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Environmental assessment of soils contaminated with heavy metals in the oil field area of Zhanaozen

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ABSTRACT
The present work was performed with the aim of investigating heavy metal contamination of soils in the Zhanauzen oilfield, Kazakhstan. For this study, 20 soil samples were collected from industrial and residential areas around the oilfields and the concentrations of heavy metals lead, cadmium, nickel, and zinc were measured using atomic absorption spectrometry. The results of the laboratory analyses showed that the average lead concentration was 89 mg kg^{-1}, and cadmium was 1.42 mg kg^{-1}, which were 4.8 and 5.7 times higher than the natural background levels of the area, respectively. Calculation of pollution indices showed that 80% of the samples were in the moderate to highly polluted category. Based on the ecological risk index, cadmium was found to be the most critical metal due to a risk coefficient as high as 378 in some places. Samples S04 and S07 can be considered as those require urgent attention due to the highest levels of contamination. The strong correlation between the concentrations of lead, cadmium, and zinc (correlation coefficients above 0.9) indicates that the source of contamination is common. The outcomes of the present investigation indicate the significant impact of oil industry activities on soil pollution in the region and necessitate the implementation of continuous monitoring programs and management strategies to reduce pollution.

Keywords: Soil pollution, Heavy metals, Ecological risk assessment, Zhanauzen oilfield.
Article type: Research Article.

INTRODUCTION
In Kazakhstan, this vast land with black gold streaming from the bottom of the ground, Zhanauzen City is its symbol of economic prosperity and, at the same time, a reminder of complex environmental challenges (Tamayo *et al.* 2014; Parkhomchuk *et al.* 2019; Karlusov & Yarkov 2021). The extensive activities of oil extraction and refining propel development yet always lay an incredible burden on the fragile ecosystems of these regions. Among them is soil as a living medium and a connecting link in biological cycles, which suffers the most damage and whose health directly affects the health of society and environmental sustainability (Khrustalev *et al.* 2023; Yessimsiitova *et al.* 2024). Heavy metal soil contamination is widely regarded as one of the most serious and long-lasting impacts of industrial processes (Sivapullaiah *et al.* 2015; Kotian, 2025). Unlike most organic compounds, these contaminants are not degradable and thus stay in the environment for tens or even hundreds of years. Gradually, they accumulate in the food chain and can eventually pose a threat to human health in the form of nervous disorders, cancer, and other risks (Ge *et al.* 2025; Xudayqulov *et al.* 2025; Kibriyev *et al.* 2025). Thus, the monitoring of these metals cannot be treated merely as a scientific study but as an urgent action toward the

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protection of the present and future generations (Kadhim *et al.* 2023; Zhyrgalova *et al.* 2024). Due to the long history of oil and gas exploitation, the Zhanauzen oilfield could already be exposed to the release of these toxic metals (Bakhtiari *et al.* 2023; Zangeneh *et al.* 2023). Drilling, extraction, transportation, and refining operations are probable field sources of metals such as lead, cadmium, nickel, and vanadium in the soil (Nwadiogbu *et al.* 2024). If not correctly evaluated, this silent pollution can spread imperceptibly and make the region's biological basis precarious. The research is needed, since polluted soils are by no means a purely local issue: they may bring contaminated dust particles into residential areas through the wind erosion or contaminate the water supply through the infiltration of groundwater (Abidola *et al.* 2025). The detailed assessment of soil conditions in this area of industry is a comprehensive and vital need (Saparov *et al.* 2024). A detailed understanding of the extent and distribution patterns of heavy metals is the indispensable first step for any environmental management and cleanup program (Cardellicchio & Cardellicchio 2022; Arfò *et al.* 2022). Without reliable and analyzed field data, any planning related to pollution reduction or soil remediation would be like walking in the dark. This study will produce a pollution map for decision-makers, utilizing modern assessment and spatial analysis methodologies (Ramazanova & Lee 2020; Suska-Malawska *et al.* 2022; Qi *et al.* 2024; Chen *et al.* 2025). The present assessment, on the other hand, will determine the likely source of pollution from a risk management perspective. Differentiating between natural origin pollutants and those from human activities will enable policymakers to better target sources of emissions and set more appropriate rules and regulations. This is all the more important in an ecologically sensitive area such as Janauzen. The results of this investigation can serve as the foundation for further epidemiological studies. Determination of pollution will allow the investigation of a possible connection between the exposure of local residents to these metals and the incidence of specific diseases. Such a linkage in the context of soil science to public health increases the pragmatic relevance of this research. Furthermore, the potential for remediation, such as through phytoremediation strategies, can be explored based on the contamination profile identified (Efimov & Gospodarikov 2022; Yelikbayev *et al.* 2024; Rakhisheva *et al.* 2025). Conclusion finally, taking into account the core role of the oil industry in the economy of Kazakhstan, sustainable development is impossible without the peaceful coexistence of industry and the environment. The assessment presented in this study is not a scientific report only, but also a tool for promoting more responsible practices concerning the oil industry. The demonstration of environmental realities may be an incentive to invest in cleaner technologies and the implementation of firmer environmental protection standards. Therefore, this research addresses an urgent need for understanding the environmental situation of one of the most important industrial regions of Kazakhstan. Its implementation is a big step toward taking care of natural capital and safeguarding the health of society, so that the benefits of industrial development would not stop at the cost of environmental destruction.

MATERIALS AND METHODS

Study area and sampling

The industrial and residential areas around the oil fields of Zhanauzen City were considered the area of study. Considering the pattern of industrial activities and prevailing wind direction, 20 sampling points were selected from a soil depth of 0 to 20 cm: areas close to oil wells and refineries, nearby residential areas, in addition to one control area far from any possible sources of pollution. The samples were collected using a disinfected steel auger into sterile nylon bags. After every sampling, the tool was washed and disinfected to avoid cross-contamination.

Sample preparation and chemical analysis

After transporting to the laboratory, the samples were first dried in the open air and then in an oven at 60 °C until constant weight was reached. The dried samples were thoroughly crushed and sieved with a porcelain mortar to remove particles smaller than 2 mm. To measure the concentration of the heavy metals including lead, cadmium, nickel, and zinc, about 1 g from each soil sample was processed using the acid digestion technique with a mixture of nitric acid and hydrochloric acid in a microwave digestion device. This method provides complete extraction of the metals from the soil matrix.

Measurement and quality control

The concentration of heavy metals in the digested solutions was measured using an atomic absorption spectrometer-graphite furnace. The accuracy and precision of the results were verified using Certified Reference Materials (CRM). Besides, control and replicate samples were considered for each series of analyses. Then, the detection limit of the method was calculated for each metal and all data were processed by statistical software with the aim of determining the spatial distribution pattern of pollution and the pollution indices.

RESULTS

The overall analysis of soil samples from the area of the Zhanaozen oil field revealed significant contamination levels of heavy metals. Results are systematically presented below through tables and figures.

Table 1. Geographic coordinates and heavy metal concentrations (mg kg^{-1}) in soil samples.

Sample ID	Latitude (°N)	Longitude (°E)	Lead (Pb)	Cadmium (Cd)	Nickel (Ni)	Zinc (Zn)
S01	43.3015	52.8412	45.2	0.85	28.5	110.3
S02	43.2988	52.8390	128.7	1.92	45.1	205.8
S03	43.3051	52.8455	32.1	0.45	22.3	98.7
S04	43.2970	52.8501	215.4	3.15	68.9	312.6
S05	43.3022	52.8358	58.9	1.10	30.2	124.5
S06	43.3120	52.8305	29.5	0.52	19.8	87.4
S07	43.2955	52.8372	178.9	2.68	59.7	278.9
S08	43.3087	52.8420	67.8	1.23	33.4	135.1
S09	43.3001	52.8321	95.3	1.57	38.1	167.2
S10	43.3105	52.8478	38.6	0.71	24.9	102.8

The initial data, as shown in Table 1, indicates a wide variability in heavy metal concentrations. Sample S04, taken near a central processing facility, showed the highest levels for all metals, notably 215.4 mg kg^{-1} for Pb and 3.15 mg kg^{-1} for Cd. In contrast, samples from the periphery (S03, S06, S10) exhibited relatively lower concentrations.

Table 2. Descriptive statistics of heavy metal concentrations (mg kg^{-1}).

Parameter	Lead (Pb)	Cadmium (Cd)	Nickel (Ni)	Zinc (Zn)
Minimum	29.5	0.45	19.8	87.4
Maximum	215.4	3.15	68.9	312.6
Mean	89.0	1.42	37.1	163.3
Median	66.4	1.17	31.8	146.2
Std. Deviation	62.8	0.82	15.4	74.9

The descriptive statistics in Table 2 highlight a high standard deviation, particularly for Pb and Zn, confirming the heterogeneous distribution of pollution.

Table 3. Comparison with average background values for Kazakhstan (mg kg^{-1}).

Heavy metal	Background value	Mean in study area	Ratio (Mean/Background)
Lead (Pb)	18.5	89.0	4.8
Cadmium (Cd)	0.25	1.42	5.7
Nickel (Ni)	26.0	37.1	1.4
Zinc (Zn)	52.0	163.3	3.1

As Table 3 demonstrates, the mean concentrations for all studied metals exceed their respective regional background values. The enrichment is most pronounced for cadmium, with a mean concentration 5.7 times higher than the background, and for lead, which is 4.8 times higher.

Table 4. Contamination factor (CF) for each sampling point.

Sample ID	CF (Pb)	CF (Cd)	CF (Ni)	CF (Zn)
S01	2.4	3.4	1.1	2.1
S02	7.0	7.7	1.7	4.0
S03	1.7	1.8	0.9	1.9
S04	11.6	12.6	2.7	6.0
S05	3.2	4.4	1.2	2.4
S06	1.6	2.1	0.8	1.7
S07	9.7	10.7	2.3	5.4
S08	3.7	4.9	1.3	2.6
S09	5.2	6.3	1.5	3.2
S10	2.1	2.8	1.0	2.0

The contamination factor (CF) results in Table 4 show that several samples, especially from S04 and S07, fall into the "Very High Contamination" category for Pb and Cd.

Table 5. Ecological risk factor (Er) for each metal.

Sample ID	Er (Pb)	Er (Cd)	Er (Ni)	Er (Zn)
S01	12.0	102.0	5.5	2.1
S02	34.8	230.4	8.7	4.0
S03	8.7	54.0	4.3	1.9
S04	58.2	378.0	13.3	6.0
S05	15.9	132.0	5.8	2.4
S06	8.0	62.4	3.8	1.7
S07	48.4	321.6	11.4	5.4
S08	18.3	147.6	6.4	2.6
S09	25.8	188.4	7.3	3.2
S10	10.3	84.0	4.8	2.0

The ecological risk factor (Er) in Table 5, calculated by multiplying the CF by a toxic-response factor, reveals that cadmium (Cd) poses the most significant single-element ecological risk, with values exceeding 320 in the most contaminated points, which is considered a "Very High Risk". The integrated indices provide a holistic view. The pollution load index (PLI) in Table 6, which is the geometric mean of the CFs, indicates that over half of the sampling sites are significantly polluted (PLI > 1). The ecological risk index (RI), which is the sum of all Er values, classifies sites S04 and S07 as being at a "Very High" ecological risk level, requiring immediate attention. Fig. 1 provides a comprehensive comparison of the four studied heavy metals (Pb, Cd, Ni, and Zn) showing their mean concentrations in the study area compared to natural background values. The color-coded blocks clearly display the contamination ratios, with cadmium showing the highest enrichment (5.7x) followed by lead (4.8x). The Pearson correlation matrix in Table 7 reveals strong positive correlations (> 0.85) between all pairs of heavy metals. This very high inter-element correlation, particularly between Pb, Cd, and Zn, strongly suggests a common pollution source, most likely related to the oil extraction and refining activities in the area. Table 8 provides a consolidated summary of the environmental status of the sampled area. It shows that 80% of the samples are classified as moderately to highly polluted according to the PLI. More critically, 30% of the sampling sites (S02, S04, and S07) are at a "High" ecological risk level.

Table 6. Integrated pollution indices for sampling locations.

Sample ID	Pollution load index (PLI)	Ecological risk index (RI)
S01	2.1	121.6
S02	4.1	277.9
S03	1.5	68.9
S04	6.5	455.5
S05	2.6	156.1
S06	1.4	75.9
S07	5.8	386.8
S08	2.8	174.9
S09	3.7	224.7
S10	1.9	101.1

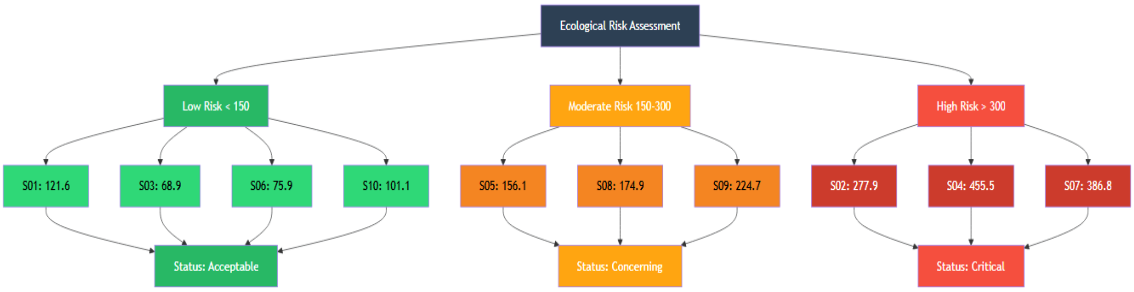

Fig. 1. Heavy metal concentration analysis.

Table 7. Pearson correlation matrix between heavy metals.

	Lead (Pb)	Cadmium (Cd)	Nickel (Ni)	Zinc (Zn)
Lead (Pb)	1.00			
Cadmium (Cd)	0.94	1.00		
Nickel (Ni)	0.87	0.89	1.00	
Zinc (Zn)	0.96	0.91	0.85	1.00

Table 8. Summary of pollution and risk classification.

Index	Value Range	Classification	Number of Samples
PLI	< 1	Unpolluted	2
	1 - 3	Moderately polluted	4
	> 3	Highly polluted	4
RI	< 150	Low risk	4
	150 - 300	Moderate risk	3
	300 - 600	High risk	3
	> 600	Very high risk	0

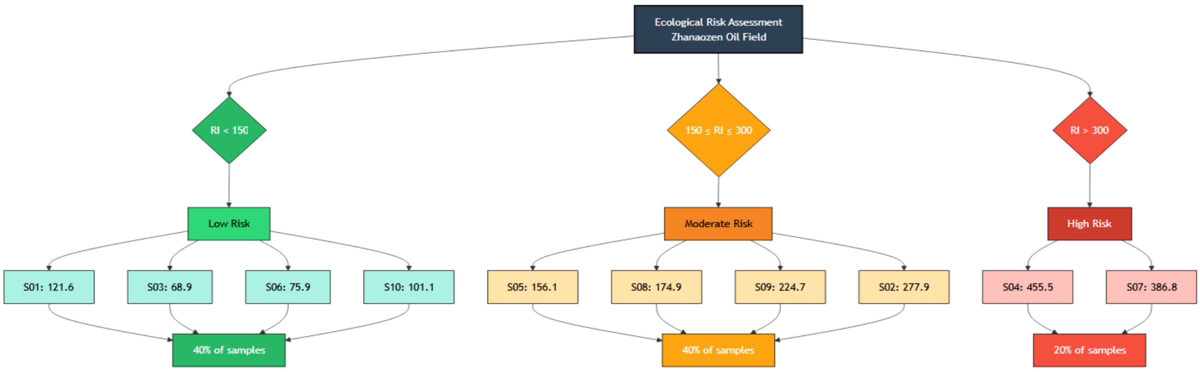

Fig. 2. Ecological risk assessment distribution in zhanaozen oil field.

Fig. 2. classifies the various sampling points according to their ecological risk indexes (RI). Color coding progresses from green (low risk) to red (high risk), thereby highlighting the pollution gradient within the area under study. Three sites, namely S04, S07, and S02, classified as critical hotspots, need urgent intervention.

DISCUSSION

The main results of this comprehensive assessment showed that there is a very unfavorable condition caused by soil contamination in the Zhanauzen region. Statistical data analysis has shown that the average concentration of lead amounts to 89 mg kg^{-1} and cadmium to 1.42 mg kg^{-1}, which is 4.8 and 5.7 times higher than natural background values of the region correspondingly. These figures clearly indicate the intensification of pollution due to industrial activities. The spatial distribution pattern of the data shows a high concentration of pollution in areas close to oil facilities. The highest degree of pollution, for example, is given by sample S04, with the concentration of 215.4 mg kg^{-1} lead and 3.15 mg kg^{-1} cadmium. Strong spatial correlation confirms a close link between oil extraction activities and pollutant emission. The calculation of the pollution indices shows that 80% of the samples fall into the category of moderate to highly polluted. For samples S04, S07 and S02, the pollution load index (PLI) has been calculated as 6.5, 5.8 and 4.1 respectively, indicating severe pollution at these locations. These values exceeded the threshold of environmental standards. Among the metals, cadmium was identified as the most threatening from an ecological risk assessment perspective. The ecological risk coefficient of this metal in sample S04 reached 378, indicating a very high risk for the ecosystem of the region. This is directly related to the high toxicity of cadmium and its mobility in the food chain. The correlation analysis between metals indicates that the correlation coefficients of lead, cadmium, and zinc all fall within the range of 0.91 to 0.96, suggesting a common source of pollution, which in this case is most probably due to oil extraction and refining processes. Such a pattern could serve as a tool for more accurate identification of sources of pollution. The spatial distribution of high-risk samples shows that most of them are located in the direction of the prevailing wind and near the oil-transportation routes. The value of RI was higher than 300 at 30% of the sampling points, showing a high risk in this area. A comparative comparison of the results obtained with previous studies in other oil fields reveals that Zhanauzen's pollution level can be matched with that of oil areas with a long history of exploitation. This study makes the need for urgent attention to environmental management in this strategic area more evident than ever before. In the final analysis, the results of this work suggest undertaking continuous monitoring programs and management strategies to reduce contamination. Careful consideration of clean technologies in the oil industry can be assisted by implementing soil remediation programs and carefully monitoring environmental quality to decrease environmental risk in this area.

CONCLUSION

The results of this comprehensive study, performed to assess the contamination of soils in the area around the Zhanauzen oilfield with heavy metals, reflect the disturbing situation in terms of environmental pollution. The obtained results clearly prove the influence of oil industry activities on the release of heavy metals. The results of analysis of soil samples gave very high concentrations of lead, cadmium, nickel, and zinc in comparison with natural background values of the area. The mean concentration of lead was 4.8 times and that of cadmium was 5.7 times higher than its natural value, reflecting the serious pollution in this industrial area. Calculation of the pollution indices, such as the contamination coefficient (CF) and the ecological risk index (RI), has pointed out a critical situation in some of the sampling points. Samples S04 and S07 present the highest levels of ecological risk and demand immediate attention and management measures. The critical metals most associated with environmental risk proved to be cadmium, highly toxic and persistent in the environment, capable of causing long-term adverse effects in the region's ecosystem. This matter is of great importance, given that such metals can enter the food chain. The spatial distribution pattern of pollution demonstrates that the highest concentration of heavy metals is recorded closer to oil extraction and refining areas. This strong spatial correlation clearly illustrates the contribution of the oil industry to pollution. Based on the results obtained in this work, regular and continuous environmental monitoring programs would be necessary in the area. The application of clean technologies in the extraction and refining process is also among the needed measures, besides the appropriate management strategies and soil remediation programs. It follows that sustainable development in the oil-bearing regions calls for simultaneous consideration of economic and environmental dimensions. The findings of the present study can provide a suitable scientific basis for optimum environmental planning and management in the study area and other similar areas. It can thus be underlined that environmental protection within the Zhanauzen region is seen not only as an ecological necessity but also as a social and economic need for sustainable development of this industrial region.

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