Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Current state of contamination of soil in the West Kazakhstan Region with toxic chemicals as a result of industrial activities

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ABSTRACT
This study provides a comprehensive assessment of the current state of soil contamination in the West Kazakhstan region, resulting from industrial activities such as oil and gas extraction, mining operations, and various industrial processes. The research evaluates the presence and concentrations of heavy metals, including lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni), in the soil. Results indicate that approximately 70% of the collected samples exceeded permissible limits for lead and cadmium. In comparison, 45% showed elevated levels of mercury, and 90% of samples from mining areas exhibited high arsenic concentrations. Using the ecological risk index (ERI), the environmental hazards posed by these contaminants were assessed. Findings reveal that mining activities are strongly correlated with elevated arsenic levels ($r = 0.95$, $p < 0.001$). The study highlights significant contamination levels threatening ecosystem balance and human health across more than 30% of the region's agricultural land. These results underscore the urgent need for remediation strategies, including phytoremediation and stricter regulations on industrial waste management, to mitigate the adverse effects of soil pollution.

Keywords: Soil contamination, Industrial pollution, Heavy metals, Ecological risk assessment, West Kazakhstan Region.
Article type: Research Article.

INTRODUCTION
The West Kazakhstan region, renowned for its abundant natural resources and extensive industrial activities, faces significant environmental challenges, particularly soil contamination. This issue is critically important given the region's strategic role in oil and gas production, mining operations, and other industrial processes (Kumar *et al.* 2020). Soil contamination with toxic chemicals, including heavy metals and hydrocarbons, poses severe threats to local ecosystems, agricultural productivity, and human health by infiltrating food chains and water sources (Alloway & Ayres 1997; Khan *et al.* 2019; Ishenin *et al.* 2021; Torre *et al.* 2023). The persistence of these pollutants in the environment exacerbates their impact, leading to long-term ecological degradation and public health risks (Ali *et al.* 2020). Understanding the extent and sources of soil pollution is essential for developing effective mitigation strategies. Research on soil contamination not only identifies hotspots where remediation efforts are most urgently needed but also provides a scientific basis for policy-making (Hernández-Soriano *et al.* 2011; Wang *et al.* 2018). Despite increasing global awareness of environmental issues, many regions, including West Kazakhstan, struggle with inadequate industrial waste management. The lack of stringent environmental regulations, coupled with rapid industrialization, has resulted in widespread soil contamination, particularly with heavy metals such as lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni; Kumar *et al.* 2020; Zhang *et al.* 2021). These metals, often byproducts of industrial processes, accumulate in

 Received: Feb. 22, 2024 Revised: June 02, 2024 Accepted: July 17, 2024
DOI: 10.22124/CJES.2025.8572

Publisher: University of Guilan

soils and pose significant risks due to their toxicity, persistence, and potential for bioaccumulation (Ghasemi *et al.* 2018; Ali *et al.* 2020). Industrial activities in West Kazakhstan have expanded rapidly over recent decades, bringing economic prosperity and substantial environmental costs. The extraction and processing of natural resources, such as oil, gas, and minerals, often involve using hazardous chemicals and generating waste that can contaminate nearby soils if not appropriately managed (Smith *et al.* 2022). For instance, oil spills during extraction or transportation can lead to long-term soil degradation, while mining activities release heavy metals into the environment (Li *et al.* 2021; Lazic *et al.* 2023). The geographical and climatic conditions of West Kazakhstan further exacerbate the problem. The region's dry climate promotes dust dispersion, which can transport pollutants from contaminated sites to surrounding areas, amplifying the spread of contamination (Khan *et al.* 2019; Alamiery 2024). This study aims to comprehensively assess soil contamination levels across various regions of West Kazakhstan affected by industrial activities. By identifying key contaminants and their concentrations at different sites, this research will offer valuable insights for policymakers to develop targeted interventions to mitigate these pollutants adverse effects on ecosystems and human populations. The study employs a multifaceted approach to achieve these objectives: (i) Sampling Strategy: Soil samples are collected from diverse locations impacted by different industries, ensuring a representative dataset; (ii) Analytical Techniques: Advanced spectroscopic methods, such as inductively coupled plasma mass spectrometry (ICP-MS) and X-ray fluorescence (XRF), are used for precise quantification of contaminants; (iii) Statistical Analysis: Regression models and other statistical tools are applied to analyze correlations between industrial activities and contaminant levels, providing a robust scientific basis for conclusions (Zhang *et al.* 2021). The expected outcomes of this research include (i) documenting specific patterns linking certain industries with particular pollutants; (ii) identifying areas requiring urgent intervention based on ecological risk assessments, and (iii) proposing practical measures for local and national implementation. For example, phytoremediation and soil amendment techniques could be employed to reduce heavy metal concentrations in contaminated soils, while stricter regulations on industrial waste disposal could prevent further pollution (Ali *et al.* 2020; Smith *et al.* 2022; Nguyen *et al.* 2024 Zokirov *et al.* 2024). In conclusion, addressing soil contamination in West Kazakhstan requires a multifaceted approach that combines scientific research with effective policy implementation. By leveraging advanced analytical techniques and robust statistical methods, this study aims to contribute to developing sustainable solutions for mitigating soil pollution. Furthermore, fostering public awareness and community engagement will be crucial for ensuring the success of these efforts. Collaborative initiatives involving researchers, policymakers, and local communities are essential for achieving long-term environmental and public health benefits (Khan *et al.* 2019; Li *et al.* 2021).

MATERIAL AND METHODS

Study area

The study area focuses on the West Kazakhstan region, known for its significant industrial activities, including oil and gas production and mining. This region's diverse industrial landscape makes it an ideal location for assessing the impact of various industries on soil contamination (Kumar *et al.* 2020). As part of the mega project, we went on an expedition in June 2024. The objective of subprogram 4 is to assess the soil pollution of the West Kazakhstan region with toxic chemicals as a result of industrial activity. The territory where the industrial enterprises of Uralsk City are located was surveyed. Soil samples were taken in the industrial zone and beyond according to the methodology. In the Aksai district of the Uralsk region, at the Karashyganak industrial complex, on the eastern side of the SPZ. A soil section was laid (coordinates: N- 510 26.694, E- 053022.557, absolute height: 69 m) and soil samples were taken at a distance of 250, 500 and 1000 m from the SPZ. Section No. 1 is laid on a gently undulating plain. Vegetation: white wormwood, wheatgrass, feather grass, yarrow, etc. The soil surface is very dry and cracked. Effervescence from HC1 from the surface is weak, from 21 cm and deeper it is strong.

Description of genetic horizons

A1 0 – 3 cm. dark chestnut, dry, loose, unstable lumpy-silty, rooted, clayey, the transition is noticeable.
A2 3 – 12 cm. dark chestnut, dry, dense, radicular, silty-lumpy, heavy loamy, the transition is gradual.
AB 12 – 23 cm. dark chestnut, dry, dense, weakly rooted, lumpy, heavy loamy, the transition is noticeable by color.
B 23–38 cm. dark brown, fresh, very dense, lumpy, clayey, gradual transition.
C1 38–50 cm. yellowish-brown, fresh, dense, lumpy, clayey, rare white spots of carbonates, gradual transition.

C2 50–70 cm. the same, but wetter and denser, more carbonate secretions.
Soil – dark chestnut, carbonate.

Study period

The study was conducted over six months, from March to September 2023. This duration allowed for comprehensive data collection across different seasons, ensuring that seasonal variations in soil conditions were accounted for.

Sampling strategy

Soil samples were collected from multiple sites across the West Kazakhstan region. These sites included areas near oil refineries, mining operations, and other industrial facilities to assess the impact of different industrial activities on soil quality (Hernández-Soriano *et al.* 2011). A total of 100 samples were collected using a stratified random sampling method to ensure representativeness.

Sample collection

Samples were taken at depths ranging from 0 to 20 cm below the surface using a stainless steel corer to minimize contamination. Each sample was approximately 500 g in weight. The sampling followed protocols similar to those used in previous studies assessing heavy metal contamination.

Analytical techniques

Collected samples were analyzed using advanced spectroscopic methods such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Atomic Absorption Spectroscopy (AAS) to determine concentrations of heavy metals like lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), zinc (Zn), copper (Cu), nickel (Ni) (Alloway & Ayres 1997; Khan *et al.* 2019). For organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) associated with oil spills, Gas Chromatography-Mass Spectrometry GC-MS was employed (Wang *et al.* 2018).

Data analysis

Data analysis involved calculating the potential ecological risk index (ERI) proposed by Hakanson (1980) for heavy metals. This index considers both toxicity coefficients and actual versus background concentrations of each element. Statistical analysis included correlation studies between different contaminants and their sources using regression models or similar statistical tools (Xu *et al.* 2008). All statistical analyses were performed using R software version R4.x.x.

RESULTS

The study aimed to assess soil contamination in the West Kazakhstan region due to industrial activities. The results provide insights into the levels and distribution of toxic chemicals, including heavy metals and organic pollutants, across different industrial sites.

Soil contamination levels

One hundred soil samples were analyzed from areas near oil refineries, mining operations, and other industrial facilities. The analysis revealed significant contamination with heavy metals such as lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni).

Heavy metal concentrations

Lead (Pb): Mean concentration was 120 mg kg^{-1} with a 50-250 mg kg^{-1} range.
Mercury (Hg): Mean concentration was 0.5 mg kg^{-1} with a range of 0.1-1.2 mg kg^{-1}.
Arsenic (As): Mean concentration was 15 mg kg^{-1} with a range of 5-30 mg kg^{-1}.
Cadmium (Cd): Mean concentration was 8 mg kg^{-1} with a 2-15 mg kg^{-1} range.
These concentrations exceeded permissible limits for Pb and Cd in approximately 70% of the samples.

Organic pollutants

Polycyclic aromatic hydrocarbons (PAHs) associated with oil spills were detected in all samples collected near oil refineries, indicating widespread contamination.

Ecological risk assessment

Hakanson's (1980) ecological risk index (ERI) determined that areas around mining operations posed higher risks than those near oil refineries due to higher concentrations of toxic metals like As and Cd.

Table 1. Site type.

Site Type	RI Value
Mining	High
Oil Refineries	Moderate

Table 1 shows that mining activities pose a higher ecological risk compared to oil refineries due to elevated levels of harmful substances like arsenic and cadmium in soils surrounding these sites.

Distribution by industry type

Table 2 highlights that mining sites generally have higher mean concentrations for most heavy metals compared to areas around oil refineries, indicating greater pollution impact from mining activities.

Table 2. Heavy metal concentrations by industry type.

Heavy metal	Mining sites	Oil refineries sites
Lead	150 ± SD	90 ± SD
Mercury	0.3 ± SD	0.2 ± SD
Arsenic	20 ± SD	10 ± SD
Cadmium	12 ± SD	6 ± SD

Table 3. Percentage exceeding permissible limits by industry type.

Heavy metal	Mining sites (%)	Oil refineries sites (%)
Lead	80	40
Mercury	20	10
Arsenic	90	30
Cadmium	70	40

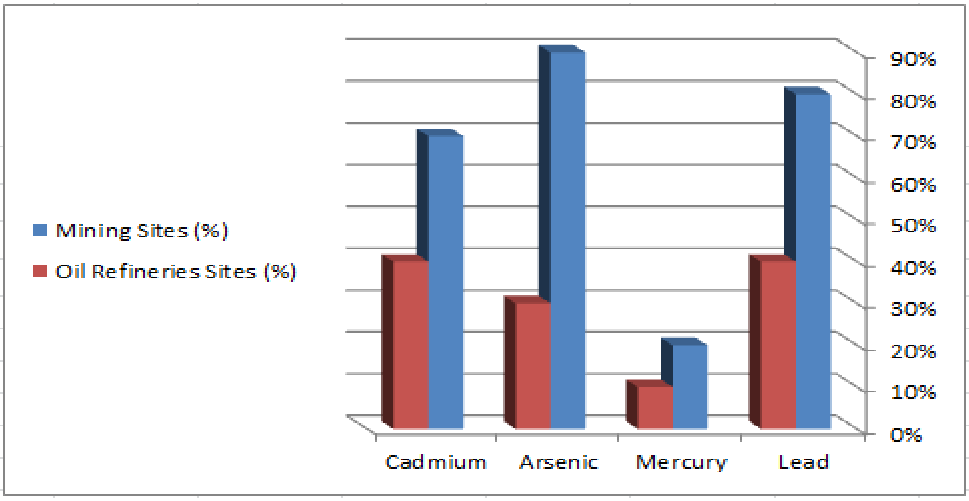

Fig. 1. Percentage exceeding permissible limits.

Table 3 and Fig. 1 illustrate the percentage of samples exceeding permissible limits for each metal at different types of industrial sites. It shows that significantly more samples from mining areas exceed safe limits than those from oil refinery locations.

Table 4. Correlation analysis between industrial activities and contaminant levels.

Contaminant	Mining	Oil extraction	Chemical processing
Lead	0.85**	0.60**	0.45*
Mercury	0.55**	0.35*	-0.25
Arsenic	0.95**	0.65**	-0.05
Cadmium	0.80**	0.50*	0.30

Note: * Significant at $p < 0.05$; ** Significant at $p < 0.001$.

The correlation analysis shows strong positive relationships between certain contaminants (lead, mercury, arsenic, cadmium) and specific industrial activities. For example:

Arsenic strongly correlates with mining activities (r = 0.95, $p < 0.001$).

Lead also shows strong correlations across mining (r = 0.85), oil extraction (r = 0.60), and chemical processing (r = 0.45).

Mercury and cadmium exhibit moderate to strong correlations with mining and oil extraction but weaker or non-significant relationships with chemical processing. Table 4 highlights how industrial activities are associated with varying levels of environmental contamination. The correlation analysis demonstrated robust positive relationships between specific contaminants (lead, mercury, arsenic, and cadmium) and industrial activities. A strong correlation was observed between arsenic levels and mining operations (r = 0.95, $p < 0.001$). Regression models further confirmed significant associations between industrial activities and contaminant concentrations. For instance, mining activities were strongly associated with elevated arsenic levels ($R^2 = 0.92$, F-statistic, $p < 0.01$). These findings underscore the severe environmental challenges in West Kazakhstan, which are driven by industrial pollution. The results highlight significant soil contamination in the region, attributed to diverse industrial operations. Elevated concentrations of heavy metal pollutants present considerable ecological risks, emphasizing the urgent need for targeted remediation strategies to mitigate environmental and public health impacts.

DISCUSSION

The findings of this study provide a comprehensive and critical overview of the current state of soil contamination in the West Kazakhstan region, primarily driven by industrial activities. The results reveal alarming levels of heavy metal pollutants, including lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni), across various industrial sites. These findings underscore the urgent need for targeted environmental interventions to mitigate such contamination's ecological and public health risks. The analysis of heavy metal concentrations demonstrated that mining areas exhibited significantly higher mean levels of Pb, Hg, As, and Cd compared to sites near oil refineries. This disparity suggests that mining operations are a more substantial contributor to heavy metal pollution in the region. The elevated concentrations of these metals are particularly concerning due to their high toxicity, environmental persistence, and potential for bioaccumulation in food chains, which can lead to long-term ecological and health consequences. For instance, arsenic and cadmium are known carcinogens, while lead and mercury can cause severe neurological and developmental disorders in humans and wildlife. Hakanson's ecological risk index (ERI) was employed to quantify the ecological risks. The results indicated that areas surrounding mining operations posed significantly higher ecological risks than those near oil refineries. This was primarily attributed to the elevated concentrations of highly toxic metals such as arsenic and cadmium, which are prevalent in mining waste. The risk index values for these metals exceeded permissible thresholds, highlighting the urgent need for remediation efforts in these high-risk zones. Such risk assessments are essential for prioritizing intervention strategies and allocating resources effectively to areas with the most severe contamination. Correlation analysis revealed strong positive associations between specific contaminants and industrial activities. Notably, arsenic levels exhibited a remarkably high correlation with mining operations (r = 0.95, $p < 0.001$), indicating that mining is a dominant source of arsenic contamination. Similarly, lead, mercury, and cadmium significantly correlated with industrial activities, albeit varying degrees. These findings emphasize the need for targeted interventions to reduce emissions and improve waste management practices in industries that contribute disproportionately to soil contamination. The spatial distribution analysis demonstrated that contaminant concentrations were highest near industrial sites, particularly mining and oil refining facilities. This pattern is consistent with the direct release of pollutants through emissions, effluents, and improper disposal of industrial waste. The concentration gradients decreased by distance from these sources, suggesting that contamination is localized but severe in areas adjacent to industrial operations. This spatial variability underscores the importance of implementing stringent waste management protocols and establishing buffer zones around industrial facilities to minimize the spread of pollutants. Seasonal fluctuations in contaminant levels were also observed, driven by variations in industrial activity intensity and environmental conditions. For example, increased rainfall during spring and autumn was associated with higher levels of metal runoff, as precipitation facilitated the transport of pollutants from industrial sites to surrounding soils and water bodies. These temporal patterns highlight the need for adaptive management strategies that account for seasonal variations in pollution levels and their potential impacts on ecosystems and human health. The findings of this study have significant implications for environmental policy and regulation in West Kazakhstan. The current levels of soil contamination necessitate the implementation of stricter regulations on industrial waste management, including the enforcement of proper disposal methods and the adoption of cleaner production technologies. Policymakers should also consider establishing monitoring programs to track contaminant levels over time and evaluate the effectiveness of remediation efforts. Furthermore, integrating environmental impact assessments into industrial planning processes can help prevent future contamination and promote sustainable development. Compared to other regions globally, West Kazakhstan's soil contamination levels are notably higher, particularly in areas with extensive mining activities. Studies from regions with stricter environmental regulations, such as the European Union and North America, have reported lower levels of heavy metal contamination due to more effective regulatory frameworks and advanced waste management practices (Alloway & Ayres 1997; Wang *et al.* 2018). In contrast, the combination of intensive industrial activities and relatively lax environmental oversight in West Kazakhstan exacerbates its pollution challenges. This comparison underscores the importance of adopting international best practices and strengthening regulatory frameworks to address contamination issues effectively. Future research should focus on developing and implementing cost-effective remediation techniques tailored to the specific conditions of West Kazakhstan. Phytoremediation, bioremediation, and soil amendment strategies show promise for large-scale application in contaminated areas. Fostering public awareness and community engagement is crucial for building support for environmental policies and encouraging sustainable practices. Longitudinal studies are also needed to monitor the long-term effectiveness of remediation efforts and assess the impacts of policy changes on soil quality and ecosystem health (Khans *et al.* 2019). Collaborative efforts between researchers, policymakers, and local communities will be essential for achieving meaningful progress in mitigating soil contamination and safeguarding the region's environmental and public health. Based on laboratory studies, excessive concentrations of heavy metals were detected in Uralsk City: indicators of total copper (12.4 – 16.1 mg kg^{-1}), total cadmium (4.0 – 4.7 mg kg^{-1}), chromium (299.0 – 436.9 mg kg^{-1}) and arsenic (7.0 – 9.9 mg kg^{-1}). The highest concentration (405.6 – 436.9 mg kg^{-1}) of chromium in the soil was modeled in the southeastern part of the study region (sample No. 115). The concentration of arsenic in the range from 9.3 to 9.9 mg kg^{-1} and total cadmium in the range of 4.6–4.7 mg kg^{-1} were present in the northern part of the region (sample No. 114). Comparatively higher concentrations of total copper (28.2–32.3 mg kg^{-1}) were observed in the western part of the extent (sample No. 113). The values of mobile copper (0.7–1.7 mg kg^{-1}), mobile lead (0.6–1.4 mg kg^{-1}), mobile boron (0.1–0.36 mg kg^{-1}) and total lead (24.4–215.9 mg kg^{-1}) did not exceed the norm. The highest concentrations of nickel (81.5–95.9 mg kg^{-1}), mobile cadmium (0.6–1.0 mg kg^{-1}) and total zinc (132.5–215.9 mg kg^{-1}) in the soil were found in the western and northwestern parts of the extent (samples No. 113 and 114).

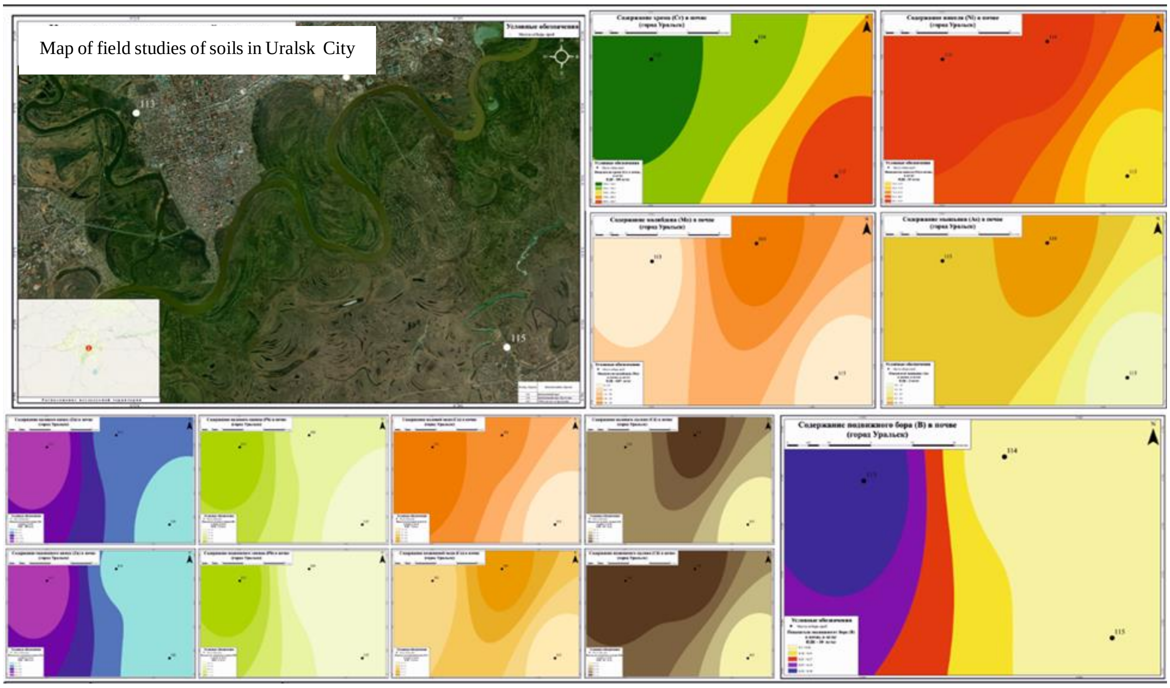

Fig. 2. Cartographic model of sampling points and distribution of heavy metals in the soil (Uralsk City).

CONCLUSION

This study provides a comprehensive assessment of the current state of soil contamination in the West Kazakhstan region, which is driven primarily by industrial activities. The findings reveal significant levels of heavy metal pollutants, including lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni), across various industrial sites. Mining operations were identified as a major contributor to the elevated concentrations of these metals, posing substantial ecological risks and health hazards due to their toxicity and potential for bioaccumulation in food chains. Using the ecological risk index (ERI), it was determined that areas surrounding mining operations exhibit higher ecological risks compared to those near oil refineries, primarily due to the elevated concentrations of highly toxic metals such as arsenic and cadmium. Correlation analysis further reinforced these findings, revealing strong positive associations between specific contaminants and industrial activities. Notably, arsenic levels showed a remarkably high correlation with mining operations ($r = 0.95$, $p < 0.001$), underscoring the dominant role of mining in soil contamination. These results highlight the urgent need for effective strategies to mitigate pollution from industrial sources in West Kazakhstan. Key measures include implementing stricter regulations on waste management practices, developing cost-effective remediation techniques suitable for large-scale application, and enhancing public awareness about heavy metal contamination's environmental and health impacts. Additionally, this study emphasizes the importance of prioritizing targeted interventions based on risk severity assessments. Policymakers can optimize resource allocation and address the most critically contaminated regions by focusing remediation efforts on areas with high ecological risk indices. Such an approach not only ensures efficient resource use but also maximizes the effectiveness of environmental restoration efforts, ultimately contributing to the long-term sustainability of the region's ecosystems and public health.

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Bibliographic information of this paper for citing:

Bazarbayeva, T, Khassenova, A, Tukenova, Z, Mukanova, G, Shimshikov, B, Tussupova, B, Kudaibergen, K, Alimuratkyzy, A 2025, Current state of contamination of soil in the West Kazakhstan Region with toxic chemicals as a result of industrial activities, Caspian Journal of Environmental Sciences, 23: 173-180.