0.04
Ca	9.94±0.24	CaO	12.80±0.31
Ti	0.14±0.0001	TiO ₂	0.29±0.005
Cr	0.05±0.0	Cr ₂ O ₃	0.07±0.0003
Mn	0.46±0.001	MnO ₂	0.76±0.002
Fe	26.98±1.11	Fe ₂ O ₃	37.9±1.22
Cu	1.16±0.0035	CuO	0.55±0.003
Zn	3.95±0.18	ZnO	3.65±0.004
Pb	0.27±0.003	ZnS	1.48±0.003

The main metal content of lead-zinc residues, as depicted in Table II, is Pb 2%-8%, Zn 3%-12%, Cu 0.5%-3%, Fe 15%-25%, Ag 10 g/t-150 g/t, Bi 0.01%-0.5%, Sb 0.1-2%, Sn 0.05%-0.3%, and Cd 0.01%-0.1%. It was found that non-metallic components include: SiO₂ 25%-40%, Al₂O₃ 8-15%, CaO 10%-20%, MgO 2%-6%, Fe₂O/FeO 20%-35%, SO₂ 1%-5%, and P₂O₅ 0.1%-0.8%. Physical properties include density from 2.8 g/cm³ to 3.5 g/cm³, particle sizes from 0.1 mm to 50 mm, dark grey to black color, sometimes metallic luster, vitreous or crystalline or a mix of both, and a porosity of 15-40%. Figure 2 illustrates the microstructure and elemental composition of the obtained samples.

According to the obtained results, the residual minerals identified in the samples included pyroxenes, olivine, melilite, magnesioferrite, zincoferrite, galena (PbS), sphalerite (ZnS), magnetite, hematite, and zinc.

Figure 3 presents the analysis of the sample matrix and its mineralogical composition. Correlation analysis revealed an extremely high positive linear relationship between the concentrations of Pb, Zn, Cu, Ni, As, Hg, Cr, and Cd at 0-1000 m from the source of contamination. This indicates the almost synchronous nature of the change in the content of all studied elements within the considered zone. The distribution profile of the elements was derived from the obtained correlation coefficients. The highest correlation coefficient values ($r \approx 0.9998-1$) were found for the Pb–Cd, Cd–Cu, Ni–As, and Zn–As pairs.

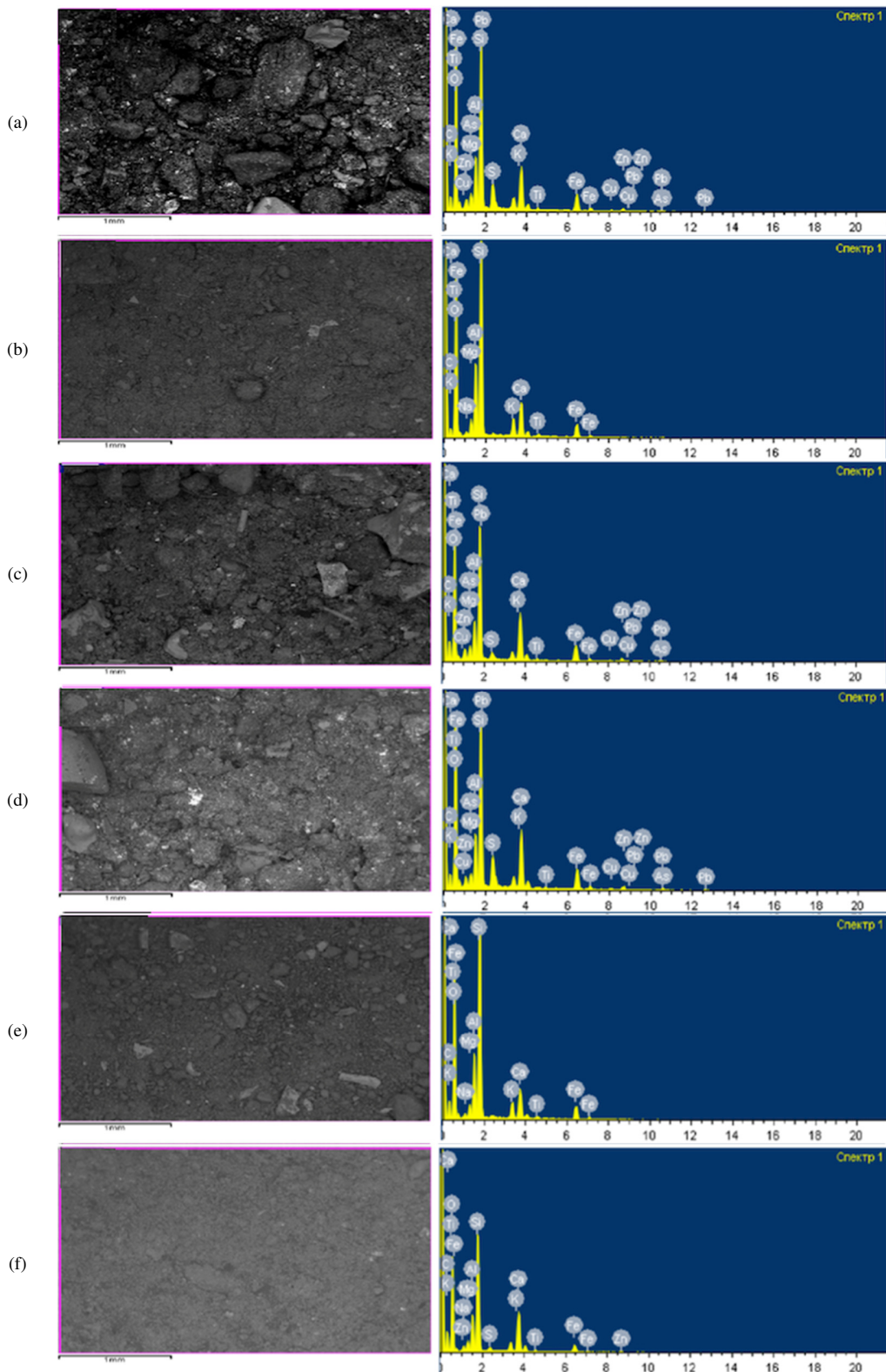


Fig. 2. Mineralogical and elemental composition of the samples: (a) – A1 sample, (b) – A2 sample, (c) – A3 sample, (d) – A4 sample, (e) – A5 sample, and (f) – A6 sample.

The minimum values ($r \approx 0.9982-0.9988$) recorded for combinations of Hg–Cr, Cr–Cd, and Pb–Cr also remain statistically significant. They are extremely high and do not reflect significant geochemical differentiation. The extremely high correlation coefficients ($r \approx 0.999-1$) can be explained by the common anthropogenic source of contamination (metallurgical waste), leading to synchronous deposition and migration of heavy metals in the soil. In 2022, the institution had to pay the state a fine of 1322762.3 tenge for 52.664358912 tons of harmful emissions into the environment allocated from the technological process. This amount is the cost of environmental damage caused to the atmosphere in financial terms. According to the previous service of the institution for this number of fines, Standard Steel KZ LLP would have to pay 144716685.8 tenge per year for 5761.7 tons. The economic assessment of environmental damage (U) is portrayed in Table III.

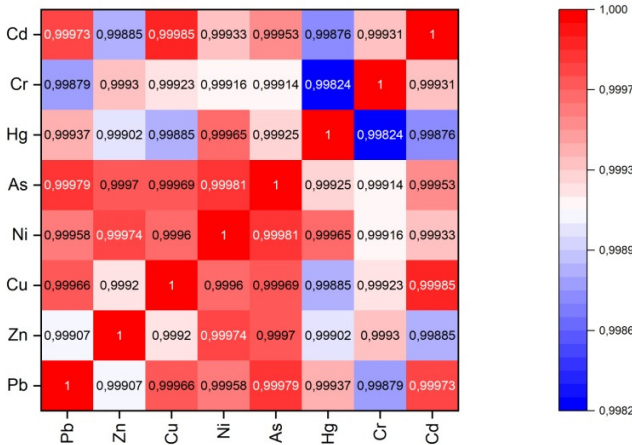


Fig. 3. Correlation matrix of heavy metal intake.

TABLE III. CHARACTERISTICS OF SAMPLES

The pollutant	C _{fact} (t/year)	C _{norm} (t/year)	Difference (t/year)	U (million tenge/year)
Pb	5761.7	0	5761.7	87.3
Zn	3785	0	3785	57.3
Cu	1475	0	1475	22.3
Fe	38560	0	38560	584.6

IV. CONCLUSIONS

This study provides a comprehensive environmental assessment of heavy metal contamination in the soil cover of Shymkent, synthesizing geochemical analysis, microstructural characterization, and economic evaluation. The findings demonstrate that metallurgical waste creates a distinct geochemical anomaly, where heavy metals such as Pb, Zn, Cu, and Fe are distributed synchronously within a 1000 m radius of the pollution source. The obtained data confirm elevated concentrations of heavy metals in the topsoil layer, exceeding permissible limits and indicating a strong anthropogenic impact associated with long-term industrial activity. Correlation analysis revealed a high positive relationship between the studied elements, suggesting a common source of

contamination and similar migration mechanisms in the soil profile. The economic assessment indicates that environmental damage from heavy metal pollution is substantial, exceeding 750 million KZT per year, with iron and lead contributing the most significantly to the total impact. These findings highlight the importance of prioritizing the specific elements in remediation and monitoring strategies. The novelty of this study lies in the integration of spatial analysis, microstructural investigation, and economic evaluation, providing a holistic understanding of contamination processes in an industrial urban environment. Finally, these outcomes have practical implications for environmental management, including the development of targeted soil remediation strategies, optimization of monitoring systems, and support for decision-making in urban land use planning.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

ACKNOWLEDGMENT

This research is supported by the Ministry of Science and Higher Education of the Republic of Kazakhstan, under grant number AP25795537 "Ecological assessment of the locations of lead on environmental objects and the development of technology for the reclamation of slag heap lands."

DATA AVAILABILITY

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

AI USE AND DECLARATION OF GENERATIVE AI USE

The authors did not use Generative AI in the preparation of this manuscript.

REFERENCE LIST STYLE AND EXAMPLES

- [1] C. J. Bronick and R. Lal, "Soil structure and management: a review," *Geoderma*, vol. 124, no. 1, pp. 3–22, Jan. 2005, <https://doi.org/10.1016/j.geoderma.2004.03.005>.
- [2] C. Huang, H. Huang, and P. Qin, "In-situ immobilization of copper and cadmium in contaminated soil using acetic acid-eggshell modified diatomite," *Journal of Environmental Chemical Engineering*, vol. 8, no. 4, Aug. 2020, Art. no. 103931, <https://doi.org/10.1016/j.jece.2020.103931>.
- [3] Y. Wang, J. Zhang, Y. Gao, Y. Fu, S. Ma, and A. Zhang, "Impact of Saline Water Irrigation on Soil Carbon Pool Composition and the Response of Carbon Emissions to Water Regulation," *Journal of Agronomy and Crop Science*, vol. 211, no. 6, 2025, Art. no. e70120, <https://doi.org/10.1111/jac.70120>.
- [4] J. Xiong, L. An, H. Lu, and C. Zhu, "Exogenous nitric oxide enhances cadmium tolerance of rice by increasing pectin and hemicellulose contents in root cell wall," *Planta*, vol. 230, no. 4, pp. 755–765, Sept. 2009, <https://doi.org/10.1007/s00425-009-0984-5>.
- [5] B. Ren, W. Wei, M. Wei, and G. Zhao, "Combined Application of Commercial Hydroxyapatite and a Straw-Derived Organic Fertilizer Immobilizes Cadmium in an Alkaline-Contaminated Soil," *Environments*, vol. 13, no. 2, Feb. 2026, <https://doi.org/10.3390/environments13020110>.
- [6] Z. Youcai and Z. Chenglong, "Amphoteric Metal Hazardous Wastes and Hydrometallurgical Processes of Zinc and Lead," in *Pollution Control and Resource Reuse for Alkaline Hydrometallurgy of Amphoteric Metal Hazardous Wastes*, Z. Youcai and Z. Chenglong, Eds. Cham: Springer International Publishing, 2017, pp. 1–11.

- [7] R. Hesami, A. Salimi, and S. M. Ghaderian, "Lead, zinc, and cadmium uptake, accumulation, and phytoremediation by plants growing around Tang-e Douzan lead-zinc mine, Iran," *Environmental Science and Pollution Research*, vol. 25, no. 9, pp. 8701–8714, Mar. 2018, <https://doi.org/10.1007/s11356-017-1156-y>.
- [8] R. Di Cagno, L. Guidi, L. De Gara, and G. F. Soldatini, "Combined cadmium and ozone treatments affect photosynthesis and ascorbate-dependent defences in sunflower," *New Phytologist*, vol. 151, no. 3, pp. 627–636, 2001, <https://doi.org/10.1046/j.1469-8137.2001.00217.x>.
- [9] K. Khaskhoussy, B. Kahlaoui, B. M. Nefzi, O. Jozdan, A. Dakheel, and M. Hachicha, "Effect of Treated Wastewater Irrigation on Heavy Metals Distribution in a Tunisian Soil," *Engineering, Technology & Applied Science Research*, vol. 5, no. 3, pp. 805–810, June 2015, <https://doi.org/10.48084/etasr.563>.
- [10] A. Rashid *et al.*, "Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health," *Agronomy*, vol. 13, no. 6, May 2023, <https://doi.org/10.3390/agronomy13061521>.
- [11] C. Shi and J. Qian, "High performance cementing materials from industrial slags — a review," *Resources, Conservation and Recycling*, vol. 29, no. 3, pp. 195–207, June 2000, [https://doi.org/10.1016/S0921-3449\(99\)00060-9](https://doi.org/10.1016/S0921-3449(99)00060-9).
- [12] R. Naz *et al.*, "Assessment of phytoremediation potential of native plant species naturally growing in a heavy metal-polluted industrial soils," *Brazilian Journal of Biology*, vol. 84, 2024, Art. no. e264473, <https://doi.org/10.1590/1519-6984.264473>.
- [13] B. Gorai, R. K. Jana, and Premchand, "Characteristics and utilisation of copper slag—a review," *Resources, Conservation and Recycling*, vol. 39, no. 4, pp. 299–313, Nov. 2003, [https://doi.org/10.1016/S0921-3449\(02\)00171-4](https://doi.org/10.1016/S0921-3449(02)00171-4).
- [14] A. Pooladi and R. Bazargan-Lari, "Simultaneous removal of copper and zinc ions by Chitosan/Hydroxyapatite/nano-Magnetite composite," *Journal of Materials Research and Technology*, vol. 9, no. 6, pp. 14841–14852, Nov. 2020, <https://doi.org/10.1016/j.jmrt.2020.10.057>.
- [15] D. M. Abdulah, A. H. A. Al-Dosky, and A. H. Mohammed, "Lead and zinc exposure in the blood of workers in municipal waste management," *Environmental Science and Pollution Research*, vol. 27, no. 10, pp. 11147–11154, Apr. 2020, <https://doi.org/10.1007/s11356-020-07722-7>.
- [16] ISO 11464:2006 Soil quality — Pretreatment of samples for physico-chemical analysis. Switzerland: International Standard, 2006.
- [17] "On approval of the Rules for economic assessment of damage from environmental pollution - IPS 'Adilet.'" https://adilet.zan.kz/rus/docs/P070000535_.