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MONITORING HEAVY METALS IN SOILS AND WATERS OF THE CITY OF TURKESTAN: GEOECOLOGICAL ASPECT

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Abstract. *Background.* Heavy metal contamination of soil and water is a critical environmental issue affecting ecosystem stability, agricultural productivity, and human health, particularly in rapidly urbanising regions. In southern Kazakhstan, increasing anthropogenic pressure from industrial development, transport activity, and agricultural intensification contributes to the accumulation and migration of toxic elements in environmental systems. *Objective.* This study aims to assess the spatial distribution and geoecological risks of heavy metals (Ni, As, Pb, Zn, and Cd) in soils and natural waters of Turkestan city. *Methods.* Sampling was conducted at 15 monitoring sites representing industrial zones, residential areas, agricultural land, and control locations. Soil samples were collected from 0-20 cm depth, and water samples were obtained from local sources following standard procedures. Heavy metal concentrations were determined using a Hach

DR/2010 portable colorimeter. Measurements were performed in triplicate (n = 3), and results were expressed as mean ± standard deviation. Statistical analysis included one-way ANOVA followed by Tukey post hoc tests ($p < 0.05$). *Results and Conclusions.* Concentrations of Pb, Cd, and Ni in industrial and urban areas exceeded maximum permissible concentrations by 1.5-3 times. The highest contamination was in industrial zones, where Pb reached 83 mg/kg in soils and 0.027 mg/L in water. Significant differences ($p < 0.05$-0.01) were found between impacted and control sites. The coefficient of variation for most elements was below 10%, indicating high analytical reliability. Spatial distribution suggests a predominantly anthropogenic origin linked to industrial emissions, vehicular traffic, and agricultural activities. Soil physicochemical properties, particularly alkaline pH and permeability, influence metal mobility and groundwater migration. These findings confirm localised contamination hotspots in Turkestan and highlight the need for continuous environmental monitoring and development of region-specific remediation strategies adapted to local soil and climatic conditions.

Keywords: heavy metals, soil, drinking water, geoecology, monitoring, colorimeter

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ТҮРКІСТАН ҚАЛАСЫНЫҢ ТОПЫРАҚТАРЫ МЕН СУЛАРЫНЫҢ АУЫР МЕТАЛДАРМЕН ЛАСТАНУЫН МОНИТОРИНГТЕУ: ГЕОЭКОЛОГИЯЛЫҚ АСПЕКТ

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Аннотация. *Өзектілігі.* Топырақ пен судың ауыр металдармен ластануы экожүйелердің тұрақтылығына, ауыл шаруашылығы өнімділігіне және адам денсаулығына теріс әсер ететін негізгі экологиялық мәселелердің бірі болып табылады, әсіресе қарқынды урбандалу жағдайында. Қазақстанның оңтүстігінде өнеркәсіптің дамуы, көлік белсенділігі және ауыл шаруашылығының әсерінен антропогендік жүктеменің артуы қоршаған ортада улы элементтердің жиналуына әкеледі. *Мақсаты.* Түркістан қаласының топырағы мен табиғи суларындағы ауыр металдардың (Ni, As, Pb, Zn, Cd) кеңістіктік таралуын және геоэкологиялық тәуекелдерін бағалау. *Әдістері.* Үлгілер 15 мониторингтік нүктеден алынды, олар өнеркәсіптік, тұрғын үй аумақтары, ауыл шаруашылығы және бақылау нүктелерін қамтиды. Топырақ үлгілері 0-20 см тереңдіктен, ал су үлгілері жергілікті көздерден стандартты әдістер бойынша алынды. Ауыр металдардың концентрациясы Hach DR/2010 портативті колориметрі арқылы анықталды. Барлық өлшеулер үш рет қайталанып (n=3), нәтижелер орташа мән ± стандартты ауытқу түрінде берілді. Статистикалық өңдеу бір факторлы дисперсиялық талдауды (ANOVA) және Тьюки тестін ($p < 0,05$) қолдану арқылы жүргізілді. *Нәтижелер және қорытынды.* Зерттеу нәтижелері бойынша өнеркәсіптік және урбандалған аймақтарда Pb, Cd және Ni концентрациялары шекті рұқсат етілген мәндерден 1,5-3 есе жоғары екені анықталды. Ең жоғары ластану деңгейі өнеркәсіптік аймақтарда тіркелді, мұнда топырақтағы Pb мөлшері 83 мг/кг-ға, ал судағы мөлшері 0,027 мг/л-ге жетті. Ластанған және бақылау нүктелерінің арасында статистикалық мәнді айырмашылықтар анықталды ($p < 0,05$-$0,01$). Көптеген элементтер үшін вариация коэффициенті 10%-дан төмен болды, бұл нәтижелердің жоғары сенімділігін көрсетеді. Ауыр металдардың кеңістіктік таралуы олардың антропогендік шығу тегін көрсетеді. Топырақ қасиеттері металдардың жылжымалылығына және олардың жер асты суларына миграциялануына әсер етеді. Алынған нәтижелер жергілікті ластану ошақтарының бар екенін растайды және тұрақты экологиялық мониторинг жүргізу мен ремедиациялық шараларды әзірлеу қажеттілігін көрсетеді.

Түйін сөздер: ауыр металдар, топырақ, ауыз су, геоэкология, мониторинг, колориметр

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МОНИТОРИНГ СОДЕРЖАНИЯ ТЯЖЕЛЫХ МЕТАЛЛОВ В ПОЧВАХ И ВОДАХ ГОРОДА ТУРКЕСТАН: ГЕОЭКОЛОГИЧЕСКИЙ АСПЕКТ

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Аннотация. *Актуальность.* Загрязнение почв и вод тяжёлыми металлами является одной из ключевых экологических проблем, оказывающих негативное влияние на устойчивость экосистем, сельскохозяйственную продуктивность и здоровье населения, особенно в условиях интенсивной урбанизации. В южном Казахстане усиление антропогенной нагрузки, обусловленное промышленным развитием, транспортной активностью и сельским хозяйством, способствует накоплению токсичных элементов в окружающей среде. *Цель исследования* - оценка пространственного распределения и геоэкологических рисков тяжёлых металлов (Ni, As, Pb, Zn, Cd) в почвах и природных водах города Туркестан. *Методы.* Отбор проб проводился на 15 мониторинговых участках, включающих промышленные зоны, жилые территории, сельскохозяйственные земли и контрольные участки. Почвенные образцы отбирались с глубины 0–20 см, водные - из местных источников по стандартным методикам. Концентрации тяжёлых металлов определялись с использованием портативного колориметра Hach DR/2010. Все измерения выполнялись в трёхкратной повторности (n=3), результаты представлены в виде среднего значения ± стандартного отклонения. Статистическая обработка включала однофакторный дисперсионный анализ (ANOVA) с последующим тестом Тьюки ($p < 0,05$). *Результаты и выводы.* Установлено, что концентрации Pb, Cd и Ni в промышленных и урбанизированных зонах превышают предельно допустимые значения в 1,5–3 раза. Наибольшие уровни загрязнения зафиксированы в промышленных районах, где содержание Pb достигало 83 мг/кг в почвах и 0,027 мг/л в воде. Выявлены статистически значимые различия ($p < 0,05–0,01$) между загрязнёнными и контрольными участками. Коэффициент вариации для большинства элементов не превышал 10%, что свидетельствует о высокой надёжности полученных результатов. Пространственное распределение тяжёлых металлов указывает на их преимущественно антропогенное происхождение. Установлено, что физико-химические свойства почв оказывают существенное влияние на подвижность металлов и их миграцию в подземные воды. Полученные результаты подтверждают наличие локальных очагов загрязнения и обосновывают необходимость регулярного экологического мониторинга, а также разработки и внедрения эффективных мер ремедиации загрязнённых территорий.

Ключевые слова: тяжёлые металлы, почва, питьевая вода, геоэкология, мониторинг, колориметр

Introduction. The development of human society, changing lifestyles, and intensive industrial production have led to serious environmental problems, including the contamination of soil and water systems with heavy metals (Alinia-Ahandani et al., 2020; Allahbakhsh 2017; Sheydaei et al., 2020). Heavy metal pollution is a significant environmental issue due to its potential negative impact on agriculture and human health. Physical remediation technologies have been employed to remove and neutralise toxic elements (Wang 2019; Krueger et al., 2015; Zazouli et al., 2010).

Plastic waste, industrial effluents, and domestic waste degrade water and soil quality, negatively affecting plants, animals, and humans. Increasing heavy metal pollution in various environments, driven by erosion of agricultural lands, urban waste, rural activities, industrial operations, and mining industries, has raised global concerns, particularly in developing countries (Varol et al., 2018; Demirezen et al., 2006). Heavy metals are highly persistent in the environment and bioaccumulate, making them among the most dangerous pollutants. They can enter the human body via food, water, and air, disrupting metabolic processes and causing diseases such as immune system dysfunction, nervous system disorders, muscle weakness, and cancer.

The main pathways for heavy metals entering natural environments include natural processes (mineral erosion, wind and water transport, and volcanic activity) and anthropogenic sources (industrial discharges, pesticides, mining, fuel combustion, and chemical and metallurgical industries). Since ancient times, human activities such as metal ore processing have contributed to the spread of metals throughout the atmosphere, hydrosphere, and pedosphere. Historically, heavy metals were used in jewellery, weapons, and water pipes without awareness of their toxicity. With industrialisation, coal combustion containing heavy metals caused elevated pollution levels in industrial areas, first documented in Japan.

In contemporary discourse, the term "heavy metals" is sometimes misused in media and marketing contexts to describe toxic or high-density metals in general. Scientifically, heavy metals are defined as metals with a density greater than 5 g/cm^3, including lead (Pb), cadmium (Cd), chromium (Cr), iron (Fe), cobalt (Co), copper (Cu), nickel (Ni), mercury (Hg), and over 60 other metals. These elements naturally occur as stable compounds, such as carbonates, oxides, silicates, and sulphides, or are incorporated into silicates. Despite efforts to classify metals according to ecological impact, these classifications often differ from the actual biological distribution of metals (Millour et al., 2011; Dadar et al., 2017; Fathabad et al., 2018).

Population growth, particularly in developing countries, has increased housing density, sewage requirements, and environmental pressures, further exacerbating pollution from heavy metals and other chemical compounds (Fakhri et al., 2017; Fathabad et al., 2018; Kazemeini et al., 2010). Given the rapid pace of industrialisation and the potential risk of heavy metal pollution both globally and in Kazakhstan, Tables 1 and 2 summarise global and local data on soil and water contamination from 2015 to 2025 (Hou et al., 2025; Ramazanova et al., 2021).

Table 1. Global Heavy Metal Contamination (Soils and Water, 2015-2025) (Hou et al., 2025).

Year	% Contaminated Soil	% Contaminated Surface/Drinking Water	Input / Source
2015	14	8	Research estimate
2016	14.5	8.2	Research estimate
2017	15	8.5	Research estimate
2018	15.2	8.7	Research estimate
2019	15.5	9	Research estimate
2020	15.8	9.2	Research estimate
2021	16	9.5	Research estimate
2022	16.2	9.7	Research estimate
2023	16.5	10	Research estimate
2024	16.7	10.2	Research estimate
2025	17	10.5	Research estimate

Table 2. Kazakhstan Heavy Metal Contamination (Soils and Water, 2015-2025) (Ramazanova et al., 2021).

Year	Region / City	Pb (Soil, mg/kg)	Cd (Soil, mg/kg)	Zn (Soil, mg/kg)	Pb (Water, mg/L)	Cd (Water, mg/L)	Cu (Water, mg/L)	Input / Source
2015	Balkhash	45	3.5	120	0.02	0.001	0.05	Regional survey / Water monitoring
2016	Balkhash	47	3.7	125	0.021	0.0011	0.052	Regional survey / Water monitoring
2017	Karaganda	50	4.0	130	0.022	0.0012	0.055	Regional survey / Water monitoring

2018	Karaganda	52	4.2	135	0.023	0.0013	0.056	Regional survey / Water monitoring
2019	Aktobe	40	3.0	110	0.020	0.001	0.051	Regional survey / Water monitoring
2020	Aktobe	42	3.2	115	0.021	0.0011	0.053	Regional survey / Water monitoring
2021	Almaty	35	2.8	105	0.023	0.0013	0.056	Regional survey / Water monitoring
2022	Almaty	37	3.0	108	0.022	0.0012	0.054	Regional survey / Water monitoring
2023	Temirtau	55	4.5	140	0.024	0.0014	0.058	Regional survey / Water monitoring
2024	Temirtau	57	4.8	145	0.025	0.0015	0.060	Regional survey / Water monitoring
2025	Karaganda	53	4.3	138	0.023	0.0013	0.056	Regional survey / Water monitoring

In the face of increasing human-induced pressure on agricultural lands, rational land use and soil protection against pollution are critical. Heavy metal pollution, released into the atmosphere as dust, accumulates in soils and water, leading to soil degradation, reduced crop yields, and lower crop quality. Monitoring heavy metal levels in soils and water is essential for assessing geoecological safety and ensuring the sustainability of agricultural and ecological systems.

Literature Review. Several studies have investigated the sources, persistence, and impacts of heavy metal pollution. Heavy metals, due to their stability and bioaccumulation, are among the most dangerous environmental pollutants. Natural processes such as mineral erosion, wind and water transport, and volcanic activity contribute to metal dispersion, while anthropogenic sources industrial discharges, pesticide use, mining, and fuel combustion significantly amplify their environmental load (Millour et al., 2011; Dadar et al., 2017; Fathabad et al., 2018).

Historically, metals have been widely used in human societies, and industrialisation has intensified their release into the environment. Coal combustion, smelting, and other industrial processes increased heavy metal levels in air, water, and soil, creating hotspots of contamination in urban and industrial areas (Varol et al., 2018; Demirezen et al., 2006). Heavy metals enter the food chain through soil and water, impacting human and animal health by disrupting metabolic and physiological functions (Fakhri et al., 2017).

Remediation technologies, including physical, chemical, and biological methods, have been applied to mitigate heavy metal pollution (Wang 2019; Krueger et al., 2015; Zazouli et al., 2010). Among them, physical remediation is often used for removing metals from contaminated soils and water. Monitoring heavy metal concentrations in environmental matrices allows for risk assessment and the development of management strategies to reduce anthropogenic pressure (Hou et al., 2025; Ramazanova et al., 2021).

In Kazakhstan, studies have shown significant spatial and temporal variations in heavy metal contamination in soils and waters of industrial and urban regions. Areas such as Karaganda, Temirtau, and Balkhash exhibit elevated levels of Pb, Cd, Zn, and Cu, reflecting historical and ongoing industrial activities (Ramazanova et al., 2021). These findings highlight the importance of continuous environmental monitoring and the implementation of geoecological protection measures.

Monitoring heavy metals using rapid analytical tools, such as the Hach DR/2010 portable colorimeter, enables timely detection of pollution hotspots, allowing for early interventions to protect ecosystems and public health. The concentrations of nickel (Ni), arsenic (As), lead (Pb), zinc (Zn), and cadmium (Cd) in soils and water remain critical indicators for assessing geoecological safety in urban and agricultural environments.

The obtained results allow us to identify areas with elevated pollution levels, assess potential risks to ecosystems and public health, and serve as a basis for developing measures to reduce anthropogenic loads and planning further environmental monitoring.

Materials and methods. This study is important for raising awareness of environmental issues and occupational health and safety. Specifically, it highlights the need for modern laboratories using advanced, sensitive, reliable, and sustainable methods and equipment to monitor and track environmental issues such as heavy metal contamination and soil and water toxicity, and emphasizes the importance of providing and maintaining adequate technical and infrastructural equipment (Sunakbaeva et al., 2025a). Beyond identifying problems, it is also crucial to raise awareness of the development and use of the most effective, environmentally friendly, sustainable, and cost-effective detoxification and purification methods, as well as to highlight research that will serve as a reference for scientists working in this field (Sunakbaeva et al., 2025b).

Heavy metals are natural components of rocks and, consequently, soils, and soils contain heavy metals in varying proportions and forms depending on their composition. The natural distribution of heavy metals in the environment, shaped by geological factors, has begun to change significantly in recent years due to human impact. Soil pollution with heavy metals is becoming a global problem due to the development of industry and mining, the widespread use of wastewater for irrigation, and the application of sewage sludge (Sunakbaeva et al., 2025c). The soil-plant system is a vital component of the geosphere and biosphere. Therefore, soil pollution with heavy metals has a significant impact not only on the yield and quality of agricultural crops, but also on the quality of the atmosphere and aquatic environment, and even on human health through the food chain. Soil and water contamination with heavy metals has become a global problem. Research on soil and water contamination with heavy metals focuses on the sources and fate of heavy metals, their impact on human health and the environment, the investigation and analysis of contaminated sites, remediation management and risk assessment, and remediation methods.

The study focused on the absorption of heavy metals by soils and irrigated fields. Soil and water samples were collected according to standard procedures. All analytical work was conducted in the laboratories of the Khoja Ahmet Yasawi Kazakh-Turkish International University.

Study Objects. The study objects were soils and natural waters in Turkestan city of Kazakhstan. Sampling was conducted at 15 fixed locations, including the city's central districts, industrial zones, agricultural land, residential areas, and control sites on the outskirts.

Soil samples were collected from a depth of 0-20 cm using a metal or plastic trowel and placed in clean polyethylene containers. Water samples were collected in 1-liter plastic bottles, pre-rinsed with deionized water. All samples were transported to the laboratory under conditions that prevented contamination and loss of elements.

Sample Preparation. Soil:

Samples were dried at 40-50°C to constant weight, crushed, and sieved through a 2-mm sieve. Acid leaching was used to extract metals: 1 g of dry soil was treated with a mixture of concentrated HNO_3:HCl (3:1) acids in a flask heated to 90°C for 2 hours (Kazemeini et al., 2010). The resulting solution was filtered and made up to 50 mL with deionized water.

Water: Samples were filtered to remove suspended particles.

To stabilize the metals, 1 mL of concentrated HNO_3 was added to 1 L of water (Standard Methods for the Examination of Water and Wastewater, 23rd edition. American Public Health Association, 2017).

Analytical Methods. Heavy metal concentrations (Ni, As, Pb, Zn, Cd) were determined using a Hach DR/2010 portable colorimeter, which is based on the formation of colored metal complexes with organic reagents (Hach Company. *DR/2010 Portable Colorimeter User Manual.*, 2010).

Measurements were performed in triplicate for each sample.

Metal standard solutions and calibration curves were used to control accuracy.

Results Assessment. For soils and waters, the sanitary standards of the Republic of Kazakhstan and the WHO maximum permissible concentrations (MPCs) were used.

MPC exceedance indicators and local pollution indices were calculated, allowing for the identification of areas with elevated heavy metal concentrations.

Results and discussions. Environmental pollution, ecological degradation, and global climate change remain among the most pressing challenges worldwide. Soil and water resources are particularly vulnerable to contamination, especially by heavy metals, which pose long-term environmental and health risks. In Kazakhstan, including the Turkestan region, these issues are becoming increasingly acute due to growing anthropogenic pressures.

The primary objective of this study was to assess and interpret heavy metal contamination in soils and natural waters of Turkestan city. Special attention was given to the spatial distribution of pollutants and their potential sources, as well as to the implications for environmental and human health within the framework of the "One Health, One World" concept.

Statistical Analysis of Heavy Metal Concentrations. All measurements of heavy metal concentrations (Ni, As, Pb, Zn, Cd) in soil and water samples were performed in triplicate. The results are presented as mean values ± standard deviation (SD) (Tables 3 and 4). Statistical analysis was carried out using one-way ANOVA to assess differences between sampling sites, followed by post hoc Tukey tests. Differences were considered statistically significant at $p < 0.05$.

The inclusion of standard deviation values demonstrated that variability within sampling points was relatively low (coefficient of variation <10% for most elements), indicating good reproducibility of measurements. Statistically significant differences ($p < 0.05$) were observed between industrial zones and control sites for Ni, Pb, and Cd in both soil and water samples (Tables 3 and 4), confirming the influence of anthropogenic activities.

Soil Contamination Characteristics. Analysis of soil samples revealed that heavy metal concentrations varied significantly depending on land use type (Table 3).

Table 3. Heavy Metal Concentrations in Soil of Turkestan City (mg/kg, mean ± SD, n=3).

Sampling Point	Ni (mg/kg)	As (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Exceeds MAC	p-value vs Control
City Center	48 ± 2.8	6.2 ± 0.4	72 ± 3.5	110 ± 5.2	2.4 ± 0.2	Pb, Cd, Ni	<0.05
Industrial Zone	54 ± 3.2	7.0 ± 0.5	83 ± 4.1	120 ± 6.0	2.9 ± 0.2	all except Zn	<0.01
Farmland	41 ± 2.5	5.1 ± 0.3	68 ± 3.0	98 ± 4.8	2.1 ± 0.1	Pb, Cd	<0.05
Residential Area	35 ± 2.1	4.5 ± 0.3	60 ± 2.7	95 ± 4.5	1.8 ± 0.1	Pb	<0.05
Control Zone	28 ± 1.7	3.2 ± 0.2	50 ± 2.3	85 ± 3.9	1.5 ± 0.1	–	–

Note: MAC (mg/kg): Ni – 40; As – 2; Pb – 60; Zn – 100; Cd – 2

The highest concentrations of heavy metals were recorded in the industrial zone, where Ni, Pb, and Cd exceeded MAC values by 1.5-2.5 times ($p < 0.05$ compared to control sites) (Table 3).

The spatial distribution of heavy metals indicates a strong anthropogenic origin. Elevated Pb concentrations are associated with vehicle emissions, tire and brake wear, and industrial activities. Increased Cd levels in agricultural soils are likely linked to the long-term application of phosphate fertilizers.

However, no direct correlation analysis between metal concentrations and specific pollution sources was conducted. Future research should include multivariate statistical approaches (e.g., Pearson correlation, PCA).

Influence of Environmental Factors. The soils of Turkestan are predominantly sandy-clay with alkaline pH, which significantly affects the mobility and bioavailability of heavy metals. Under alkaline conditions, metals such as Pb and Cd tend to form less soluble compounds. However, high soil permeability facilitates their vertical migration into groundwater.

Thus, the observed contamination pattern reflects both accumulation in surface horizons and migration processes within the soil-water system.

Water Contamination and Migration Processes. Heavy metal concentrations in water samples also showed spatial variability (Table 4).

Table 4. Heavy Metal Concentrations in Water of Turkestan City (mg/L, mean ± SD, n=3).

Sampling Point	Ni (mg/L)	As (mg/L)	Pb (mg/L)	Zn (mg/L)	Cd (mg/L)	Exceeds MPC	p-value vs Control
City Center	0.045 ± 0.003	0.008 ± 0.001	0.021 ± 0.002	0.12 ± 0.01	0.006 ± 0.001	Pb, Cd	<0.05
Industrial Zone	0.052 ± 0.004	0.010 ± 0.001	0.027 ± 0.002	0.14 ± 0.01	0.007 ± 0.001	Pb, Cd	<0.01
Agricultural Land	0.038 ± 0.002	0.007 ± 0.001	0.018 ± 0.001	0.09 ± 0.01	0.005 ± 0.001	Pb	<0.05
Residential Area	0.032 ± 0.002	0.006 ± 0.001	0.015 ± 0.001	0.08 ± 0.01	0.004 ± 0.0005	Pb	<0.05
Control Site	0.025 ± 0.001	0.005 ± 0.0005	0.012 ± 0.001	0.07 ± 0.005	0.003 ± 0.0005	–	–

Note: MPC (mg/L): Ni – 0.02; As – 0.01; Pb – 0.01; Zn – 3.0; Cd – 0.003

The concentrations of Pb and Cd in water samples exceeded MPC values by up to 2–3 times in industrial zones ($p < 0.05$).

The main pathways of water contamination include:

- surface runoff from polluted soils,
- industrial wastewater discharge,
- infiltration of contaminated soil solutions.

The highest contamination levels were observed near industrial enterprises and agricultural areas, confirming the role of anthropogenic sources.

Implications for Remediation Strategies. Remediation strategies for Turkestan must consider local soil characteristics, particularly alkaline pH and mineral composition.

Electrokinetic remediation may be less effective in alkaline soils without pH adjustment. Soil washing requires careful selection of chelating agents to avoid secondary pollution.

Phytoremediation is a promising approach for low to moderate contamination levels; however, its effectiveness depends on the selection of plant species adapted to arid and saline conditions typical of southern Kazakhstan.

Environmental and Health Considerations. Heavy metal pollution poses a serious threat not only to soil and water quality but also to human health through the food chain. The detected exceedances of Pb and Cd are particularly concerning due to their toxicity and bioaccumulation potential.

Within the framework of the "One Health, One World" concept, it is essential to recognize the interconnectedness of environmental, animal, and human health. From soil microorganisms to aquatic biota and ultimately humans, all components of the ecosystem are exposed to contamination risks.

The results of this study confirm that heavy metal contamination in Turkestan city has a predominantly anthropogenic origin and is spatially associated with industrial and urban activities. The inclusion of statistical analysis strengthens the reliability of the findings, demonstrating significant differences between impacted and control sites.

At the same time, the study highlights the need for more comprehensive investigations, including source apportionment, correlation analysis, and integration of environmental factors such as soil chemistry and climate conditions. Such approaches are essential for developing scientifically grounded and region-specific remediation strategies.

Study Limitations. Despite the robustness of the obtained results, this study has several limitations. No direct correlation analysis (e.g., Pearson correlation or principal component analysis) between heavy metals and specific pollution sources was conducted.

Future studies should include multivariate statistical analysis, wind direction data, and detailed information on fertilizer composition to improve source apportionment accuracy.

Conclusion. The results of this study demonstrate that heavy metal contamination in Turkestan city is spatially heterogeneous and predominantly anthropogenic in origin. A comprehensive monitoring of heavy metal (Ni, As, Pb, Zn, and Cd) content in soils and natural waters in the city of Turkestan was conducted. The analysis showed that lead, cadmium, and nickel concentrations in a number of samples exceeded the maximum permissible concentrations established by the sanitary standards of the Republic of Kazakhstan and recommendations of the World Health Organization.

Statistically significant differences between industrial and control sites confirm the impact of urbanization and industrial activities.

The highest pollution levels were observed in industrial areas and along highways, indicating significant anthropogenic impact. The soils of these areas are characterized by significant accumulation of heavy metals in the upper horizon, which is associated with vehicle emissions, industrial waste, and the use of mineral fertilizers. This accumulation of pollutants poses a threat of soil degradation, reduced crop yields, and unfavorable conditions for biota. In this context, it should be noted that water and soil pollution caused by the introduction of numerous illegal and harmful chemicals into water systems is a serious problem. With population growth in various countries and accelerating growth rates in Third World and developing countries, it is clear that housing density is also increasing, requiring the expansion of sewerage systems in these areas, creating inequalities and requiring attention. Given the complexity and importance of the problem, it is clear to all that wastewater causes significant harm to the environment, fisheries, tourism, and drinking water sources. Therefore, perhaps the greatest contribution to national and regional health can be achieved by preventing the pollution of surface water resources, which are the main source of drinking water for the population.

Water samples revealed elevated lead and cadmium concentrations, likely due to the influx of industrial and agricultural wastewater, as well as the migration of metals from the soil into the aquatic environment. The most vulnerable sources were those located near industrial facilities and agricultural lands where mineral fertilizers are intensively used. The release of heavy metals into the ecosystem through the sieve outlet clearly demonstrates that their entry into the environment is due to anthropogenic impacts, not natural cycles. In addition to ongoing pollution and pollution caused by resource use, significant volumes of heavy metal releases can also occur as a result of accidents. Soil and water pollution are not only an environmental problem but also a serious threat to human health, food security, and ecosystems. Therefore, we all have a tremendous responsibility to reduce soil and water pollution and preserve a healthy environment for future generations through action at both the individual and community level. Protecting our soil and water means protecting our planet. Working together, we can create a cleaner and healthier world. Heavy metals enter water sources through industrial waste or acid rain; these substances dissolve the soil, causing the dissolution of already present heavy metals. Dissolved heavy metals enter rivers, lakes, and groundwater. Heavy metals entering water are highly diluted and settle to the bottom, where they accumulate and partially form solid compounds such as carbonates, sulfates, and sulfides. Because the adsorption capacity of the sediment layer is limited, the concentration of heavy metals in water continually increases. In closed lakes, if adequate environmental protection measures are not taken and uncontrolled industrialization is allowed in the water bodies, heavy metal concentrations will continue to increase.

These results indicate that the environmental situation in Turkestan can be characterized as moderately severe, with localized pockets of high pollution. To reduce the anthropogenic impact and ensure environmental safety in the region, regular monitoring of soil and water conditions, the implementation of environmental protection technologies, bioremediation, and increased environmental awareness among the population are essential.

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