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THE STATE OF SOIL POLLUTION BY HEAVY METALS IN KOSTANAY REGION

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Abstract. Kostanay Region of the Republic of Kazakhstan is one of the leading agricultural areas of the country, with vast expanses of arable land. However, the intensive development of the mining industry (e.g., ZHAGOK - Zhezkazgan Mining and Metallurgical Plant, TBRU - Torgai Bauxite Mining Administration), SSGPO - Sokolov–Sarbai Mining Production Association JSC in close proximity to cultivated fields has led to significant anthropogenic environmental pollution, particularly involving the accumulation of heavy metals in soils.This study presents monitoring data on the content of mobile forms of heavy metals (Pb, Cu, Cr, Zn, Cd) in the soils of five industrial-agricultural centers in the region (Kostanay, Zhetykara, Arkalyk, Lisakovsk, Rudny) from 2017 to 2024, obtained using atomic absorption spectrometry.The results reveal consistent exceedances of the maximum permissible concentrations (MPCs) for copper, chromium, and especially cadmium, including occasional sharp spikes likely linked to industrial emissions. Analysis of annual average concentrations indicates that cadmium and copper represent the greatest threat to agricultural systems due to their bioaccumulative potential and their capacity to disrupt biogeochemical processes in soils.This study underscores the urgent need for systematic environmental monitoring, adaptive agricultural management under industrial pressure, and the implementation of eco-technologies and remediation measures to ensure sustainable land use and food security.

Keywords: heavy metals, agroecology, soil pollution, remediation, Kostanay region.

INTRODUCTION

Kostanay Region is one of the main agricultural centers of Kazakhstan, with the largest tracts of agricultural land in the country, amounting to 18.0 million hectares [1]. According to the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, in 2023 the average crop yields were: cereals and legumes – 10.7 centners per hectare, potatoes – 194.1 c/ha, and oilseeds – 7.2 c/ha. At the same time, the region hosts several major mining enterprises. These include the Sokolov-Sarbai Mining and Processing Production Association (SSGPO) in Rudny – the largest producer of iron ore pellets and concentrate exported to China; Varvarinskoye in the village of Varvarinka – a mining and processing plant extracting gold and copper ores, with an annual capacity exceeding 4 million tons; and Kostanay Minerals in Zhitikara – one of the global leaders in chrysotile-asbestos extraction and processing, ranked fourth in the world by total reserves [2].

During the extraction and processing of iron, copper, and asbestos ores, toxic elements such as lead, copper, cadmium, and zinc may enter the soil. In the absence of proper environmental control, these metals can transform into mobile forms and accumulate in agricultural crops, posing risks to food safety, public health, and the region's export resilience. In this context, the systematic monitoring of soils and agricultural raw materials in areas adjacent to industrial facilities is of particular relevance.

Pollution of agricultural soils by heavy metals is one of the most pressing global environmental challenges, directly impacting agricultural productivity, food safety, and human health. Numerous international and regional studies emphasize the critical role of metals such as cadmium, lead, arsenic, mercury, and chromium, which enter the soil through atmospheric deposition, wastewater discharge, fertilizers, pesticides, and industrial activities. For example, a large-scale assessment by Haodong Zhao et al. evaluated contaminated areas in China using the Pollution Index (PI) and the Potential Ecological Risk Index (PERI), revealing significant concentrations of heavy metals – particularly cadmium, which was identified as the most hazardous element across most regions [3].

A similar study conducted in the Kostanay region of Kazakhstan (within the Sokolovsko-Sarbai Mining and Processing Plant area) recorded a high ecological risk index – up to 447 based on Hakanson's method – with pronounced exceedances of cadmium, arsenic, lead, and zinc. These findings underscore the urgent need for localized environmental monitoring and risk mitigation measures [4].

The need to improve land assessment is also emphasized in international documents. According to the EU Soil Strategy for 2030 (European Commission, 2021), soil monitoring should be based on regular collection of data on pollution, organic carbon, degradation, and anthropogenic risks using geospatial information and remote sensing. The recommendations of the FAO Global Soil Partnership (GSP) emphasize the importance of standardized sampling methods, assessment of heavy metal bioavailability, maintenance of geoinformation databases, and integration of national monitoring with global systems such as GSOCmap and SoilSTAT [5, 6].

In practice, despite the presence of contamination, it is possible to cultivate agricultural crops provided that agrochemical recommendations are followed. Babichev A.N. et al. indicate that technical crops can be grown on soils exceeding the maximum permissible concentrations (MPC), and that remediation methods and the use of neutralizing agents are also applicable [7]. In turn, Ivantsova E.A. and Vodolazko A.N. emphasize the importance of adjusting land bonitation assessments, taking into account heavy metal pollution, especially in regions under industrial pressure [8].

The issue of pollutant bioavailability is addressed in the work by Decong Xu et al., which demonstrates that soil pH, organic matter content, and potassium levels significantly affect the uptake of metals by cereal crops. This is particularly true for cadmium, which is actively accumulated in rice and wheat [9]. A meta-analysis [10] confirms that in several regions, the concentrations of cadmium and lead in soils and agricultural products systematically exceed permissible limits, especially under long-term application of mineral fertilizers.

An additional contribution to understanding the sources of contamination is provided by a study conducted in the karst landscapes of China, where the use of the PMF (Positive Matrix Factorization) model revealed that 32% of soil pollution is attributed to geogenic factors, 31% to agricultural activities, and 19% to mining operations [11]. Similar assessments have been carried out in other regions – for example, in Chengdu (China), where APCS-MLR (Absolute Principal Component Scores – Multiple Linear Regression) modeling identified anthropogenic pressures as the main drivers of cadmium, lead, and zinc contamination in soils [12], as well as in the Liwa region (UAE), where localized exceedances of nickel, chromium, and lead were detected near infrastructural sites [13].

Special attention should be paid to the impact of heavy metals on microbiological and enzymatic processes in soils. For example, a study in Bangladesh demonstrates that the content of cadmium, lead, and chromium is negatively correlated with dehydrogenase and urease activity, indicating suppression of the soil microflora and a decline in fertility [14].

In the Russian context, anomalously high concentrations of copper, zinc, lead, and cadmium have been identified in the Yelizovsky district of Kamchatka, with both natural geochemical factors and anthropogenic activities (such as municipal waste burning, transportation, and industrial emissions) considered as sources of contamination [15].

Many authors [16, 17] provide a classification of pollution sources (atmospheric deposition, manure, fertilizers, pesticides), describe the mechanisms of metal uptake and accumulation in plants, and analyze modern remediation strategies. These include the selection of crop varieties with low metal accumulation, physiological blocking, water regime management, phytoremediation, and chemical soil amelioration. The authors also systematize contemporary approaches to reducing the bioavailability of metals and offer a classification of phytoremediation technologies based on contaminant type and plant tolerance. Particular attention is given to the synergy between various methods – for example, the combination of liming, organic fertilizers, and selective breeding has been shown to sustainably reduce cadmium and lead accumulation in plant biomass. In addition, the studies highlight the cumulative impact of pollutants on the central nervous system, immunity, and carcinogenesis, especially under chronic exposure. Pogorelov A.V. [18] also emphasizes the complexity of accounting for all influencing factors within agroecological zones.

Given the high agricultural importance of the region and the presence of major mining enterprises, the assessment of anthropogenic pressure on soils is particularly relevant. Considering the exceedances of heavy metal concentrations identified in previous studies and their ability to transform into bioavailable forms requiring environmental control, this study aims to assess the level and dynamics of soil contamination with heavy metals in the Kostanay region and to determine the potential environmental risks for agricultural landscapes.

To achieve this aim, the following objectives were set**:**

1. to collect and perform laboratory analysis of soil samples for lead, copper, chromium, zinc, and cadmium;

2. to compare the obtained concentrations with current regulatory standards and identify areas of exceedance;

3. to analyse the spatial and temporal patterns of contamination for the period 2017–2024;

4. to identify probable anthropogenic sources of pollutants and conduct a preliminary environmental risk assessment.

MATERIALS AND METHODS

Soil sampling for the study of heavy metal content was carried out in accordance with GOST R 58595–2019 "Soils. Sampling" using a composite method, in which 5–10 individual samples were collected from each site at a depth of 0–20 cm and combined into one composite sample weighing at least 1 kg. Sampling was conducted in dry weather using clean spades or soil augers, with strict adherence to measures preventing cross-contamination. Each sample was labeled and documented with details of the location, date, depth, and sampling conditions. Samples were packed in sealed containers and transported to the laboratory no later than 24 hours after collection, with temperature conditions not exceeding +4 °C maintained when necessary.

The determination of mobile forms of heavy metals (lead, copper, chromium, zinc, and cadmium) in soil samples was carried out according to the procedure PND F 16.1:2:2.2:2.3.78–2013 (an officially approved Russian guideline for the determination of mobile forms of heavy metals in soils) using flame atomic absorption spectrometry (FAAS). Air-dried soil was sieved through a 1 mm mesh; a 1 g subsample was taken and extracted with ammonium acetate buffer solution at pH 4.8. The resulting filtrate was analyzed on a spectrometer at the following characteristic wavelengths: Pb – 217.0 nm, Cu – 324.8 nm, Cr – 357.9 nm, Zn – 213.9 nm, Cd – 228.8 nm.

Each sample was analyzed in triplicate, followed by the calculation of the mean value and standard deviation. The detection limits were as follows: Pb - 0.5 mg/kg, Cu - 0.3 mg/kg, Cr - 0.4 mg/kg, Zn - 0.2 mg/kg, and Cd - 0.01 mg/kg; the relative error did not exceed 10%. Calibration was performed using five-point calibration curves (R^2 ≥ 0.999). Quality control was ensured through the analysis of certified reference materials, blank samples, and periodic checks of signal stability. The applied method provides the required sensitivity for determining mobile metal fractions and assessing environmental impact.

The approach used in this study is consistent with international monitoring principles set out in the Guidelines for Soil Description FAO and in the analytical section of the EU Soil Strategy for 2030, which emphasizes the need for spatial referencing of samples, systematic sampling, and risk assessment for agroecosystems.

RESULTS AND DISCUSSION

As part of the study, soil samples were analyzed for the content of heavy metals – lead, copper, chromium, zinc, and cadmium – over the period from 2017 to 2024. The samples were collected in five settlements of the Kostanay region (table 1), each characterized by varying degrees of anthropogenic pressure and industrial activity:

Kostanay is the administrative center of the region, a city with developed infrastructure and moderate industrial activity. Sampling points were located in areas remote from major industrial facilities, allowing the obtained data to be used as a background reference.

Zhetykara is a city with a high level of industrial impact, primarily due to the operations of the Zhitikara Asbestos Mining and Processing Plant (ZHAGOK). Samples were taken in areas potentially affected by emissions and waste from the enterprise.

Arkalyk is a center for bauxite mining and processing, home to the Torgai Bauxite Mining Administration (TBRU). Sampling points included sites located near zones of ore storage, transportation, and processing, enabling the assessment of heavy metal contamination in soils.

Lisakovsk is a city with a developed mining industry, including facilities related to raw material processing. Sampling locations covered both residential and suburban areas potentially exposed to anthropogenic influences.

Rudny is a major industrial hub where the Sokolov-Sarbai Mining and Processing Production Association (SSGPO) is located. Samples were collected from areas exposed to mining and beneficiation activities, including zones near waste dumps and transport routes.

Table 1 – Soil sampling points of Kostanay region

№	Sampling location	Geographical coordinates	
		Latitude	Longitude
1	Kostanay	53.208065	63.633238
2	Zhetykara	52.179362	61.267467
3	Arkalyk	50.251804	66.925047
4	Lisakovsk	52.5449	62.494423
5	Rudny	52.977777	63.111987

Each sampling point was selected taking into account the spatial distribution of potential pollution sources and anthropogenic pressure, which made it possible to carry out a comparative analysis of soil contamination levels with heavy metals across different areas of the region.

Table 2 – Concentrations of heavy metals in the soils of Kostanay region

Heavy metal	Pb (mg/kg)	Cu (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	Cd (mg/kg)
MPC（mg/kg)	32,0	3,0	6,0	23,0	-
2017					
Kostanay	20,95	1,75	0,45	13,15	0,15
Zhetykara	26,80	0,98	0,40	14,70	0,30
Arkalyk	37,00	1,98	2,03	14,50	0,31
Lisakovsk	21,80	0,56	0,43	12,80	0,24
Rudny	28,35	0,83	0,43	17,15	8,83
2018					
Kostanay	24,40	2,55	0,39	14,30	0,18
Zhetykara	22,10	1,15	0,62	15,45	0,28
Arkalyk	46,75	2,50	1,03	22,00	0,30
Lisakovsk	15,16	1,86	0,88	13,10	0,21
Rudny	18,73	2,26	0,74	14,65	0,20
2019					
Kostanay	24,83	2,55	0,30	11,70	0,17
Zhetykara	27,87	1,35	0,57	12,65	7,61
Arkalyk	33,76	7,60	1,40	21,00	0,33
Lisakovsk	10,79	5,80	0,93	23,75	0,33
Rudny	15,07	15,10	0,86	13,80	0,25
2020					
Kostanay	24,83	2,55	0,30	11,70	0,17
Zhetykara	27,87	1,35	0,57	12,65	0,60
Arkalyk	33,76	7,60	1,40	21,05	0,33
Lisakovsk	10,79	5,80	0,93	23,75	0,33
Rudny	15,07	15,10	0,86	13,80	0,25
2021					
Kostanay	10,45	10,22	10,31	10,40	10,28
Zhetykara	9,38	9,11	9,25	9,30	9,14
Arkalyk	6,27	6,03	6,15	6,33	6,05
Lisakovsk	4,82	4,79	4,76	4,90	4,74
Rudny	7,15	7,44	7,05	7,21	7,10

Table 2 (continued)

2022					
Kostanay	31,66	2,66	0,72	12,79	0,15
Zhetykara	14,89	1,25	0,71	12,40	0,19
Arkalyk	14,79	2,05	1,15	13,95	0,26
Lisakovsk	11,59	1,58	0,82	10,75	0,18
Rudny	17,07	2,81	2,09	10,25	0,31
2023					
Kostanay	25,40	2,67	0,54	15,35	0,22
Zhetykara	21,36	1,18	1,83	10,86	0,47
Arkalyk	25,03	2,00	1,90	18,08	0,32
Lisakovsk	12,35	3,81	2,09	21,75	0,26
Rudny	17,49	2,00	1,23	12,65	0,27
2024					
Kostanay	18,90	3,26	0,61	13,75	0,18
Zhetykara	11,21	1,10	0,55	10,90	0,17
Arkalyk	16,55	2,35	1,45	17,10	0,29
Lisakovsk	11,20	1,75	0,68	12,05	0,20
Rudny	17,65	2,06	3,48	7,90	0,25

The analysis of heavy metal content in the soils of the Kostanay region for the period 2017–2024 revealed persistent exceedances of the maximum permissible concentrations (MPC) for lead in Arkalyk during 2017–2020, indicating a pronounced technogenic load in previous years. Exceedances of the MPC for copper were episodic and were observed mainly in Arkalyk, Lisakovsk, and Rudny in 2019–2020, while in Zhetikara copper concentrations remained within regulatory limits throughout the entire study period. Exceedances of the permissible zinc concentrations were recorded primarily in Lisakovsk, where Zn levels reached or surpassed threshold values in 2019–2020 (table 2).

Isolated anomalously high cadmium values were identified in Zhetikara and Rudny; however, chromium concentrations at all observation sites generally remained within regulatory limits. The most environmentally vulnerable areas in terms of heavy metal contamination were Arkalyk, Rudny, and Lisakovsk, where the greatest amplitudes of variation and MPC exceedances were recorded [19-21].

Major industrial enterprises in the region are the likely sources of contamination, including the Zhetikara Asbestos Mining and Processing Plant (ZAGOK), the Torgai Bauxite Mining Administration (TBMA), and the Sokolov–Sarbai Mining and Processing Association (SSGPO). Their activities contribute to a significant anthropogenic load through dust emissions, ore transportation, waste rock disposal, and wastewater discharge. Considering the identified exceedances and spatial patterns of contamination, these territories are recommended for inclusion in the list of priority environmental control zones, with the establishment of regular soil monitoring and assessment of risks to human health and natural ecosystems.

Table 3 – Statistical indicators and environmental indices of heavy metal content in soils for 2017–2024 in the Kostanay region

Indicator	Pb	Cu	Cr	Zn	Cd
MPC (mg/kg)	32,0	3,0	6,0	23,0	-
2017	26,98	1,22	0,75	14,46	1,97
2018	25,03	2,06	0,73	15,10	0,23
2019	22,06	6,68	0,81	16,58	1,74
2020	22,06	6,68	0,81	16,60	0,34
2021	7,61	7,12	7,10	7,27	7,06
2022	17,80	2,07	1,10	12,83	0,22
2023	20,33	2,33	1,52	15,34	0,30
2024	15,10	2,30	1,35	12,34	0,22
Mean (mg/kg)	19,797	3,784	1,822	13,908	1,560
SD	9,185	3,564	2,379	4,486	2,952
95% CI low	16,951	2,679	1,085	12,518	0,645
95% CI high	22,644	4,888	2,560	15,298	2,475
PI	0.619	1.261	0.304	0.605	3.120
Ei (PERI)	3.093	6.306	0.607	0.605	93.600
Igeo	-0. 600	-3. 309	-5. 849	-3. 279	3.379

An analysis of the average annual concentrations of heavy metals in soils of the Kostanay region for 2017–2024 [22] shows that lead (Pb) concentrations in 2017–2020 ranged from 22 to 27 mg/kg, approaching the maximum permissible concentration (32 mg/kg). In 2021, a sharp decrease in Pb content to 7.61 mg/kg was observed; however, subsequent years demonstrated repeated fluctuations toward higher values, preventing the identification of a stable downward trend (table 3).

Copper (Cu) concentrations exceeded the MPC (3.0 mg/kg) only in 2019–2021, reaching the highest value in 2021 (7.12 mg/kg). In all other years, copper concentrations remained within regulatory limits, indicating that the anthropogenic influence was episodic rather than continuous.

Chromium (Cr) concentrations exceeded the regulatory threshold (6.0 mg/kg) only in 2021, reaching 7.10 mg/kg. In all other years, Cr levels remained well below the permissible level, suggesting a single episode of increased elemental input.

Zinc (Zn) concentrations remained within acceptable limits throughout the entire observation period, ranging from 7 to 17 mg/kg. Minor increases were recorded in 2019–2020 and 2023, but no exceedances of the MPC were detected.

Cadmium (Cd), despite the absence of an officially established MPC for soils, exhibited pronounced interannual variability. The highest values were recorded in 2017 (1.97 mg/kg), 2019 (1.74 mg/kg), and particularly in 2021 (7.06 mg/kg), indicating isolated periods of potentially hazardous inputs.

The greatest variability was observed for Pb (SD = 9.19 mg/kg) and Cd (SD = 2.95 mg/kg), which is associated with periodic anomalous emissions in specific areas, primarily Rudny and Zhetikara. Copper and chromium also demonstrated elevated standard deviation values (3.56 and 2.38 mg/kg, respectively), confirming significant interannual fluctuations. The most stable concentrations were observed for Zn (SD = 4.49 mg/kg).

According to the ecological indices, most metals (Pb, Cu, Cr, and Zn) remain at acceptable or background levels, not contributing to significant environmental pressure: PI and Igeo indicate the absence of contamination, while PERI values confirm low ecological risk. A slight exceedance of the MPC was recorded only for copper (PI = 1.26), although its environmental risk remains low. In contrast, cadmium (Cd) is the primary contaminant: its PI = 3.12 indicates a pronounced exceedance of normative levels, PERI ≈ 94 characterizes high ecological risk, and the positive Igeo value (3.38) reflects strong geochemical pollution. Thus, the overall environmental situation is assessed as satisfactory, but with a clear technogenic load from Cd, requiring targeted monitoring and control.

Particular attention should be given to the spatial distribution of contamination: elevated concentrations of Cd, Cu, and Pb were observed mainly in areas with high industrial activity—Rudny, Zhetikara, Arkalyk, and Lisakovsk-which correlates with the presence of large mining and processing enterprises, including SSGPO (Rudny), the Zhetikara Asbestos Mining and Processing Plant, Kostanay Minerals JSC (Zhetikara), the Arkalyk Bauxite Mine, the Varvarinskoye Mining and Processing Plant, as well as metallurgical and beneficiation facilities. The operations of these enterprises lead to dust emissions, tailings accumulation, ore transportation, and metal processing, which are likely sources of episodic heavy metal inputs into surrounding soils.

Overall, the dynamics of heavy metal concentrations in the region's soils reflect the presence of both short-term episodes of exceedances (Cu, Cr, Cd) and periodic approaches to the MPC for Pb. This highlights the need for systematic environmental monitoring, identification of specific emission sources, and regular assessment of soil conditions in the Kostanay region.

Based on the presented graph illustrating the dynamics of average concentrations of heavy metals (Pb, Cu, Cr, Zn, Cd) in soils for 2017–2024, the following conclusions can be drawn:

1. *Lead (Pb).* In 2017–2020, Pb concentrations ranged from 22 to 27 mg/kg, approaching the MPC (32 mg/kg). In 2021, a sharp decrease to 7.61 mg/kg is observed, after which concentrations partially increase but remain well below the regulatory threshold. The dynamics indicate a reduction in anthropogenic load after 2020, despite continuing fluctuations (figure 1).

2. *Copper (Cu).* Exceedances of the MPC (3 mg/kg) were recorded only in 2019–2021, when concentrations ranged from 6.68 to 7.12 mg/kg, with the maximum recorded in 2021. In all other years, Cu levels remained within acceptable limits, suggesting a short-term rather than a continuous anthropogenic influence.

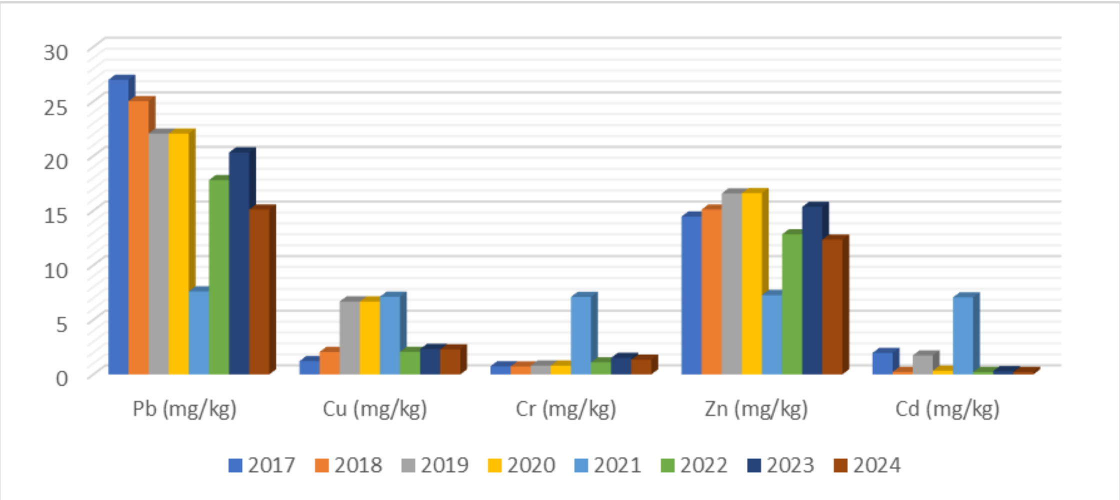

Figure 1 – Dynamics of heavy metal content in soils of the Kostanay region

3. *Chromium (Cr).* The MPC (6 mg/kg) was exceeded only in 2021 (7.1 mg/kg). In all other years, Cr concentrations ranged from 0.73 to 1.52 mg/kg, far below the regulatory limit, indicating a single episode of elevated elemental input.

4. *Zinc (Zn).* Zn concentrations remained within permissible levels throughout the entire observation period. Slightly elevated values were observed in 2019–2020 and 2023; however, no exceedances of the MPC were detected. Overall, Zn demonstrates stable behavior.

5. *Cadmium (Cd).* The highest Cd concentrations were recorded in 2017 (1.97 mg/kg), 2019 (1.74 mg/kg), and especially in 2021 (7.06 mg/kg). In other years, concentrations remained low (0.22–0.34 mg/kg). Although no official MPC is established, the pronounced spike in 2021 may pose an environmental hazard due to the high toxicity of Cd.

The greatest environmental risks are associated with episodic exceedances of Cu, Cr, and Cd-particularly in 2021-as well as with periodic approaches of Pb concentrations to regulatory limits. Zn levels remain stable and environmentally safe. The obtained results highlight the need for regular monitoring and for identifying the sources of anthropogenic contamination.

In addition to anthropogenic sources, the natural properties of the region's soil cover play a significant role in shaping the spatial distribution of heavy metals. Wind erosion, which is characteristic of the steppe zone of the Kostanay region, facilitates the transport of dust particles from tailings storage facilities and industrial sites, leading to the secondary deposition of metals at considerable distances from emission sources.

The granulometric composition also determines the degree of migratory activity: light sandy and loamy-sandy soils have low sorption capacity and promote increased mobility of Cd, Pb, and Zn, whereas heavier loam and clay horizons ensure their retention. The acid–alkaline regime is another important factor: the slightly alkaline soils (pH 7.5–8.2) predominant in the region reduce the mobility of Pb and Cr, while simultaneously increasing the solubility and bioavailability of Cd. High soil carbonate content contributes to the formation of poorly soluble compounds of Pb and Zn, limiting their vertical and horizontal migration. Thus, natural factors substantially modify the behavior of heavy metals in soils, which must be taken into account when interpreting observed trends and assessing environmental risks.

A map of the maximum concentrations of heavy metals (Pb, Cr, Zn, Cd) and copper (Cu) in the Kostanay Region is presented in figure 2.

These elements are classified as priority pollutants according to international land-quality assessments presented in the FAO Global Soil Pollution Assessment. Their high toxicity and tendency to accumulate in plants pose risks to food security and public health. The obtained results are consistent with the provisions of the EU Soil Strategy for 2030, which emphasizes the need for early detection of soil degradation, identification of pollution sources, and spatial modeling of risks for agroecosystems. To improve the regional soil-monitoring system, it is recommended to implement GIS technologies for developing digital maps of contamination and metal migration, apply remote sensing data (Sentinel-2, Landsat-8/9) to assess land degradation and technogenic disturbances, employ bioindicators (plants, microorganisms, lichen indices) for early detection of toxic impacts, expand the network of automated monitoring stations, and integrate national datasets into international platforms such as GSOCmap and SoilSTAT for comparison with global trends.

The identified patterns of heavy metal distribution in the soils of the Kostanay region indicate the presence of several environmental risks associated with both continuous anthropogenic pressure and episodic emissions. Cadmium poses the greatest hazard, as pronounced interannual fluctuations and high values of environmental indices indicate a significant risk to ecosystems and human health. The risk of chronic lead exposure persists in industrial areas where its concentrations in previous years approached the MPC. Short-term spikes in copper and chromium levels reflect the likelihood of irregular technogenic impacts capable of disrupting the biogeochemical state of soils. Additional risks are associated with localized contamination in industrial centers, the transport of dust particles from tailings storage facilities, and potential declines in soil fertility due to the toxic effects of metals. Taken together, these factors highlight the need for regular monitoring, control of anthropogenic sources, and assessment of potential impacts on the population and agricultural areas. Thus, the results of the study not only confirm the presence of significant environmental risks but also form the basis for developing a regional sustainable land-use program aligned with modern international approaches to soil protection.

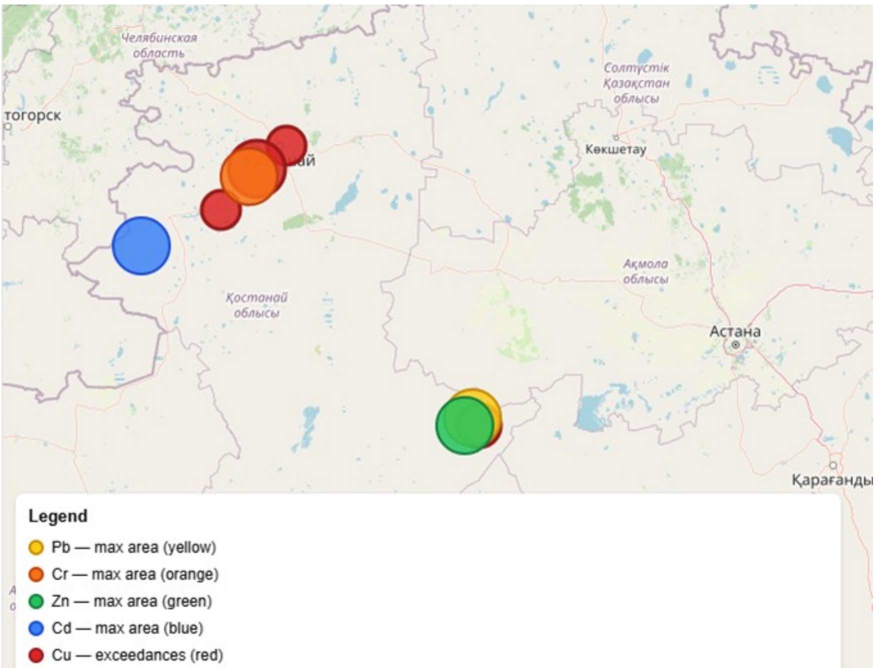

Figure 2 – Map of maximum heavy metal concentrations (Pb, Cr, Zn, Cd) and copper (Cu) exceedance zones in the Kostanay Region

CONCLUSION

The analysis of heavy metal concentrations in agricultural soils of the Kostanay region for the period 2017–2024 revealed that the region's agro-industrial potential is subject to significant environmental risks due to anthropogenic contamination. Persistent exceedances of copper, chromium, and especially cadmium levels recorded near major mining enterprises pose a threat to the safety of agricultural products, disrupt the agrochemical balance of soils, and potentially reduce crop yields. Cadmium, even in low concentrations, can accumulate in cereals and oilseed crops, posing a hazard to the food chain. The results of this study confirm the urgent need for systematic agroecological monitoring and the implementation of environmental protection practices in agriculture - such as liming, phytostabilization, and the application of organic fertilizers - to minimize the migration of toxicants into plants and ensure the sustainability of agroecosystems. Thus, this work not only identifies the scale and sources of contamination but also provides a scientific basis for developing safe land-use strategies under industrial pressure.

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ТҮЙІН

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ҚОСТАНАЙ ОБЛЫСЫНДАҒЫ ТОПЫРАҚТЫҢ АУЫР МЕТАЛДАРМЕН ЛАСТАНУ ЖАҒДАЙЫ

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Қазақстан Республикасының Қостанай облысы - егістік алқаптары кең, еліміздің жетекші ауылшаруашылық аймақтарының бірі. Алайда тау-кен өнеркәсібінің (мысалы, ЖАГОК - Жезқазған тау-кен металлургия комбинаты, ТБРУ - Торғай боксит кен басқармасы, ССКӨБ - Соколов-Сарыбай тау-кен өндірістік бірлестігі АҚ) егістік жерлерге жақын орналасуы қоршаған ортаның елеулі антропогендік ластануына, әсіресе топырақта ауыр металдардың жиналуына алып келуде. Бұл зерттеуде облыстың бес өнеркәсіптік-ауылшаруашылық орталығында (Қостанай, Жетіқара, Арқалық, Лисаковск, Рудный) 2017–2024 жылдар аралығында топырақтағы ауыр металдардың (Pb, Cu, Cr, Zn, Cd) жылжымалы формаларының құрамы атомдық-абсорбциялық спектрометрия әдісімен анықталды. Алынған нәтижелер мыс, хром және әсіресе кадмий бойынша шекті рұқсат етілген концентрациялардың (ШРК) тұрақты түрде асып кеткенін көрсетті. Сондай-ақ, өнеркәсіптік шығарындылармен байланысты болуы мүмкін күрт секірулер де тіркелді. Орташа жылдық концентрацияларды талдау кадмий мен мыстың биоаккумулятивтік әлеуеті мен топырақтағы биогеохимиялық процестерді бұзу қабілетіне байланысты ауылшаруашылық жүйелеріне ең үлкен қауіп төндіретінін көрсетеді. Зерттеу нәтижелері жүйелі экологиялық мониторингтің, өнеркәсіптік қысым жағдайында ауыл шаруашылығын бейімдеп басқарудың, сондай-ақ жер ресурстарын тұрақты пайдалануды және азық-түлік қауіпсіздігін қамтамасыз ету үшін экологиялық технологиялар мен рекультивациялық шараларды енгізудің маңыздылығын көрсетеді.

Түйінді сөздер: ауыр металдар, агроэкология, топырақтың ластануы, ремедиация, Қостанай облысы.

РЕЗЮМЕ

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СОСТОЯНИЕ ЗАГРЯЗНЕНИЯ ПОЧВ ТЯЖЁЛЫМИ МЕТАЛЛАМИ В КОСТАНАЙСКОЙ ОБЛАСТИ

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Костанайская область Республики Казахстан представляет собой один из ведущих аграрных регионов страны, обладающий значительными площадями сельскохозяйственных угодий. Однако интенсивное развитие горнодобывающей промышленности (ЖАГОК, ТБРУ, ССГПО и др.) вблизи посевных территорий сопровождается техногенным загрязнением окружающей среды, включая поступление тяжёлых металлов в почвы. В настоящем исследовании проведён мониторинг содержания подвижных форм тяжёлых металлов (Pb, Cu, Cr, Zn, Cd) в почвах пяти промышленных и аграрных центров региона (Костанай, Жетыкара, Аркалык, Лисаковск, Рудный) за 2017– 2024 гг. по методике атомно-адсорбционной спектрометрии. Полученные данные выявили устойчивые превышения предельно допустимых концентраций по меди, хрому и особенно кадмию, с эпизодами резких скачков, вероятно, обусловленных промышленными выбросами. Анализ среднегодовых концентраций показал, что именно кадмий и медь представляют наибольшую потенциальную опасность для агросистем, ввиду их способности накапливаться в сельхозпродукции и нарушать биогеохимические процессы в почвах. Работа подчёркивает необходимость системного экологического контроля и адаптивного управления сельским хозяйством в условиях промышленной нагрузки, а также использования природоохранных технологий и стратегий ремедиации для обеспечения устойчивого землепользования и продовольственной безопасности.

Ключевые слова: тяжёлые металлы, агроэкология, почвенное загрязнение, ремедиация, Костанайская область.

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