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Spatial heterogeneity of soil pollution by heavy metals in areas of chromite ore mining

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ABSTRACT

The spatial distribution of heavy metal contamination in the soil cover around the Don Mining and Processing Plant (Don MPP), a major chrome ore deposit and processing hub in Western Kazakhstan, was investigated through a comprehensive environmental assessment. Eighteen soil samples were collected across an anthropogenic gradient radiating from the industrial complex, including disturbed areas, reclamation mounds, and virgin soils. Physico-chemical characterization of the soil revealed neutral to moderately alkaline pH (7.15–8.25) and low organic matter content (0.85 %–2.15 %). Total concentrations of chromium (Cr), nickel (Ni) and copper (Cu) were determined to assess pollution levels of the soil resulting from chrome-ore extraction and processing. Chromium and nickel exhibited significant enrichment, with maximum values reaching ~1,850 mg kg^{-1} and ~480 mg kg^{-1}, respectively, far exceeding the national permissible limits. Geostatistical mapping indicated heavily localized contamination plumes emanating from the mine dumps and processing zones, while copper enrichment was moderate and largely confined to industrial yards. The results highlight the persistence of heavy-metal pollution in the soil cover of mining-impacted landscapes and underline the need for targeted remediation and continuous monitoring of soils in the vicinity of major ore deposits.

Keywords: Soil cover, Heavy metal, Pollution, Environmental assessment, Deposit, Don MPP (Mining and processing plant), Chrome ore
Article type: Research Article.

INTRODUCTION

Mining and ore processing activities are among the most significant anthropogenic sources of heavy metal pollution in terrestrial ecosystems. Metals such as chromium (Cr), nickel (Ni), copper (Cu), and lead (Pb) are persistent in soils, non-biodegradable, and capable of entering the food chain through bioaccumulation, posing long-term ecological and human health risks (Briffa *et al.* 2020; Haghighizadeh *et al.* 2024; Jomova *et al.* 2025). The spatial distribution of these elements in mining environments is typically heterogeneous, reflecting complex interactions among emission sources, topography, soil properties, and climatic factors (Chen *et al.* 2021; Sun *et al.* 2024; Lu *et al.* 2024). Assessing this spatial heterogeneity is crucial for evaluating environmental risk and designing effective remediation strategies. Chromium, in particular, is of global environmental concern due to its dual oxidation statesincluding the relatively stable trivalent form (Cr^{3+}) and the highly toxic and mobile hexavalent form (Cr^{6+}; Ukhurebor *et al.* 2021). Chromite ($FeCr_2O_4$) mining and ferrochrome processing are major sources of Cr contamination, releasing fine particulate matter and metalliferous waste that can persist in surface soils for decades (Khan *et al.* 2024). Nickel and copper often accompany chromium in ultramafic and lateritic deposits, compounding the pollution problem through synergistic toxic effects (Kierczak *et al.* 2021). Khromtau City, located in Western Kazakhstan, hosts one of the world's largest chromite ore deposits, mined by the Don Mining and Processing Plant (Don MPP), a branch of TNC Kazchrome JSC. The Don MPP produces the majority of Kazakhstan's chromium output and represents a major industrial hub in the region. However, the intensive

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extraction, processing, and waste disposal activities have led to extensive environmental transformation, including degradation of soil structure, loss of fertility, and heavy metal accumulation (Beketova *et al.* 2019). Previous regional studies have reported elevated Cr and Ni concentrations in soils beside the mining areas in Kazakhstan and Central Asia, often exceeding international guideline values (Safarov *et al.* 2023; Bazarbayeva *et al.* 2025).
Despite these findings, systematic investigations on the spatial heterogeneity of soil contamination in Khromtau remain limited. Most earlier assessments have focused on point measurements rather than spatially continuous modeling, leaving uncertainties in the extent and intensity of contamination. The integration of field surveys, laboratory analyses, and geostatistical modeling provides a more comprehensive approach to quantifying the spread and behavior of heavy metals in industrial landscapes (Maramis *et al.* 2021; Jia *et al.* 2024; Zhakypbek *et al.* 2025). Therefore, this study aimed to (i) characterize the physico-chemical properties of soils within and around the Don MPP; (ii) quantify total concentrations of Cr, Ni, and Cu; (iii) evaluate the spatial distribution patterns of contamination using geostatistical methods; and (iv) assess the effectiveness of reclamation efforts and potential environmental risks. The results provide an essential scientific basis for environmental management, remediation planning, and sustainable land use in one of Kazakhstan's most industrially impacted mining regions.

MATERIALS AND METHODS

Study area

The study was conducted in an industrial hub specializing in chromite ore extraction and processing, located in the vicinity of Khromtau, a city in the Aktobe Region of Western Kazakhstan. Khromtau lies within the dry steppe climatic zone, which is characterized by arid continental conditions with hot summers, cold winters, and low annual precipitation (200–250 mm on average). The natural vegetation consists primarily of xerophytic steppe grasses and shrubs, which have been largely replaced in industrial areas by sparse, secondary vegetation due to heavy anthropogenic disturbance. The current state of the vegetation is depicted in Fig. 1.

Fig. 1. Vegetation cover in the industrial zone beside Khromtau.

The predominant soils of the region are dark chestnut soils (Haplic Kastanozems), formed on dark brown, dense sandy loams interspersed with thin layers of loam and sand. These soils are moderately calcareous, with well-developed humus horizons under natural conditions. However, their properties have been significantly modified by mining, ore processing, and reclamation activities. The region is heavily influenced by large-scale industrial operations, primarily the Don Mining and Processing Plant (Don MPP), a branch of TNC Kazchrome JSC, which is the main source of chromium ore in Kazakhstan. In addition to chromite mining, the nickel and copper extraction contribute to the local environmental load. The Don MPP complex includes open-pit quarries, tailing dumps, ore enrichment facilities, and auxiliary industrial zones, all of which contribute to intense soil contamination by heavy metals such as Cr, Ni, and Cu through atmospheric deposition, wastewater infiltration, and solid waste accumulation. The Don mining and processing zone is represented in Fig. 2. The study area comprised both heavily disturbed industrial territories (e.g., external dumps, quarry margins, and concentrator sites) and peripheral lands with varying degrees of anthropogenic impact. In addition, reclamation mounds (areas where restoration efforts were undertaken approximately ten years prior) were investigated to assess postreclamation soil recovery. For comparative purposes, nearby virgin soils unaffected by direct mining influence were also sampled to provide baseline data on natural soil properties and metal concentrations.

Fig. 2. Don mining and processing zone.

Soil sampling design

Site Selection

To capture the spatial heterogeneity of heavy metal pollution and assess the influence of anthropogenic activities across the Don Mining and Processing Plant (Don MPP) zone, a systematic site selection strategy was employed. A total of 18 representative monitoring sites (designated as Sites Nº1–Nº18; Fig. 3) were established along environmental gradients reflecting varying degrees of industrial influence, geomorphological setting, and land use.

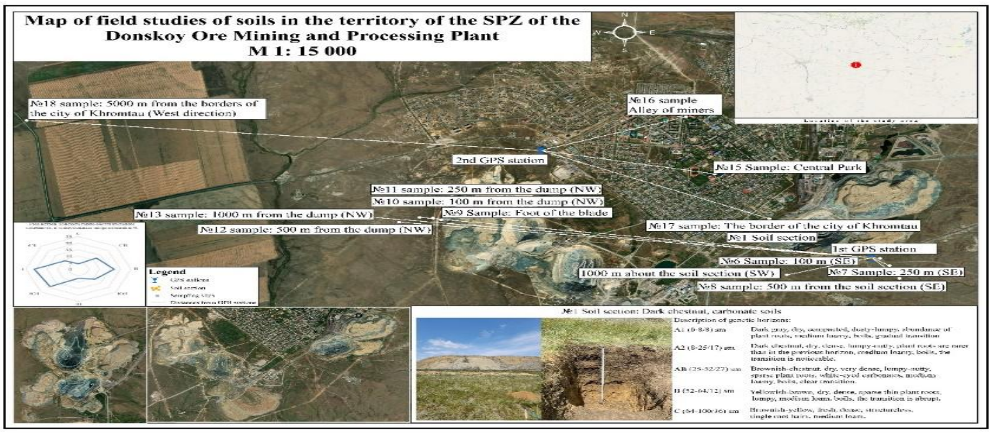

Fig. 3. Map of field studies of soils in the territory of the SPZ of the Don Mining and Processing Plant.

The primary criterion for site selection was the distance and orientation from major pollution sources, including open-pit mines, ore concentrators, tailing and waste dumps, and industrial processing areas. Additional factors included terrain configuration, prevailing wind direction, soil type, vegetation cover, and reclamation history. Sampling points were organized along transects radiating from the principal industrial dumps, following both northwestern and southeastern directions, to capture directional trends in heavy metal dispersion. These transects included sampling sites located at approximate distances of 100 m, 250 m, 500 m, and 1000 m from the dump perimeter. This design enabled assessment of contaminant attenuation with increasing distance from emission sources. To establish a rigorous comparative baseline and account for varying levels of anthropogenic influence, the spatial framework incorporated both control and urban reference sites. Site Nº18 served as the background control, positioned approximately 5,000 m west of Khromtau in an area demonstrably unaffected by industrial emissions. Concurrently, Sites Nº15 (Central Park) and Nº16 (Alley of Miners) acted as urban reference points, capturing soils subjected to moderate, generalized anthropogenic load typical of an urban environment. The remaining monitoring sites were distributed across distinct geomorphological and functional zones, strategically covering areas defined by recent technogenic deposits, sparse vegetation, and severely degraded soil horizons, representing the highest impact zone (Disturbed Industrial Grounds). Furthermore, sampling included Reclamation Mounds, which were formed during restoration efforts approximately one decade prior to sampling and represent partially recovered soils under post-remediation conditions. Finally, Peripheral Virgin Lands, characterized by native steppe soils with minimal antecedent anthropogenic disturbance, provided a boundary for natural background variation. This comprehensive spatial resolution enabled the comparative evaluation of pollution gradients between industrial, transitional, and background zones, ensuring high environmental representativeness.

Sample collection

At each of the 18 monitoring sites, soil cuttings were excavated to visually assess the morphological characteristics and stratigraphy of the soil profile. Field descriptions included soil color, structure, texture, carbonate content, horizon thickness, and vegetation type. For laboratory analyses, composite soil samples were collected from the surface layer (0–20 cm), which represents the most reactive zone of heavy metal accumulation due to direct exposure to atmospheric deposition and industrial fallout. In selected representative profiles, additional samples were obtained from subsurface horizons to evaluate vertical migration patterns of pollutants. Sampling was carried out using clean plastic and stainless-steel tools (scoops and augers) to avoid contamination. Each composite sample was derived from three subsamples collected within a 5 m radius and homogenized in the field to minimize micro-site variability. Samples were placed in pre-cleaned polyethylene bags, labeled with the site code, coordinates, and sampling depth, and then transported to the laboratory under controlled conditions to prevent cross-contamination or chemical alteration.

Sample preparation

In the laboratory, the soil samples underwent standardized pre-treatment prior to analysis:

Air-drying: Samples were air-dried at room temperature (~20 °C) until constant weight, avoiding exposure to direct sunlight or high temperatures that could alter chemical composition.

Cleaning and sieving: Visible plant residues, stones, and coarse fragments were manually removed. The dried samples were gently disaggregated using an agate mortar and pestle to prevent metal contamination, then sieved through:

a 2.0 mm mesh for general physico-chemical analyses (e.g., pH, EC, organic matter, and granulometry); and

a 0.15 mm mesh for total heavy metal determination (Cr, Ni, and Cu).

Homogenization and storage: The sieved samples were thoroughly mixed to ensure homogeneity and stored in airtight, labeled polyethylene containers under dry, dark conditions until laboratory analysis.

All sampling, handling, and preparation procedures were conducted in accordance with ISO 11464:2006 [16] (Soil Quality – Pretreatment of Samples for Physico-Chemical Analysis) and established environmental monitoring standards to ensure analytical accuracy and sample integrity.

Laboratory analyses

All analytical work was conducted at the UNESCO Chair for Sustainable Development Laboratory, Faculty of Geography and Environmental Sciences, Al-Farabi Kazakh National University (Almaty, Kazakhstan). Laboratory procedures followed internationally recognized protocols, including Arinushkina (1970), ISO 11047:1998 (International Organization for Standardization 1998), and ISO 11464:2006, with rigorous quality assurance and control measures applied throughout. The analytical workflow consisted of two major stages: determination of physico-chemical properties and heavy metal concentrations.

Physico-chemical properties

The fundamental physico-chemical properties of the soils were assessed using standard, well-established analytical methods designed to characterize the soil's textural composition, structure, acidity, and organic matter content. These properties are critical for understanding the environmental behavior, mobility, and retention of heavy metals within the soil matrix.

Granulometric and microaggregate composition

The particle-size distribution was determined using the pipette method according to Arinushkina (1970). Before analysis, organic matter was removed with 10% hydrogen peroxide (H_2O_2), and soil aggregates were dispersed with 0.05 M sodium hexametaphosphate ($Na_4P_2O_7$). The fractions of sand (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (< 0.002 mm) were quantified to classify soils according to the USDA soil texture triangle. The microaggregate composition was determined following Arinushkina's microaggregate stability method, which evaluates the proportion of water-stable aggregates (0.25–1 mm). This indicator reflects the degree of structural degradation or stability under anthropogenic stress and provides insight into the effects of mining and reclamation activities on soil structure.

Soil reaction (pH)
The soil pH was measured potentiometrically in a 1:2.5 soil-to-water suspension (w/v) using a calibrated pH meter (HANNA HI 2215 or equivalent). The measurement provides information on the acid-base status of the soil, which controls metal solubility and the chemical speciation of pollutants. Each sample was analyzed in triplicate, and mean values were used for interpretation.

Organic matter (OM) content
The organic matter content was determined by the Tyurin method, which involves wet oxidation of organic carbon using potassium dichromate ($K_2Cr_2O_7$) in a sulfuric acid medium (H_2SO_4), followed by titration with ferrous sulfate ($FeSO_4$). The organic carbon content obtained was multiplied by 1.724 to estimate the total organic matter percentage (OM%). This parameter serves as a key indicator of soil fertility, buffering capacity, and the ability to immobilize heavy metals.

Heavy metal determination
The total concentrations of chromium (Cr), nickel (Ni), and copper (Cu)—the primary pollutants associated with chromite ore extraction and processing—were quantified in the soil samples. The procedures included acid digestion of the solid phase followed by instrumental analysis using spectrometric techniques.

Acid digestion
Approximately 0.5 g of finely ground soil (<0.15 mm) was weighed into Teflon digestion vessels and subjected to wet acid digestion using a concentrated acid mixture of nitric acid (HNO_3), perchloric acid ($HClO_4$), and hydrofluoric acid (HF) in a closed digestion block or microwave digestion system (CEM MarsXpress). The samples were digested at a controlled temperature until a clear solution was obtained, indicating complete decomposition of the silicate matrix. After cooling, the digests were filtered through Whatman No. 42 filter paper and diluted to 50 mL with deionized water.

Instrumental analysis
The concentrations of chromium (Cr), nickel (Ni), and copper (Cu) in soil samples were determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and Atomic Absorption Spectrometry (AAS), depending on instrument availability and the required detection sensitivity. ICP-OES (PerkinElmer Optima 5300 DV) was employed for simultaneous multielement analysis, utilizing emission lines at 267.716 nm for Cr, 231.604 nm for Ni, and 324.754 nm for Cu. Complementary single-element measurements were conducted using AAS (PerkinElmer AAnalyst 400) with analytical wavelengths set at 357.9 nm for Cr, 232.0 nm for Ni, and 324.8 nm for Cu. Calibration curves were prepared using certified multi-element standard solutions (Merck, Germany) across a concentration range of 0.1–10 mg L^{-1}. The calibration coefficients (R^2) consistently exceeded 0.999, confirming excellent linearity. Method detection limits were 0.01 mg kg^{-1} for Cr and Ni, and 0.005 mg kg^{-1} for Cu. All analyses were performed in triplicate, and results are reported on a dry-weight basis (mg kg^{-1}).

Quality assurance and quality control (QA/QC)
Strict quality assurance and control (QA/QC) protocols were implemented at all stages of analysis to ensure the precision, accuracy, and reproducibility of results. The following measures were applied:
Triplicate analyses: All samples were analyzed in triplicate, and results were reported as mean ± standard deviation.
Standard Reference Materials (SRMs): Analyses included certified reference soils (e.g., CRM 7001 Loamy Soil) to verify the accuracy of metal determinations. Recovery rates ranged between 92% and 105%, within acceptable limits for environmental monitoring.
Reagent blanks: Blank samples were processed alongside soil samples to monitor potential contamination during digestion and analysis.

Instrument calibration: Calibration standards were prepared daily, and verification was performed every 10 samples to correct for instrumental drift.

Relative standard deviation (RSD): Analytical precision was ensured by maintaining RSD values below 5% for replicate measurements.

Cross-validation: Where possible, ICP-OES results were cross-checked against AAS measurements to confirm consistency and reliability.

All data were stored in a dedicated database with full traceability, enabling verification and long-term comparability with future monitoring campaigns.

RESULTS AND DISCUSSION

Physico-chemical characteristics of soils

The basic physico-chemical characteristics of the 18 soil samples collected across the Don MPP impact zone are summarized in Table 1. The soils generally correspond to the dark chestnut type typical of the dry steppe zone, but they have been strongly altered in disturbed and reclaimed areas. The soil reaction (pH) across the study area ranged from 7.15 to 8.25, indicating neutral to moderately alkaline conditions. The elevated alkalinity in the dump-proximal sites (e.g., Nº9, Nº5) is consistent with alkaline tailings and chromite waste material, which may raise the soil pH through carbonate enrichment. The alkaline conditions generally limit metal solubility and mobility but promote accumulation in the solid phase, increasing long-term contamination risks (Petruzzelli *et al.* 2025).

The organic matter (OM) content ranged from 0.85% to 2.15%, with the lowest values in quarry and dump edge sites, confirming topsoil loss and low biological productivity under strong anthropogenic pressure. Soils from control and urban green zones (e.g., Nº15, and Nº18) retained relatively higher OM contents (> 2.0%), consistent with greater vegetation input. The low OM in disturbed soils likely reduces metal complexation capacity, leading to weaker retention of heavy metals in the organic fraction (Zhong *et al.* 2025). Granulometric analysis showed that the soils were mainly sandy loam to medium loam, characteristic of the steppe's parent material. However, the external dumps (e.g., Nº5, and Nº9) exhibited a coarse, gravelly texture and poor structure, with inclusions of crushed rock and slag fragments. Such heterogeneity reflects technogenic material accumulation, reduced water-holding capacity, and hindered pedogenic development (Sokolov *et al.* 2021).

Table 1. Basic physico-chemical characteristics of soils in the Don MPP study area.

Site No.	Location Description	pH	OM (%)	Texture	Carbonate (%)	EC (µS cm^{-1})
1	100 m NW from dump	8.10	0.95	Sandy loam	7.8	320
3	250 m NW from dump	7.90	1.05	Sandy loam	6.9	280
5	100 m SE from dump	8.15	0.90	Loam	8.2	350
7	500 m SE from dump	7.85	1.20	Medium loam	7.0	260
9	Foot of dump (Disturbed)	8.25	0.85	Gravelly loam	9.5	410
10	Reclamation mound	7.70	1.45	Loam	6.8	240
12	1000 m SE (Periphery)	7.60	1.80	Loam	5.9	210
15	Central Park (urban control)	7.30	2.05	Loam	5.1	195
18	Virgin land control (5000 m W)	7.15	2.15	Loam	4.9	185

Heavy metal concentrations

The total concentrations of chromium (Cr), nickel (Ni), and copper (Cu) in soils are presented in Table 2, together with the local background values (Bn) for dark chestnut soils and the Kazakhstan Maximum Permissible Concentrations (MPCs). Chromium exhibited the highest overall concentrations, ranging from 120 to 1,850 mg kg^{-1}, exceeding the MPC in 67% of sampling sites. The strongest contamination was recorded adjacent to dumps and the concentrator area (Sites Nº5, Nº9, and Nº10), confirming these as primary contamination hotspots. The elevated Cr levels (up to six times the permissible limit) reflect both direct deposition of chromite dust and accumulation of chromium-bearing tailings. Nickel followed a similar spatial pattern, with concentrations of 35–480 mg kg^{-1}, and half of all sites exceeding the MPC. The parallel increase of Cr and Ni confirms their geochemical association within the chromite ore body. The steep decline of Ni concentrations with distance from the dump suggests that aerial fallout and surface runoff are dominant deposition pathways. Copper showed moderate enrichment, ranging from 18 to 155 mg kg^{-1}, with only 17% of sites exceeding the MPC. Elevated Cu values beside industrial workshops and transport zones (e.g., Nº5) likely result from equipment wear, lubricants, and fuel residues, marking Cu as a secondary anthropogenic contaminant compared to Cr and Ni.

Table 2. Total heavy metal concentrations (mg kg^{-1}) in soils of the Don MPP zone.

Site No.	Location Description	Cr	Ni	Cu	Cr/Bn	Ni/Bn	Cu/Bn	Cr/MPC	Ni/MPC	Cu/MPC
1	100 m NW dump	980	310	95	8.2	8.9	3.2	3.3	2.1	0.95
3	250 m NW dump	720	220	70	6.0	6.3	2.3	2.4	1.5	0.70
5	100 m SE dump	1,450	400	155	12.1	11.4	5.1	4.8	2.7	1.55
7	500 m SE dump	540	180	65	4.5	5.1	2.1	1.8	1.2	0.65
9	Foot of dump	1,850	480	120	15.4	13.7	4.0	6.2	3.2	1.20
10	Reclamation mound	330	140	58	2.8	4.0	1.9	1.1	0.9	0.58
12	1000 m SE	250	90	40	2.1	2.6	1.3	0.8	0.6	0.40
15	Central Park	180	75	35	1.5	2.1	1.2	0.6	0.5	0.35
18	Virgin land control	120	35	18	1.0	1.0	1.0	0.4	0.2	0.18
Bn (background)	—	120	35	18	—	—	—	—	—	—
MPC (Kazakhstan)	—	300	150	100	—	—	—	—	—	—

Spatial heterogeneity and contamination gradients

Geostatistical analysis demonstrated strong spatial dependence for both Cr and Ni concentrations, characterized by nugget-to-sill ratios below 25% and short spatial ranges (300–500 m). This indicates that heavy metal contamination is highly localized and strongly linked to specific emission sources, rather than diffuse atmospheric inputs. The short correlation range (~300 m) derived from the variogram analysis confirms that industrial point sources dominate metal deposition patterns. These results align with prior studies in similar chromite-mining regions, where localized contamination declines sharply beyond 500–700 m from emission centers (Hart 2012).

Contamination assessment

To quantify soil pollution severity, the Geoaccumulation Index (Igeo) and Contamination Factor (CF) were calculated (Table 3). According to Müller's classification, Igeo values >3 correspond to "highly contaminated" soils (Muler 1969). Most industrial and dump-adjacent sites fall into this category for Cr and Ni, while Cu contamination remains low to moderate. Contamination Factor (CF) values corroborate these findings: Cr CFs up to 15.4 and Ni CFs up to 13.7 indicate very high contamination intensity close to emission sources.

The Pollution Load Index (PLI), calculated as the geometric mean of the CF values for the three metals, ranged from 0.9 (control) to 4.8 (industrial core), indicating a transition from unpolluted to highly polluted conditions along the industrial–natural gradient.

Relationships between heavy metals and soil properties

Correlation analysis (Table 4) revealed significant relationships between heavy metal concentrations and key soil parameters. A strong positive correlation between Cr and Ni ($r = 0.87$) reflects their common geochemical and anthropogenic origin. Both metals showed negative correlations with OM, suggesting that low organic matter reduces metal retention, increasing the fraction of exchangeable ions. The moderate positive correlation between pH and Cr ($r = 0.41$) indicates that slightly higher alkalinity favors chromium fixation in less soluble trivalent forms.

Reclamation efficiency and environmental implications

Soils from reclamation mounds (N°10) exhibited intermediate contamination levels, with Cr and Ni concentrations reduced compared to active industrial zones but still above background values. This suggests that earlier reclamation measures (mainly topsoil replacement and regrading) were insufficient to fully immobilize contaminants. The persistent metal enrichment indicates recontamination from windblown dust and incomplete isolation of the underlying spoil material. Despite reduced mobility under alkaline conditions, the total metal burden represents a long-term ecological risk. Environmental factors such as acid rain, surface erosion, or human disturbance could mobilize metals, threatening surrounding ecosystems (Alloway 2012). Future remediation should thus integrate phytostabilization, organic amendments, and continuous monitoring to enhance immobilization and soil recovery.

Table 3. Heavy metal contamination indices in soils of the Don MPP zone.

Site No.	Cr (Igeo)	Ni (Igeo)	Cu (Igeo)	Cr (CF)	Ni (CF)	Cu (CF)	Pollution Category
1	3.8	2.9	1.5	8.2	8.9	3.2	Highly contaminated
3	2.8	2.2	0.8	6.0	6.3	2.3	Moderately–high
5	4.6	3.4	2.2	12.1	11.4	5.1	Highly contaminated
9	4.8	3.5	1.9	15.4	13.7	4.0	Highly contaminated
10	1.5	1.2	0.6	2.8	4.0	1.9	Moderately contaminated
15	0.6	0.3	0.2	1.5	2.1	1.2	Slightly contaminated
18	0.2	-0.5	-1.2	1.0	1.0	1.0	Uncontaminated

Table 4. Pearson correlation coefficients between heavy metals and selected soil properties (n = 18).

Parameter	Cr	Ni	Cu	pH	OM (%)
Cr	1.00	0.87	0.45	0.41	-0.62
Ni	—	1.00	0.39	0.36	-0.55
Cu	—	—	1.00	0.19	-0.31
pH	—	—	—	1.00	-0.22
OM	—	—	—	—	1.00

CONCLUSION

The investigation revealed that soils surrounding the Don Mining and Processing Plant (Don MPP) are substantially affected by heavy metal contamination, primarily from chromium and nickel associated with chromite ore extraction and processing. The surface soils (0–20 cm) showed high Cr (up to 1,850 mg kg^{-1}) and Ni (up to 480 mg kg^{-1}) concentrations, exceeding Kazakhstan's environmental standards by severalfold. Copper enrichment was moderate and spatially limited to industrial facilities. Geostatistical analyses demonstrated localized contamination plumes with short spatial ranges (300–500 m), confirming that heavy metal accumulation is strongly source-dependent and restricted mainly to areas immediately surrounding the dumps and concentrator. The spatial structure indicates that dust fallout and surface runoff are the principal dispersion mechanisms, with minimal long-range atmospheric transport. The soils' neutral to alkaline pH and low organic matter content influence metal mobility and retention. While alkalinity favors metal fixation and reduces immediate leaching risk, it also leads to persistent accumulation in the solid phase. The low organic carbon levels further limit natural stabilization mechanisms, increasing long-term environmental vulnerability under changing conditions.

Reclamation zones established a decade ago exhibited partial recovery of physical soil properties but continued to show elevated Cr and Ni concentrations, reflecting incomplete isolation of contaminated substrates and ongoing atmospheric deposition. Future management should emphasize:

Determination of bioavailable and toxic Cr(VI) fractions to assess ecological risk;

Implementation of phytoremediation or chemical stabilization techniques suited to alkaline, low-OM soils; and

Establishment of a long-term monitoring program integrating soil, vegetation, and water analyses.

In conclusion, the Don MPP area represents a case of persistent, spatially heterogeneous heavy metal pollution resulting from historical and ongoing mining activities. Addressing these challenges requires a combination of scientific monitoring, regulatory oversight, and adaptive remediation practices to support the sustainable development goals of Western Kazakhstan's mining regions.

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