

Analysis of the physicochemical properties and particle-size distribution of soils in the Khromtau region

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Abstract: The article analyzes the physicochemical properties and particle-size distribution of dark brown soils in the Khromtau region. The study areas included territories adjacent to the Don Mining and Processing Plant, areas near waste heaps (terricones), and agricultural lands used for crop cultivation. Soil samples were collected from different genetic depth horizons. The following parameters were determined: soil bulk density, humus content, total and mobile forms of nitrogen, phosphorus, and potassium, soil solution reaction (pH), the total content and ionic composition of water-soluble salts, as well as the particle-size distribution of the soils. The soil reaction was found to be weakly alkaline to alkaline (pH 7.6–8.5), while the salinity level remained low, indicating non-saline conditions. Particle-size analysis revealed a progressive increase in the proportion of fine fractions (fine silt and clay) in deeper soil layers, which negatively affects the soil moisture-aeration regime through compaction. The obtained results establish a solid baseline to develop scientifically based recommendations for the rational and sustainable use of soils and land resources in the region.

Keywords: soil cover; soil profile; morphological characteristics; chemical composition; particle-size distribution; dark brown soil; deposit; Don mining and processing plant.

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1. Introduction

The city of Khromtau represents one of the major industrial centers in the Aktobe region. It hosts the Don Mining and Processing Plant, which operates one of the largest chromium deposits in Kazakhstan. The soils surrounding the city are characterized as dark brown, typical of the dry steppe climate, and have undergone significant transformation driven by both human activities and climatic conditions (Mukanova, 2025; Koshim, 2015).

Dark brown soils cover several districts of the region, spanning a total area of approximately 3.6 million hectares; consequently, their distinct investigation is of paramount importance for the economic interests of agriculture (Safarov, 2023).

The topography of the region is highly diverse: while the western and eastern sectors are predominantly plains, the central part exhibits a hilly terrain. The complexity of the geological structure significantly

influences soil thickness as well as its physicochemical properties. Dark brown soils with a light texture (light particle-size distribution) dominate the central districts, whereas loamy soils prevail in the western and southwestern areas (Novikova, 1968). The chromium deposits surrounding the city further exacerbate the environmental situation. The industrial load primarily stems from the extraction of chromium, copper, and nickel ores (Koshim, 2015; Shakirzyanova, 2011).

The region ranks second globally in terms of chromium reserves, which leads to a high concentration of environmentally hazardous industrial facilities. The industrial infrastructure encompasses mining operations, processing plants, thermal power generation, and municipal utilities (Bazarbayeva, 2025; Mukanova, 2021). As a result of this technogenic impact, alterations occur in the structure and composition of the soil, preventing it from fully executing its ecological functions (Baltabayeva, 2023). Currently, soil degradation is pronounced, and its agricultural suitability is declining, which amplifies not only environmental but also socio-economic risks. Therefore, a comprehensive study of soil composition, structure, and the patterns of their transformation is of particular significance (Kalybekov, 2019; Osintseva, 2023).

The objective of this study is to analyze the physicochemical properties and particle-size distribution of dark brown soils in the Khromtau region. According to classical soil science concepts, physicochemical characteristics and particle-size distribution play a decisive role in regulating water-air regimes, nutrient availability, biological activity, and the overall fertility of soils (Kachinsky, 1965; Dobrovolsky & Nikitin, 2012; Shein, 2005). The soil within the area between the Don Mining and Processing Plant (MPP) in Khromtau and the adjacent agricultural fields was selected as the object of research. This specific area is characterized by the juxtaposition of a high-impact technogenic industrial zone and land allocated for agricultural use. In this regard, a comprehensive assessment of the ecological status of the soil cover is critically important.

In the map illustrating the spatial distribution of the study area (Figure 1), soil sampling points are arranged systematically; sampling via this method enables the evaluation of dynamics in the soil's ecological status (Alimuratkyzy, 2025). This approach facilitates the determination of distribution patterns regarding anthropogenic loads and the identification of high-risk zones. Furthermore, the grid-based arrangement of the research points ensures the representativeness of the obtained data (Khassenova, 2025; Wu, 2014; Grygar, 2025).



Figure 1. Spatial distribution of the study area

Unlike previous studies conducted in the Khromtau industrial zone, which mainly focused on geoecological assessment, heavy metal contamination, and remote sensing analysis (Koshim, 2015; Mukanova, 2025), the present study provides a detailed characterization of the physicochemical and

particle-size properties of dark brown soils located between the Don Mining and Processing Plant, waste heaps, and agricultural lands. The novelty of this research lies in the integrated assessment of soil bulk density, agrochemical parameters, water-soluble salts, and particle-size distribution across different genetic horizons, allowing evaluation of soil profile transformation under long-term technogenic influence. The obtained results provide baseline data for future monitoring of soil degradation and environmental changes in the Khromtau region.

2. Materials and methods

During the field research phase, soil profiles were established across territories experiencing varying degrees of natural and anthropogenic impacts. A total of two representative soil profiles (P-1 and P-2) were selected for detailed investigation. Profile P-1 was established between the Don Mining and Processing Plant and adjacent agricultural land, whereas Profile P-2 was established near waste heaps (terricones). For each horizon, laboratory analyses were performed in triplicate, and mean values are presented in the tables.

Laboratory analyses of the soil samples were conducted using standard methodologies widely accepted in the field of soil science: particle-size and microaggregate distributions were determined via the Kachinsky method; total organic carbon (humus) according to Tyurin; total nitrogen by the Kjeldahl method; carbonate carbon dioxide (CO²) using the Geissler-Maximyk method; cation exchange capacity (CEC) and exchangeable calcium (Ca²⁺) and magnesium (Mg²⁺) via the Gedroiz method; exchangeable sodium (Na⁺) and potassium (K⁺) using flame photometry; and water extract analysis according to Arinushkina. Furthermore, the pH of the soil suspension was measured colorimetrically; bulk density was determined using the Nekrasov auger core method; available phosphorus was analyzed via the Machigin method; available potassium according to Protasov; hydrolyzable nitrogen by the Tyurin and Kononova method; total phosphorus using the Pemberton method; total potassium via the Smith method; and bulk elemental analysis of the soil was conducted according to Gedroiz (Kachinsky, 1965; Jarsjö, 2017; Fernández-Martínez, 2014; Kim, 2025).

Within the framework of cartographic research methods, archival materials and field observation data were processed. Based on geographic information systems (GIS) technologies and remote sensing (RS) data, the specific soil sampling locations were precisely identified (Guo, 2025; Zeng, 2022; Woszczyk, 2018).

AI-assisted language editing tools (FixMeBot; ChatGPT) were used solely for grammatical and stylistic improvement. All scientific analyses, interpretations, and conclusions were performed by the authors.

3. Results

The high level of anthropogenic load within the territory of the Don Mining and Processing Plant has resulted in a substantial transformation of the soil cover. Driven by industrial activities, open-pit mines, external waste dumps, industrial sites, and processing complexes have completely lost their natural state. Consequently, soil fertility has declined, and its morphological and physicochemical properties have undergone significant alterations. In numerous areas, the fertile topsoil has been entirely removed, and the relief has undergone repeated mechanical leveling, leading to the formation of distinct anthropogenically modified (technogenic) landscapes in the region.

To characterize the soil morphology and determine its physicochemical properties, soil pits were excavated within the study area (coordinates: N – 50°14.725' / E – 58°22.055', absolute elevation: 401 m). The field analysis revealed that the soils in this specific area exhibit a dark brown coloration, and the local topography is characterized by a flat plain. Soil samples were subsequently collected to assess the physicochemical composition under laboratory conditions.

Soil Profile No. 1 was excavated in an area located 300 m south of a major open-pit mine featuring high waste heaps (terricones) adjacent to agricultural fields (Figure 2). The local topography is characterized as a flat, pristine steppe, with a total projective vegetation cover of 60 %. The plant community is predominantly composed of fescue-feather grass (*Festuca-Stipa*) and wormwood

(*Artemisia*), intermixed with calendula (*Calendula officinalis*), elecampane (*Inula*), common soapwort (*Saponaria officinalis*), and various other herbaceous species. The open-pit mines operating for chromium ore extraction are clustered around the Don Mining and Processing Plant (MPP). These open pits are surrounded by massive waste heaps reaching heights of 30 to 50 meters. The soil type is classified as a dark brown calcareous (carbonate) medium loam.



Figure 2. Soil profile established between the Don MPP and the agricultural field

Depth, cm	Horizon Description
A1 0 – 12 cm	Dark dark-brown color, dry, fine granular structure, dusty, presence of plant roots, heavy loam, presence of small stones; effervesces with 10 % hydrochloric acid (HCl); gradual transition to the subsequent horizon.
A2 12 – 22 cm	Dark dark-brown color, fresh (slightly moist), presence of plant roots, moist, heavy loam, stony, effervesces with 10 % hydrochloric acid (HCl); distinct transition to the subsequent horizon.
B1 22 – 30 cm B2 30 – 56 cm	Greyish dark-brown color, fresh (slightly moist), highly stony, presence of salt spots, plant roots are rare, heavy loam, presence of small gravelly stones; effervesces with 10 % hydrochloric acid (HCl); distinct transition to the subsequent horizon.
C 56 – 80 cm	Dark greyish-brown color, presence of whitish spots of salts and oxides, highly stony, heavy loam, effervesces with 10 % hydrochloric acid (HCl).

The wheat agricultural field is characterized by an open plain with sparse vegetation cover, indicating that the soil surface is highly susceptible to wind and water erosion. Such conditions contribute to the degradation of the soil's physical properties, a reduction in organic matter content, and the rapid dissemination of pollutants.

The proximity of agricultural lands to the industrial zone exacerbates the risk of heavy metals and other technogenic contaminants accumulating in the soil matrix. This, in turn, may exert a detrimental impact on the stability and sustainability of the agroecosystem.

In the vicinity of the chromium ore extraction sites, adjacent to the waste heaps (terricones), Soil Profile No. 2 was excavated within the dark brown soil zone to serve as a control/monitoring point (Figure 3) (coordinates: N – 50°16.306' / E – 58°30.262', absolute elevation: 403 m). The local topography is characterized as an undulating plain. The vegetation community is predominantly composed of fescue and feather grass (*Festuca-Stipa*), interspersed with wormwood (*Artemisia*) and various other herbaceous species. The total projective vegetation cover ranges between 70 % and 80 %.



Figure 3. Soil profile established adjacent to the waste heaps (terricones)

Depth, cm	Horizon Description
A1 0 – 9 cm.	Dark dark-brown color, porous, fine granular dusty structure, abundant vegetation, medium sandy loam, absence of foreign inclusions, small stones are rare; effervesces with 10 % hydrochloric acid (HCl); the transition to the subsequent horizon is distinct, defined by a change in density.
A2 9 – 22 cm.	Dark dark-brown color, compacted, fresh (slightly moist), presence of plant roots, fine granular dusty structure, presence of small stones, medium loam; effervesces with 10 % hydrochloric acid (HCl); the transition to the subsequent horizon is distinct, defined by a change in density.
B1 22 – 32 cm.	Dark-brown color, fresh (slightly moist), blocky-granular structure, presence of whitish spots of salts and carbonates, medium loam, dense; effervesces with 10 % hydrochloric acid (HCl); continuous, solid bedrock (stones) underlies below the depth of 32 cm.

The soil profile delineates the morphological structure of the soil within the study area. Distinct horizons, a shallow upper humus layer, and signs of compaction in the lower genetic horizons are evident across the profile. This structural state is interpreted as a direct consequence of long-term anthropogenic impact.

Soil physicochemical parameters (including pH, organic carbon/humus content, salinity levels, and heavy metal accumulation) serve as primary indicators for assessing the ecological stability of the ecosystem. In sampling points located proximate to the industrial zone, these parameters are

highly likely to deviate from baseline (background) values, whereas a relative improvement in ecological conditions is anticipated moving toward the agricultural fields.

The soil profile was established within a territory situated in the immediate vicinity of the waste heaps (terricones) in the Khromtau region. This area represents a technogenic landscape characterized by the accumulation of mining waste and is defined by a high level of anthropogenic stress exerted on the surrounding environment.

A flat steppe landscape is observed adjacent to the waste heaps. The vegetation cover is sparse, primarily comprising drought-resistant (xerophytic) herbaceous species. This ecological condition reflects a reduction in the naturally developed soil fertility and indicates an overwhelming technogenic impact. Pronounced signs of wind erosion create favorable conditions for the widespread dissemination of fine particulate matter.

The proximity of the waste heaps intensifies environmental risks, such as atmospheric dust pollution, heavy metal accumulation, and the disruption of the soil's native chemical composition.

The soil profile demonstrates weakly differentiated genetic horizons and a shallow topsoil layer. The thickness of the humus horizon is severely constrained, and the soil exhibits a light coloration, indicating an insufficient concentration of organic matter. With increasing depth, distinct compaction is observed in the lower horizons, resulting from the degradation of their physical properties.

The inclusion of technogenic materials within the profile matrix is highly apparent, demonstrating the infiltration and integration of particulate matter originating from the waste heaps into the soil horizons. This condition exerts a detrimental effect on the soil's moisture-aeration regime, thereby reducing the overall stability of the ecosystem.

The ecological status of the soils surrounding the waste heaps is continually shaped by the interplay of natural and anthropogenic factors. Consequently, these territories are classified as high-risk environmental zones that require systematic and continuous monitoring.

Table 1. Soil bulk density (structure density)

Soil Profile	Depth, cm	Tin No.	Mass of empty tin, g	Mass of soil before drying, g	Mass of soil after drying, g	Mass of absolutely dry soil, g	Mass of evaporated water, g	Moisture content, %	Mean moisture content, %	Bulk density, g/cm ³	Mean bulk density, g/cm ³
P-1, Agricultural field	0-12	23	74.92	196.00	190.40	115.48	5.60	4.85	5.67	1.22	1.20
		13	75.60	194.00	186.10	110.50	7.90	7.15		1.16	
		22	77.52	199.00	193.20	115.68	5.80	5.02		1.22	
	12-22	21	75.03	218.00	206.77	131.47	11.23	8.54	8.65	1.38	1.42
		15	74.18	227.00	213.21	139.03	13.79	9.92		1.46	
		10	75.44	193.00	184.29	108.85	8.71	7.50		1.14	
	22-30	11	74.60	215.92	201.06	126.46	14.86	11.75	11.49	1.33	1.36
		12	74.07	212.94	198.87	124.80	14.07	11.27		1.31	
		14	81.00	233.26	217.88	136.88	15.68	11.45		1.44	

During the research, the soil bulk density (structural density) in the Khromtau region (Khromtau, sampling point P-1) was determined using integrated field and laboratory methods. Samples were collected from genetic horizons at depths of 0–12 cm, 12–22 cm, and 22–30 cm (Table 1).

The soil bulk density was determined via the core (cylinder) method. Sampling was performed in triplicate for each horizon, during which the initial mass, mass prior to drying, and oven-dry mass

were sequentially measured. Following the determination of the absolutely dry soil mass, the soil moisture content, density, and bulk density values were calculated.

This methodology is widely utilized to assess the degree of soil compaction, the status of the moisture-aeration regime, and the extent of anthropogenic impact.

The obtained results demonstrate that within the upper 0–12 cm layer, the soil bulk density is relatively low, ranging approximately from 1.14 to 1.22 g/cm³. This horizon is characterized by a higher relative concentration of organic matter and a loose structural arrangement. However, the low moisture content (4.8–7.1 %) reflects the positioning of the soil under arid climatic conditions. In the 12–22 cm layer, the bulk density ranges between 1.38 and 1.46 g/cm³, indicating a notable compaction of the soil matrix. This structural state may be attributed to the intensification of mechanical compaction on agricultural lands and the subsequent disruption of the native soil structure. With increasing depth, the bulk density in the 22–30 cm horizon reaches higher values (1.31–1.44 g/cm³), illustrating a pronounced trend of soil compaction. An increase in moisture content was observed in this horizon, where the dense structural framework may impede the free movement of water and air.

Table 2. Agrochemical properties of dark brown soils

Sampling Location	Depth, cm	Humus, %	Total			Mobile			pH	CO ₂
			Nitrogen %	Phosphorus %	Potassium %	Nitrogen mg/kg	Phosphorus, mg/kg	Potassium mg/kg		
P-1, Agricultural field	0-12	3.12	0.196	0.115	2.405	32.2	6	220	7.7	0.16
	12-22	2.50	0.168	0.101	2.206	24.3	18	560	8.1	0.16
	22-30	2.17	0.154	0.108	2.201	20.1	2	220	8.2	0.19
	30-56	-	-	0.105	2.334	-	2	230	8.5	0.26
	56-80	-	-	0.070	1.860	-	4	260	8.3	0.48
P-2, Adjacent to waste heaps (terraces)	0-9	4.58	0.210	0.180	2.767	61.6	72	700	7.6	0.26
	9-22	3.93	0.196	0.178	2.747	36.4	40	580	8.0	0.19
	22-32	2.64	0.168	0.153	2.605	28.0	40	450	8.4	0.16

Note*: "-" not determined.

During the research, the agrochemical properties of dark brown soils in the Khromtau region (Khromtau, sampling point P–1) were comprehensively evaluated across various depth horizons ranging from 0 to 80 cm (Table 2). The core parameters determined included humus content, total nitrogen, total phosphorus, total potassium, mobile nutrient elements, soil reaction (pH), and carbonate content.

According to the obtained results, the highest concentration of humus is observed in the upper soil horizons. In Soil Profile No. 1, the humus content within the 0–12 cm layer is 3.12 %, whereas it decreases to 2.50–2.17 % with increasing depth. This distribution pattern is attributed to the accumulation of organic residues primarily on the soil surface and the high level of biological activity within this specific horizon. In Soil Profile No. 2, the humus content is relatively high (4.58–2.64 %), indicating a somewhat more favorable agroecological state of this territory.

Humus content and nitrogen concentrations were not determined in the 30–56 cm and 56–80 cm horizons because these deeper layers are located below the main humus-accumulative horizon. According to established soil science approaches, the determination of humus and available nitrogen is primarily conducted in the upper soil horizons where organic matter accumulation and biological activity are concentrated.

The total nitrogen content across all soil samples ranges from low to moderate levels (0.070–0.210 %). This parameter correlates closely with the humus content and serves as a fundamental indicator of soil fertility.

The total phosphorus content varies within the range of 0.101–0.180 %, indicating a moderate phosphorus content. The potassium content is relatively high (1.860–2.767 %), which is linked to the characteristic mineralogical composition inherent to dark brown soils.

The content of mobile nitrogen varied considerably between the investigated sites. The soils adjacent to the waste heaps (P-2) were characterized by higher concentrations of available nitrogen, ranging from 28.0 to 61.6 mg/kg in the upper horizons. In contrast, agricultural soils (P-1) contained lower amounts of mobile nitrogen, estimated at 20.1–32.2 mg/kg in the upper 30 cm layer. In both profiles, the nitrogen content generally decreased with depth, indicating the accumulation of organic matter and nutrients in the surface horizons. The highest concentration of mobile nitrogen (61.6 mg/kg) was recorded in the 0–9 cm layer of soils located near the terricones.

The content of mobile phosphorus varies significantly across the genetic horizons. In Soil Profile No. 2, this parameter reaches 72 mg/kg within the 0–9 cm layer, demonstrating a high level of supply, whereas in the other horizons, the mobile form of phosphorus remains at low or moderate levels.

The mobile potassium content is high across all investigated horizons (220–700 mg/kg), indicating that the soil is well-supplied with potassium, thereby creating favorable conditions for the cultivation and growth of agricultural crops.

The reaction of the soil solution varies from weakly alkaline to alkaline (pH 7.6–8.5). This property is characteristic of dark brown soils and is directly associated with the presence of carbonates. The carbonate content, measured as CO₂, increases with depth, rising from 0.16 % to 0.48 %. This condition indicates an intensifying influence of carbonate parent rocks in the lower horizons of the soil profile.

The obtained agrochemical parameters indicate that the fertility of the dark brown soils in the Khromtau region stands at a moderate level. The relatively low concentrations of humus and nitrogen, particularly in territories proximate to industrial zones, demonstrate that the soils have been subjected to anthropogenic stress. Furthermore, the deficit of available phosphorus necessitates the implementation of agrotechnical measures, specifically fertilizer application.

Overall, the investigated soils are suitable for agricultural use; however, systematic monitoring of their agrochemical status is required to ensure long-term environmental sustainability.

Table 3. Content of water-soluble salts in dark brown soils $\frac{\%}{M.EQ.}$

№	Depth, cm	Water extract of absolutely dry soil								
		Total soluble salts, %	Alkalinity		Cl ⁻	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
			Total HCO ₃ ⁻	CO ₃ ²⁻						
P-1, Agricuilt ural field	0-12	0.021	0.0625	0.000	0.000	0.033	0.0222	0.0111	0.02	0.0333
	12-22	0.028	0.0607	0.000	0.000	0.0461	0.0222	0.0105	0.02	0.025
	22-30	0.028	0.0607	0.000	0.000	0.0444	0.0222	0.0105	0.02	0.025

	30-56	0.027	0.0607	0.002	0.033	0.05	0.0222	0.0105	0.02	0.0333
	56-80	0.087	0.0611	0.000	0.000	0.0475	0.0222	0.0105	0.0234	0.0333
P-2, Adjacent to waste heaps (terricon es)	0-9	0.026	0.0607	0.000	0.000	0.05	0.0222	0.0111	0.02	0.0375
	9-22	0.027	0.0625	0.000	0.000	0.05	0.0222	0.0105	0.02	0.0333
	22-32	0.026	0.06	0.000	0.000	0.05	0.0222	0.0105	0.02	0.0333

The research results indicate that the concentration of water-soluble salts in the dark brown soils of the Khromtau region is low (Table 3). The total soluble salts content in the soil solution at sampling point P–1 varies between 0.021 % and 0.087 %, confirming a weak/negligible level of salinity across all investigated genetic horizons.

Vertical distribution analysis demonstrates a relative increase in salt content within the 56–80 cm horizon. This trend indicates an accumulation process of soluble salts in the lower horizons; however, these values do not signify soil alkalization or salinity development.

Regarding the ionic composition, calcium Ca^{2+} and sulfate SO_4^{2-} ions are predominant, characterizing the typical calcium-sulfate type of salinity inherent to dark brown soils. The low concentration of sodium Na^+ ions indicates the absence of a solonetzization (alkalization) risk. Furthermore, chloride ions Cl^- and carbonates CO_3^{2-} were detected at exceptionally low levels.

In the soil of the agricultural field, the total soluble salt content is approximately 0.081 %, exhibiting a slightly higher value compared to the industrial zones. This variation is attributed to the continuous influence of agricultural land use and the specific soil moisture regime.

The increase in total soluble salts observed in the 56–80 cm horizon of Profile P-1 is likely associated with the accumulation of soluble compounds in the lower part of the profile due to limited downward water movement and the influence of carbonate parent material. However, the measured value remains below the threshold of saline soils.

Overall, the investigated dark brown soils are classified as non-saline and are evaluated as highly favorable for agricultural production and utilization.

Table 4. Particle-size distribution of soil profiles

Sampling Location	Depth, cm	A.C.H % H ₂ O	% Fraction content of absolutely dry soil						
			Sum of fractions, mm						
			Sand, mm		Dust, mm			Silt, mm	Physical clay
			1.0-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001	Fractions < 0.01
P-1, Agricultural field	0-12	4.76	30.00	25.50	30.24	2.94	1.68	9.66	14.28
	12-22	5.32	8.45	40.43	10.56	9.72	21.97	8.87	40.56
	22-30	5.66	10.09	23.34	24.17	5.94	30.10	6.36	42.40
	30-56	5.48	5.80	15.07	26.66	11.00	39.36	2.12	52.48
	56-80	5.18	9.98	64.71	22.78	0.84	0.84	0.84	2.53
	0-9	3.34	19.51	41.59	30.62	1.24	6.21	0.83	8.28

P-2, Adjacent to waste heaps (terricones)	9-22	3.84	25.44	34.63	27.87	5.82	5.41	0.83	12.06
	22-32	3.82	18.34	42.57	35.77	0.42	0.83	2.08	3.33

Based on the classical Kachinsky classification of soil texture, the investigated soils demonstrate considerable textural variability. In Profile P-1 (agricultural field), the content of physical clay (<0.01 mm) ranges from 2.53 % to 52.48 %, indicating a transition from a loose sandy texture (2.53 %) in the deepest horizon (56–80 cm) to a sandy loam (14.28 %) in the surface layer, reaching medium loam (40.56–42.40 %) and heavy loam (52.48 %) textures in the middle part of the profile. In Profile P-2 (adjacent to waste heaps), the content of physical clay varies from 3.33 % to 12.06 %, classifying these horizons sequentially as cohesive sand (8.28 %), sandy loam (12.06 %), and loose sand (3.33 %). Thus, Profile P-1 is characterized by a substantially heavier textural composition and distinct vertical differentiation, whereas Profile P-2 consists predominantly of loose and cohesive light-textured sandy matrices (Table 4).

The particle-size distribution analysis revealed substantial differences between the two investigated soil profiles. In Profile P-1, the upper horizon (0–12 cm) is dominated by sand and dust fractions, which together account for approximately 85 % of the soil mass. Such a composition promotes favorable aeration and water infiltration conditions. However, with increasing depth, the proportion of fine particles gradually increases. The content of physical clay rises from 14.28 % in the surface horizon to 52.48 % at a depth of 30–56 cm, indicating a significant accumulation of fine material in the subsurface layers.

The highest content of physical clay was observed in the 30–56 cm horizon, where fine fractions predominate over coarse particles. Such textural characteristics may reduce soil permeability, increase bulk density, and negatively affect the soil moisture–air regime. In contrast, the deepest horizon (56–80 cm) contains a high proportion of sand particles, particularly the 0.25–0.05 mm fraction, reflecting the influence of the parent material on soil formation processes.

Profile P-2, located adjacent to the terricones, exhibits a more uniform particle-size distribution. Sand and dust fractions dominate throughout the profile, while the content of physical clay remains low, varying from 3.33 % to 12.06 %. Compared with the agricultural field soil, this profile is characterized by a lighter texture and a lower degree of compaction.

The predominance of coarse fractions in the surface horizons contributes to good aeration and drainage properties, whereas the accumulation of physical clay in the middle horizons of Profile P-1 increases water-holding capacity but may restrict root penetration under conditions of excessive compaction. Overall, the particle-size distribution data indicate that the soils of the Khromtau region are generally characterized by light- to medium-textured materials, although significant textural differentiation occurs within the agricultural profile. The observed increase in physical clay content with depth suggests the development of compact subsurface horizons, highlighting the need for continuous monitoring of soil physical properties under both agricultural and technogenic influences.

4. Discussion

The results obtained in the course of our comprehensive research indicate that the key physicochemical and morphological properties of dark brown soils in the investigated Khromtau region are determined by both natural soil-forming processes and long-term intensive anthropogenic influences associated with chromium mining activities. Pronounced changes in soil morphological characteristics, agrochemical properties, and particle-size composition were particularly evident in areas located near the Don Mining and Processing Plant and adjacent waste heaps (terricones). These findings are fully consistent with previous studies conducted in industrial regions of Kazakhstan, which have reported significant alterations in soil physical and chemical properties under technogenic impact.

According to the analytical data, the soil bulk density progressively increases with depth, a phenomenon that underscores an intensifying trend of soil compaction. The elevated bulk density values within the 12–30 cm horizons may be associated with long-term anthropogenic disturbance, including mechanical impacts related to industrial and agricultural activities, alongside the general disruption of the soil's native structural framework. Prior studies have similarly demonstrated that soil compaction in technogenic zones induces a degradation of the moisture-aeration regime, ultimately culminating in physical soil degradation.

The vertical distribution of humus and nutrients within the investigated soil profiles follows the classical pattern typical of zonal dark brown soils, with the highest concentrations occurring in the upper surface horizons and gradually decreasing with depth. In Profile P-1, established on the agricultural field, the humus content progressively decreased from 3.12 % in the upper 0–12 cm horizon to 2.50 % in the 12–22 cm layer, and reached a minimum of 2.17 % at a depth of 22–30 cm. A similar trend was observed in Profile P-2 near the terricones, where the humus content decreased from a maximum of 4.58% in the surface layer (0–9 cm) to 3.93 % in the 9–22 cm horizon, and further down to 2.64 % at a depth of 22–32 cm. The higher humus content recorded in the upper horizons of Profile P-2 may be associated with the preservation of natural steppe vegetation and the accumulation of plant residues in the surface layer. The general decline in total nitrogen and available nutrients with depth reflects both the natural reduction in organic matter content and the genetic differentiation of the soil horizons.

Available phosphorus concentrations were generally low to moderate in both studied profiles, indicating a moderate phosphorus supply status. In contrast, the potassium content remained relatively high throughout the profiles (ranging from 1,860 to 2,767 mg/kg), which directly reflects the specific mineralogical composition of the parent material and the natural nutrient status of regional dark brown soils.

The reaction of the soil solution was weakly alkaline to alkaline throughout both soil profiles, with pH values ranging from 7.6 to 8.5. These values are highly characteristic of dark brown soils formed under arid and semi-arid climatic conditions of Western Kazakhstan. The documented increase in carbonate content with depth reflects the geogenic influence of carbonate-rich parent materials and the downward migration of carbonates within the soil profile. Despite the alkaline reaction, the investigated soils cannot be classified as saline or solonchic, since the total content of soluble salts remained low (0.021–0.087 %), and no evidence of significant salinization was detected.

According to the particle-size classification developed by N.A. Kachinsky, the investigated soils demonstrate considerable textural variability. In Profile P-1 (agricultural field), the content of physical clay (<0.01 mm) varies drastically from 2.53 % to 52.48 %, indicating a clear transition from sandy loam in the surface horizon to medium to heavy loam textures in the middle part of the profile. The deepest horizon (56–80 cm) is characterized by a sandy texture due to the low content of physical clay. In contrast, Profile P-2 contains only 3.33–12.06 % physical clay and is therefore classified mainly as sandy and sandy loam. These differences indicate a substantially heavier granulometric composition in the agricultural profile compared with the soils adjacent to the terricones.

The particle-size distribution data further show that sand and dust fractions predominate in the upper horizons of both profiles, whereas the proportion of physical clay increases with depth, particularly in Profile P-1. The accumulation of fine particles in the subsurface horizons may contribute to increased soil density, reduced permeability, and deterioration of the moisture–air regime. Such conditions can restrict root penetration and reduce the effectiveness of water infiltration. Conversely, the predominance of sand fractions in Profile P-2 promotes better drainage and aeration but may reduce water-holding capacity. The presence of technogenic material and industrial dust near the waste heaps may also influence the observed granulometric composition and contribute to profile heterogeneity.

Overall, the investigated dark brown soils remain relatively stable with respect to their agrochemical characteristics and do not exhibit signs of industrial salinization. Nevertheless, the observed vertical differentiation of physical clay, together with changes in nutrient distribution and

carbonate accumulation, indicates ongoing transformations of soil properties under the combined influence of natural and anthropogenic factors. These findings emphasize the importance of continuous environmental monitoring of soil quality in mining regions of Western Kazakhstan and the implementation of measures aimed at preventing physical degradation and maintaining soil fertility.

Although heavy metal contamination is considered one of the major environmental concerns in mining regions, the present study focused primarily on physicochemical, agrochemical, and particle-size characteristics of soils. Heavy metal concentrations were not determined within the framework of this investigation and should be addressed in future studies aimed at assessing ecological risks associated with chromium mining activities in the Khromtau region.

5. Conclusion

In synthesis, this study demonstrates that the physicochemical and structural attributes of the dark brown soils in the Khromtau region are simultaneously governed by natural pedogenic pathways and chronic technogenic pressure stemming from chromium mining operations. The comparative assessment between the cultivated matrix (Profile P-1) and the industrially exposed landscape adjacent to the waste heaps (Profile P-2) unveils distinct variations in their agrochemical dynamics and particle-size distribution frameworks.

The research findings demonstrate a pronounced trend of soil compaction within areas located proximate to the industrial zone. The progressive increase in soil bulk density with depth, rising from 1.14-1.22 g/cm³ to 1.38-1.46 g/cm³, delineates a clear degradation of the moisture-aeration regime and may indicate the development of unfavorable physical conditions within the soil profile. This structural alteration may be associated with anthropogenic disturbance and long-term land-use impacts and the emergence of technogenic landscapes.

The vertical allocation of soil organic matter and macro-nutrients adheres to classical zonal regularities, demonstrating a pronounced surface accumulation that progressively attenuates down the profile gradient. The documented humus content varies between 2.17 % and 4.58 %, while the total nitrogen and phosphorus concentrations fluctuate within the ranges of 0.070-0.210 % and 0.101-0.180 %, respectively. Conversely, the potassium baseline remains consistently elevated throughout both profiles (1.860-2.767 %), validating a strong mineralogical dependence on the native, potassium-rich parent material of the region.

The soil solution reaction exhibits a consistent weakly alkaline to alkaline shift (pH 7.6-8.5), driven by the buffering capacity of the carbonate system. The upward gradient of carbonate accumulation discovered in the lower genetic horizons suggests the downward redistribution of carbonates within the profile and highlights the geogenic influence of the underlying parent bedrock. Crucially, the low abundance of water-soluble salts confirms that these soils indicate non-saline conditions, lacking any current risks of active solonchization.

Evaluated through the classical particle-size classification of N.A. Kachinsky, the profiles demonstrate pronounced textural differentiation along the vertical axis. Profile P-1 (agricultural land) marks a distinct lithological transition from a sandy loam surface horizon into relatively dense medium to heavy loam textures within the middle tiers, before shifting into a sand-dominated texture in the basal horizon. In juxtaposition, the profile configuration of Profile P-2 is predominantly characterized by coarser sandy and sandy loam textures. Across both sites, the mass proportion of physical clay (<0.01 mm) spans a wide range from 2.53 % to 52.48 %, corroborating an intense structural heterogeneity.

The progressive accumulation of physical clay within the subsurface horizons of Profile P-1 reveals the development of dense, restrictive layers that significantly impair hydraulic conductivity and further deteriorate the soil moisture-aeration regime through compaction. On the contrary, the sand-dominated framework of Profile P-2 facilitates rapid drainage and high aeration capacity, but introduces limitations regarding moisture retention, rendering the topsoil potentially more susceptible to wind erosion and technogenic dust loading. These structural divergences illustrate the synergetic

impact of pristine soil-forming factors and modern technogenic disturbances on the physical integrity of the soil cover.

Conclusively, the findings provide a useful basis for ecological zoning, land-use planning, and future soil monitoring programs in the Khromtau region.

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7. Author Contributions

Conceptualization: A.A. and G.M.; methodology: B.Sh.; software: A.A.; validation: A.A., G.M. and A.O.; formal analysis: T.B.; investigation: A.A.; resources: A.N.; data curation: B.Sh.; writing - original draft preparation: A.A.; writing - review and editing: G.M.; visualization: A.O.; supervision: A.O.; project administration: T.B. All authors have read and agreed to the published version of the manuscript.

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Хромтау өңірі топырағының физика-химиялық қасиеті мен гранулометриялық құрамын талдау

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Аңдатпа: Мақалада Хромтау өңіріндегі қарақоңыр топырақтардың физика-химиялық қасиеті және гранулометриялық құрамы талданды. Зерттеу нысандары ретінде Дөң кен-байыту комбинатына іргелес аумақтар, террикондар маңы және ауылшаруашылық мақсатта пайдаланылатын егістік жерлер таңдалды. Топырақ үлгілері әртүрлі тереңдік қабаттарынан алынып, көлемдік салмақ, гумус мөлшері, жалпы және жылжымалы азот, фосфор, калий, топырақ ерітіндісінің реакциясы, суда еритін тұздардың мөлшері мен иондық құрамы, сондай-ақ гранулометриялық құрамы анықталды. Топырақ реакциясы сілтілі (рН 7,6–8,5) тұздану деңгейі төмен. Гранулометриялық талдау терең қабаттарда ұсақ фракциялардың артуын анықтап, бұл жағдайдың су-ауа режиміне әсер ететінін көрсетті. Алынған нәтижелер өңірдегі жер ресурстарын және топырақты ұтымды пайдалану бойынша ғылыми негізделген ұсыныстар әзірлеуге мүмкіндік береді.

Түйін сөздер: топырақ жамылғысы; топырақ кескіні; морфологиялық сипаттама; химиялық құрамы; гранулометриялық құрамы; қара қоңыр топырақ; кен орны; Дөң кен байыту комбинаты.

Анализ физико-химических свойств и гранулометрического состава почв Хромтауского региона

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Аннотация. В статье проанализированы физико-химические свойства и гранулометрический состав тёмно-каштановых почв Хромтауского региона. В качестве объектов исследования были выбраны территории, прилегающие к Донскому горно-обогатительному комбинату, участки вблизи терриконов, а также сельскохозяйственные угодья, используемые под пашню. Почвенные образцы были отобраны из различных глубинных горизонтов. Определялись объемная масса почвы, содержание гумуса, общий и подвижный азот, фосфор и калий, реакция почвенного раствора, содержание водорастворимых солей и их ионный состав, а также гранулометрический состав почвы. Установлено, что реакция почвенного раствора является щелочной (рН 7,6–8,5), при этом уровень засоления характеризуется как низкий. Гранулометрический анализ показал увеличение содержания мелких фракций в более глубоких слоях почвы, что оказывает влияние на водно-воздушный режим почв. Полученные результаты позволяют разработать научно обоснованные рекомендации по рациональному использованию почв и земельных ресурсов региона.

Ключевые слова: почвенный покров; почвенный разрез; морфологическая характеристика; химический состав; гранулометрический состав; тёмно-каштановая почва; месторождение; Донский горно-обогатительный комбинат.