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Effects of Gold Mining on the Physicochemical Properties of Soils at the Akbakai Gold Deposit

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Abstract

Open-pit gold mining in arid regions can lead to long-term environmental degradation through the accumulation of toxic metal(loid)s in soils. This study investigates soil contamination and quality degradation around the Akbakai gold deposit, located in the Zhambyl region of southern Kazakhstan, a semi-desert zone characterized by low organic matter, coarse soil textures, and fragile ecosystems. Field sampling included six representative soil profiles (SP) excavated from man-made mining dumps and surrounding areas. We conducted a comprehensive assessment of physical, agrochemical, granulometric, and geochemical properties, with a focus on total and available concentrations of metal(loid)s using microwave-assisted acid digestion and DTPA extraction methods. The results revealed that surface soils were moderately alkaline (pH 8.1-9.2) and low in organic matter (humus <2%), that are with coarse-textured horizons dominated by medium sand. Soil salinity and sodicity were variable, with total salt content ranging from 0.06% to 1.1% and available sodium percentage reaching up to 23.8%. Risk quotient analysis identified multiple soil horizons where contaminant levels surpassed environmental safety thresholds. The findings confirm significant anthropogenic contamination at the Akbakai gold deposit, especially in upper soil layers formed on mining waste.

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1. Introduction

Mining continues to be a cornerstone of economic development, however, its environmental repercussions in (semi)arid regions remain a major concern.[1] In these areas, the weathering of mine tailings is governed by unique climatic conditions – characterized by infrequent but intense rainfall and prolonged dry spells, which promote salt efflorescences and wind-driven dispersion of contaminants.[2,3] Studies from northern Mexico have shown that seasonal salt formations on mine tailings enhance the concentration and subsequent redistribution of contaminants by wind.[4,5] Similar findings in southeastern Spain[6] and the southwestern United States[7] demonstrate that arid environmental processes control contaminant mobility in profound ways, establishing a critical background for the current work. In addition, research in Chile,[8] Australia,[9] South Africa,[10] and Iran[11] has further illuminated how evaporation-induced salt concentration, periodic wetting events, and episodic rainfall trigger the mobilization of contaminants from mine tailings under arid and semi-arid conditions.

Gold ore deposits, by nature, exhibit distinct geochemical characteristics that influence the behavior and distribution of various elements during weathering.[12] Globally, these deposits, ranging from the disseminated Carlin-type ores in the United States to polymetallic veins in Central Asia, are intimately linked with sulfide mineralization.[13] Gold mining in Kazakhstan has profoundly altered the physicochemical properties of surrounding soils due to the intensive extraction of polymetallic ores such as gold, copper, and zinc. This mining activity generates vast quantities of tailings and overburden materials, contributing to elevated concentrations

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of heavy metals like lead (Pb), cadmium (Cd), zinc (Zn), arsenic (As), and copper (Cu) in nearby soils. In East Kazakhstan's Ridder area, both active and abandoned mines have led to significant contamination of soils and water bodies, with some rivers and near-mine soils exceeding global heavy metal averages by multiple folds. Similar patterns are observed in the Kostanay region, where agricultural lands adjacent to mining and processing facilities show concentrations of As, Cd, Hg, Pb, Zn, Ni, and Cu well above Kazakhstan's environmental safety thresholds.[14-16] The ecological risk index (RI) for these areas ranges from 137 to 447, indicating moderate to high contamination levels. Such contamination alters key soil parameters, including acidification due to acid mine drainage (AMD), reduced cation exchange capacity (CEC), increased electrical conductivity (EC), and the depletion of organic matter and microbial activity, all of which reduce soil fertility and disrupt ecosystem function. These changes pose substantial ecological and human health risks, particularly in riparian zones near rivers like Ridder, Filippovka, and Ulba, where Zn, Cd, and Pb concentrations exceed WHO and EPA safety standards by factors of four to seven. Furthermore, the bioaccumulation of toxins from contaminated soils into food crops poses a direct risk to human health. Mechanistically, the impacts are driven by AMD from sulfide oxidation, the long-term contamination from tailings and waste rock, and the redistribution of metals via erosion and runoff into agricultural and aquatic systems. Therefore, regular monitoring and assessment of soil quality near Kazakhstan's gold deposits are critical. Long-abandoned sites in Kostanay and East Kazakhstan continue to pose environmental threats, underscoring the need for remediation before such lands can be safely reused for agriculture. [16-18]

In Kazakhstan, gold deposits often share similar features, for instance, deposits like Bakyrchik are associated with ore bodies where natural oxidation processes lead to significant elemental leaching.[19,20] These inherent geochemical traits suggest that mining activities can profoundly alter the surrounding soils by releasing a suite of contaminants into the environment.[21] Despite extensive international research on the weathering of mine tailings, studies focused on the geochemical impacts of open-pit mining in Kazakhstan are notably scarce.[2,3,22] While numerous investigations in regions such as Mexico, Spain, and the United States have documented the dispersion of contaminants under arid conditions, few studies have directly addressed the specific conditions prevalent in southern Kazakhstan.[12,23] The Akbakai gold deposit, discovered in 1968 in the Zhambyl Region of southern Kazakhstan, is one of the largest quartzes, sulfide vein deposits in the Central Asian Metallogenic Belt.[19,20] It is hosted by Ordovician terrigenous sedimentary units (sandstones, siltstones, conglomerates) and Devonian volcanic-sedimentary rocks, with later Devonian granitoid and gabbro-diabase intrusions. Mineralization occurs in steeply dipping quartz veins, where pyrite and arsenopyrite together comprise over 75 % of the sulfides and free gold (0.1-1 mm) accounts for 80-85 % of the Au content.[12,23] Mining commenced in 1975 using open-pit and sublevel drift methods, employing scraper winches and trolley haulage to bring broken ore to surface. Crushed ore is processed in a cyanide leach-carbon-in-pulp (CIP) plant: a dilute sodium-cyanide solution (100-500 ppm CN^- at pH > 10.5) dissolves gold, which is then recovered on activated carbon, and tailings are detoxified prior to impoundment. Annual throughput has increased from 0.85 Mt to 1.2 Mt following a second-stage plant expansion by JSC AK Altynalmas.[24]

The present study aims to fill this gap by characterizing the vertical distribution and mobility of contaminants in soils impacted by the Akbakai open-pit mine. By drawing parallels with established research from other arid regions, this work not only establishes a robust geochemical framework but also emphasizes the novelty of investigating the Akbakai gold deposit, where prior studies are virtually nonexistent. The insights gained will serve as a critical basis for developing targeted remediation strategies and sustainable land management practices, thereby contributing valuable knowledge to the global understanding of mining impacts in arid environments.

2. Materials and methods

2.1 Materials and soil sampling

The study was carried out at the Akbakai open-pit gold mining site in the Zhambyl region of southern Kazakhstan (Fig. 1a). Six representative soil profiles (SP 1-6) were excavated on the mining-waste dumps to examine vertical soil development and contamination. Additionally, samples were collected from Point 1 and 2 because these locations showed the strongest signs of technogenic disturbance. The soils in the tailing area also displayed highly variable colors, so extra samples were taken there to determine which heavy metals predominated. Each profile was described in the field for standard morphological features, including horizon depths, color, texture, structure, moisture, and root presence (Fig. 1, Table 1).

Diagnostic horizons were identified for each profile according to the criteria of the national soil classification system. In the USSR soil classification, the undisturbed soils of this semi-desert region are typically classified as Gray-Brown Desert soils (Serozems), characterized by a shallow humus-rich layer over a calcareous or gypsum-enriched

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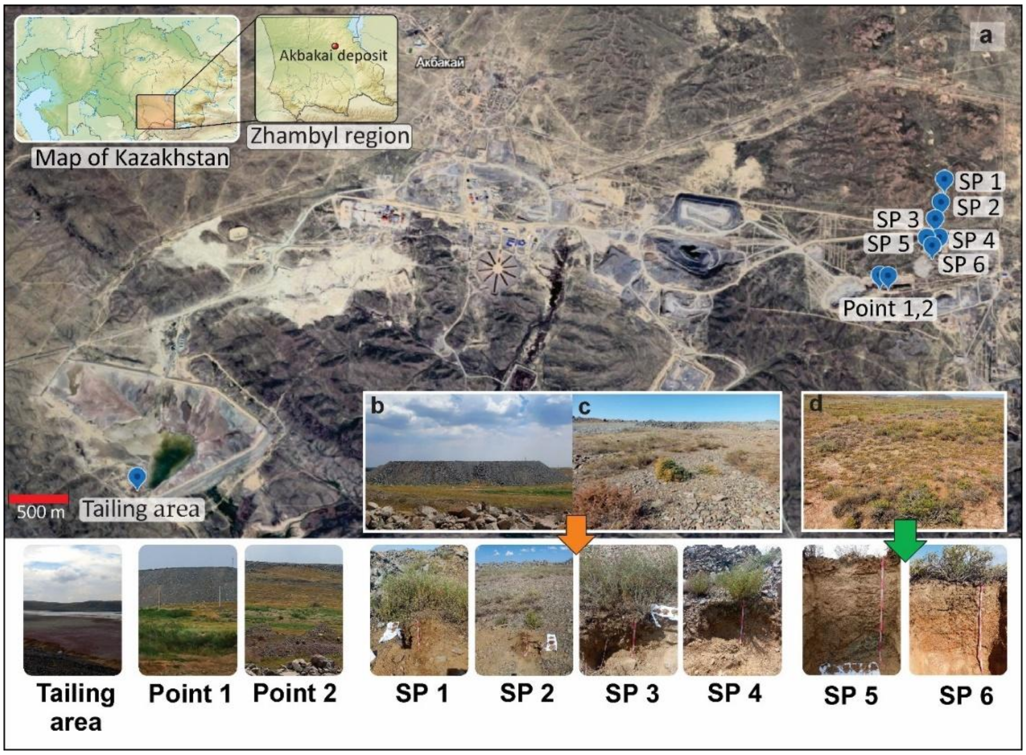

Fig. 1: Objects of the study srea and soil profiles. Note: (a) Akbakai deposit region; (b) 50-year-old anthropogenic dump (SP 1-4); (c) surface of the dump pile; (d) outer zone encompassing technogenically disturbed areas and adjacent natural soils (SP 5,6).

subsoil.[25] The nascent soils forming on the Akbakai waste dumps, lacking well-differentiated horizons, can be considered primitive man-made soils in the Soviet system.[26] Correspondingly, under the World Reference Base for Soil Resources (WRB, 2022) classification, the native reference soil would qualify as a Haplic Calcisol (arid, carbonate-rich desert soil), whereas the mine dump soils are classified as Technosols due to their anthropogenic origin and the presence of mine waste materials in the profile.[27]

2.2 Physico-chemical characterization

Soil humus was determined by the Walkley-Black dichromate oxidation method, with results cross-validated by the loss-on-ignition (LOI) method (550 °C combustion of ground samples) for accuracy.[28] Essential nutrient elements, including total nitrogen (TN), phosphorus (TP), and potassium (TK), were measured using standard soil extraction and analysis. In brief, available nitrogen (AN) was assessed by Kjeldahl digestion or a modified Berthelot reaction, available phosphorus (AP) by Olsen's bicarbonate extraction, and available potassium by neutral ammonium acetate extraction. Extracted N, P, and K were quantified colorimetrically or by flame photometry as appropriate.[29,30]

Soil pH was measured in a 1:2.5 (w/v) soil-to-distilled water suspension using a calibrated glass electrode pH meter, following standard methods.[31] EC and soluble salt content were determined by shaking soil in deionized water (1:5 ratio), filtering, and analyzing the extract for major anions (Cl^-, SO_4^{2-}, HCO_3$^-$) and cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) using ion chromatography and flame photometry.[32] Total soluble salts were measured gravimetrically by evaporating a known volume of the filtrate and weighing the residue, allowing classification of soil salinity.[33]

To evaluate sodicity, available sodium was extracted from soils with 1 M ammonium acetate (pH 7) and measured by atomic absorption or inductively coupled plasma spectrometry. The available sodium percentage (ESP) was then calculated as the ratio of Na^+ to the CEC on an equivalent basis.[34]

We also computed a sodicity index (K_s) for each sample to quantify the degree of sodium hazard. Soils were categorized as non-sodic, weakly sodic, moderately sodic, or strongly sodic based on their ESP and K_s values, using published threshold criteria.[35] For example, an ESP exceeding 15% ($K_s > 4$) would classify a soil as strongly sodic under these guidelines.[36]

All analyses were conducted with appropriate quality control, including the use of method blanks and duplicate samples, and the resulting chemical data were interpreted with reference to international soil standards and national diagnostic guidelines.[37]

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Table 1: Locations and characteristics of soil profiles and areas.

Soil profiles and areas	Location characteristics	Geo-coordinates
SP 1	50-year-old man-made dump	45° 7′ 38.60″ N, 72° 43′ 25.19″ E
SP 2	50-year-old man-made dump	45° 7′ 29.86″ N, 72° 43′ 24.98″ E
SP 3	50-year-old man-made dump	45° 7′ 19.41″ N, 72° 43′ 25.09″ E
SP 4	50-year-old man-made dump	45° 7′ 18.97″ N, 72° 43′ 25.69″ E
SP 5	The outer territory of man-made damaged areas and natural areas	45° 7′ 17.74″ N, 72° 43′ 24.63″ E
SP 6	The outer territory of man-made damaged areas and natural areas	45° 7′ 17.68″ N, 72° 43′ 26.95″ E
Point 1	Surface soils of technogenically disturbed area	45° 7′ 7.60″ N, 72° 43′ 7.25″ E
Point 2	Surface soils of technogenically disturbed area	45° 07′ 07.60″ N, 72° 43′ 07.29″ E
Tailing area	Multicolored residues (black, grey, red) beside the collected water	45° 5′ 44.62″ N, 72° 39′ 11.02″ E

2.3 Determination of metal contents

Prior to chemical analysis, all soil samples were air-dried at room temperature and passed through a 2 mm sieve to remove stones and organic debris.[38] A subsample of approximately 10 g was pulverized in an agate mortar to <75 µm to ensure homogeneity. An aliquot (0.50 ± 0.01 g) of the fine powder was weighed into TFM digestion vessels.[39,40]

Each sample was digested using a closed-vessel microwave system (Milestone ETHOS UP). The digestion mixture consisted of 9 mL HNO_3 (65% v/v, suprapur) + 3 mL HCl (37% v/v, suprapur) + 2 mL HF (40% v/v, trace metal grade). The program ramped from ambient to 180 °C over 15 min, held for 30 min, then cooled to <50 °C. After cooling, digestates were transferred to 50 mL polypropylene tubes and brought to volume with ultrapure water (18.2 MΩ·cm).[41,42]

Total element concentrations (As, Cd, Co, Cr, Cu, Ni, Pb, Zn, etc.) were measured by inductively coupled plasma optical emission spectrometry (ICP-OES; Thermo Scientific iCAP 7400) and inductively coupled plasma mass spectrometry (ICP-MS; Agilent 7900) for elements at trace levels. Calibration employed five-point multi-element standard curves (0, 1, 5, 10, 50 µg L^{-1}), with correlation coefficients (r^2) exceeding 0.999.[43]

Method detection limits (MDLs) were calculated as three times the standard deviation of seven procedural blanks: e.g., As 0.05 mg kg^{-1}, Cd 0.01 mg kg^{-1}, Pb 0.02 mg kg^{-1}, Zn 0.03 mg kg^{-1}. Limits of quantification (LOQs) were defined as 10× blank standard deviation.[44]

To ensure data integrity, the following QA/QC measures were implemented: One blank per batch (n = 10) to monitor contamination; blanks were consistently below MDLs. 10% of samples were digested and analyzed in duplicate; relative standard deviation (RSD) was <5% for all elements. Samples spiked at low (5 mg kg^{-1}) and high (50 mg kg^{-1}) levels; average recoveries ranged 88-105% (n = 14). NIST SRM 2709a Soil was included with each digestion batch; recoveries were within 90-110% of certified values. After every 10 samples, a mid-level standard was re-measured; drift remained <3%.[45,46]

Available metal fractions were extracted following Lindsay and Norvell (1978)[47] Briefly, 10 g of air-dried soil (<2 mm) was shaken with 20 mL of DTPA extracting solution (0.005 M diethylenetriaminepentaacetic acid, 0.1 M triethanolamine, 0.01 M $CaCl_2$; pH 7.3) at 20 °C for 2 h on a horizontal shaker. The suspension was centrifuged at 4 000 rpm for 15 min, and the supernatant was filtered through a 0.45 µm membrane. DTPA-extractable metal concentrations were then determined by ICP-OES. This fraction represents the labile, readily mobilizable pool of metals in soil.[47,48]

All QA/QC results met international guidelines (US EPA Method 3052; ISO 17025), confirming the accuracy, precision, and reliability of the metal determinations.

2.4 Particle size analysis

The grain size distribution of each soil sample was analyzed to determine soil texture, as texture influences water retention and contaminant transport in soils. Prior to analysis, soil samples were chemically dispersed using a 5% sodium hexametaphosphate solution to break up aggregates and ensure individual particles were measured.[49] The particle-size fractions were then determined by the pipette method. Sand (2000-50 µm), silt (50-2 µm), and clay (<2 µm) fractions were quantified for each sample, and soil textural classes were assigned based on the relative percentages of these fractions. The particle size results provide insight into the soil's physical behavior, for instance, soils with a high sand content tend to have greater permeability and aeration but lower water-holding capacity. By comparing textures of native soil and mine spoil samples, we can infer the influence of mining material on soil structure and its potential effects on vegetation growth and leaching of contaminants.

2.5 Statistical analysis

All data collected from field observations and laboratory measurements were analyzed using statistical software to understand variability along soil profiles and between different sampling sites. Summary statistics (means, standard deviations, and ranges) were computed for key soil properties in each horizon. We used analysis of variance tests to determine whether differences in soil parameters with depth and between profiles were statistically significant at the 95% confidence level ($p < 0.05$). In addition, Pearson correlation analysis was performed to examine relationships between

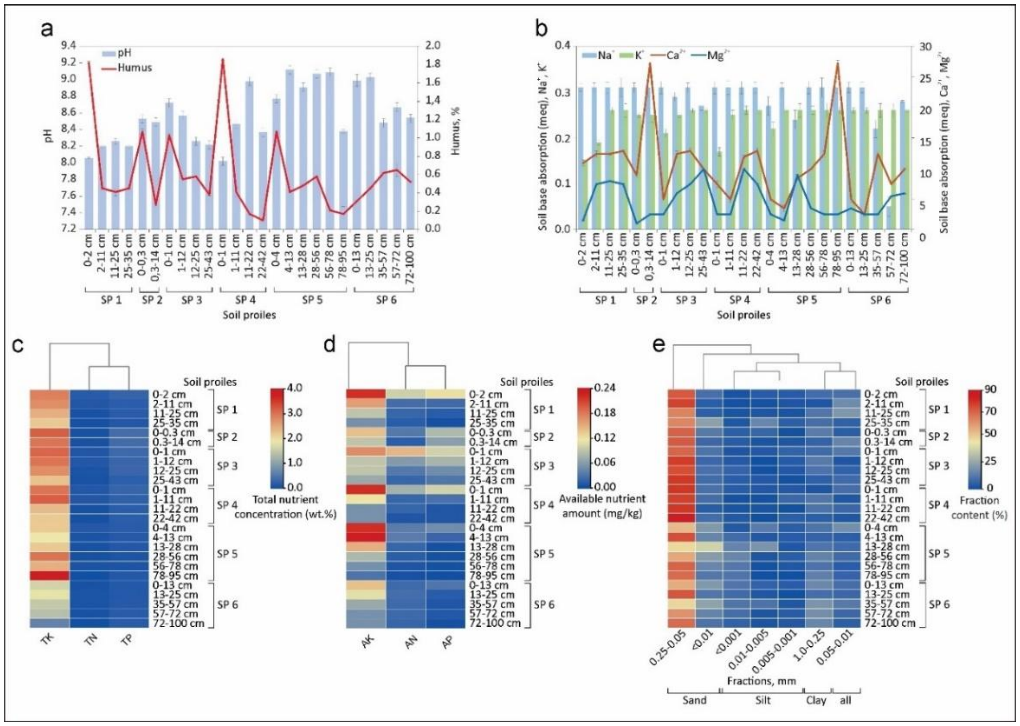

Fig. 2: Analysis results of soil chemical and agrochemical properties. Note: (a) pH and humus content; (b) Soil base absorption of major metal ions; (c) Total major nutrient concentrations (TK = total K_2O; TN = total N; TP = total P_2O_5); (d) Available nutrient amounts (AK = available K_2O; AN = available N; AP = available P_2O_5); (e) Granulometric composition of soils (fraction size in mm).

variables such as potentially toxic elements content and soil organic matter or clay content. All statistical computations and graphing were carried out using R software and IBM SPSS Statistics 27.

3. Results and discussion

3.1. Soil chemical and agrochemical properties

The soils studied at the Akbakai gold deposit, including those from both the mining dumps (yard soils) and surrounding undisturbed areas (regional soils), are generally characterized by low fertility and poor organic matter content. The vertical distribution of key agrochemical indicators revealed distinct stratification, with nutrient-rich horizons confined to surface layers and a rapid decline in values with increasing depth.

Soil pH across all profiles was alkaline, ranging from 8.05 to 9.30 (Fig. 2a). The highest value occurred in the upper horizon of SP 5, while the lowest was recorded in SP 1. In SP 1, pH rose slightly down to 25 cm before declining in deeper layers. Overall, regional soils (8.5-9.2) were marginally more alkaline than yard soils (8.1-8.9), reflecting their more stable carbonate buffering capacity.

Humus content was highest in the surface horizons of SP 1 and SP 4 (1.8% and 1.9%, respectively), while SP 6 exhibited consistently low humus values, peaking at only ~0.2% (Fig. 2a). Most profiles had their humus concentrated in the 0-4 cm layer, indicative of limited organic matter accumulation due to sparse vegetation and ongoing exposure. Profile SP 4, which 0-1 cm. These patterns are typical of early soil formation on supported thicker plant cover, exhibited 1.1% humus in the top anthropogenic materials under arid conditions, where litter accumulation and microbial processing are limited.

The distribution of Na^+, K^+, Ca^{2+}, and Mg^{2+} across the soil profiles revealed that available base contents varied both with depth and soil type (Fig. 2b). Na^+ concentrations were relatively stable (0.3 meq) in most samples, except in deeper layers of SP 6 (as low as 0.06 meq). Potassium (K^+) levels varied more strongly with depth. For instance, in SP 1, K^+ increased from 0.15 meq at the surface to 0.27 meq at 25-35 cm. Profiles SP 2 and SP 3 showed moderate K^+ levels throughout, while SP 6 maintained consistent values (0.26 meq).

Ca^{2+} concentrations were generally higher in deeper horizons. SP 5 at 78-95 cm and SP 2 at 0-14 cm showed peak values (0.37 meq). Magnesium (Mg^{2+}) also accumulated at depth. For instance, in SP 1, Mg^{2+} increased from 0.04 to 0.1 meq, with a maximum in SP 2 at 0.13 meq. These patterns reflect both the parent material's carbonate content and the limited leaching in arid conditions.

The total nitrogen (TN), phosphorus (TP), and potassium (TK) concentrations followed predictable trends based on organic matter distribution (Fig. 2c). Surface layers were richer in nutrients, especially in profiles with more plant cover. SP 1 recorded the highest TN at 0-2 cm (0.168 wt.%), while SP 5 showed the lowest value (0.014 wt.%) in the 78-95 cm horizon. Total phosphorus was highest in SP 2 (0-3 cm, 0.384 wt.%) and lowest in SP 5 (0.072 wt.%). Potassium showed a different trend, with much higher concentrations than TN or TP. Notably, SP 5 had the highest TK value in its deepest layer

(78-95 cm, 3.75 wt.%), possibly due to unweathered potassium-bearing minerals. SP 1 exhibited consistently high TK levels across all horizons, while SP 6 recorded the lowest TK (0.625 wt.%).

Plant-available nutrients (Fig. 2d) showed high variability along the profiles. Available nitrogen (AN) peaked in SP 3 (0-1 cm, 0.14 mg/kg) and dropped sharply in deeper layers, especially in SP 5 (78-95 cm, 0.0056 mg/kg). A similar trend was seen for available phosphorus (AP), highest in SP 2 (0-2 cm, 0.122 mg/kg) and lowest in SP 5 (28-78 cm, 0.003 mg/kg). Available potassium (AK) was generally more abundant than AN and AP, with SP 5 recording both the highest (4-13 cm, 0.23 mg/kg) and lowest (78-95 cm, 0.03 mg/kg) values. Profile SP 3 presented an interesting anomaly, with relatively low TN (0.098%) but high AN (146 mg/kg), suggesting active mineralization possibly due to localized microbial hotspots.

Granulometric analysis (Fig. 2e) revealed a predominance of medium sand (0.25-0.05 mm) in yard soils (72.5-84.0%), while regional soils had a broader distribution (45.5-74.4%) and a higher proportion of clay and silt. Coarse sand made up 6.0-13.0% of yard soils, while silt and clay combined remained under 10.0%. In contrast, regional soils had up to 15.0% clay and more balanced sand-silt ratios.

The physical structure of the yard soils, dominated by medium sand, enhanced aeration and water permeability but severely limited water-holding capacity. This contributed to poor moisture retention and restricted plant growth, hindering natural soil recovery processes. In SP 1, four visible horizons were established, showing some degree of early soil development, with light sandy loam textures at 25-35 cm.

Arid and semi-arid climates promote soil salinization, and mining sites can exacerbate this through the exposure of salt-bearing minerals.[50] In the Akbakai profiles, salinity was observed to increase with depth, a pattern that has been reported in other drought-prone regions. For instance, a study of Solonchak soils in a semi-arid area found that total soluble salt content in the subsoil was roughly three times higher than in the topsoil.[51] This indicates net downward movement of saline solutions: limited rainfall infiltrates and dissolves minerals, carrying ions downward, then intense evaporation draws the moisture back up, precipitating salts at an intermediate depth. The predominant salts accumulating in such profiles are typically chlorides and sulfates of sodium and calcium, which is consistent with the Akbakai site where gypsum ($CaSO_4$) and other soluble salts may form with depth . This vertical salinity stratification, lower electrical conductivity at the surface, rising to a salic horizon below, reflects insufficient leaching to flush salts completely out of the profile. It is an early indicator of pedogenic Solonchak development under arid conditions. Similarly, on exposed mine wastes, episodic wetting (from sparse rain or surface runoff) followed by rapid evaporation can form surface salt crusts, that trap and concentrate both salts and associated metals. Alcolea-Rubio *et al.*, (2023) characterized saline efflorescence crusts on tailings in Southeast Spain and found these crusts to contain Cd, As, Zn, Pb, and Cu at concentrations far above those in the bulk wastes, underscoring the acute environmental risk posed by surface-accumulated salts. [52]

One of the most notable outcomes of our study is the rapid buildup of humus on rehabilitated mine wastes (Fig. 2). Achieving 1.8-1.9 % humus in just five decades corresponds to an average accumulation rate of 0.036 % humus yr^{-1}. In contrast, undisturbed semi-arid sandy soils typically maintain total organic matter below 1 % (0.6 % humus), owing to low biomass inputs and enhanced mineralization under dry conditions. Modeling studies for coarse-textured soils under moderate residue inputs (~5 000 lb ac^{-1} yr^{-1}) and decomposition rates of 3-5 % yr^{-1} predict an equilibrium organic-matter content of 1.5–1.7 %, equivalent to ~0.9-1.0 % humus, over many decades.[53] Viewed in this light, our observed humus levels on the 50-year dumps are not only consistent with, but slightly exceed, the rates projected for natural semi-arid systems, suggesting that added organic amendments or vegetation colonization on the dumps has effectively accelerated soil-building processes.[54]

3.2 Soil salinization and chemical composition analysis

Soil salinization was evaluated across all profiles by measuring the concentrations of major cations and anions. Ca^{2+} concentrations varied significantly among profiles, reaching a maximum of 12.49 meq in SP 1 and dropping to as low as 0.28 meq in SP 5. SO_4^{2-} levels were generally high compared to other anions, with the maximum concentration observed in SP 6 at 15.05 meq and the lowest at the surface of SP 6 (0.48 meq). Mg^{2+} showed its highest value of 2.31 meq in SP 4 (in the 22-42 cm horizon), while the lowest concentration (0.28 meq) was found in SP 6. Concentrations of other salt ions (Na^+, K^+, Cl^-, and HCO_3^-) were consistently lower than those of Ca^{2+}, SO_4^{2-}, and Mg^{2+}. Carbonate (CO_3^{2-}) concentrations were nearly undetectable in all profiles, except for a minor occurrence (0.2 meq) in the 13-28 cm horizon of SP 5 (Fig. 3a).

Ionic composition expressed as a percentage of total dry weight (DW) further confirmed these trends. Across all profiles, SO_4^{2-} concentrations were highest, with values increasing with depth. In SP 6, the maximum SO_4^{2-} concentration reached 0.723% of dry weight at 100 cm, while the surface exhibited only 0.023% of dry weight. Similarly, Ca^{2+} also displayed higher proportions in deeper layers compared to the upper portions, whereas the percentages of Na^+, K^+, Cl^-, and HCO_3^- were minimal throughout the profiles (Fig. 3b).

Total salt content was determined by summing the concentrations of all measured ions. The results indicate that deeper soil layers generally harbor higher total salt concentrations. For example, SP 1 showed a total salt concentration nearly 5 times higher in deeper horizons compared to the surface; SP 2 exhibited a threefold increase.

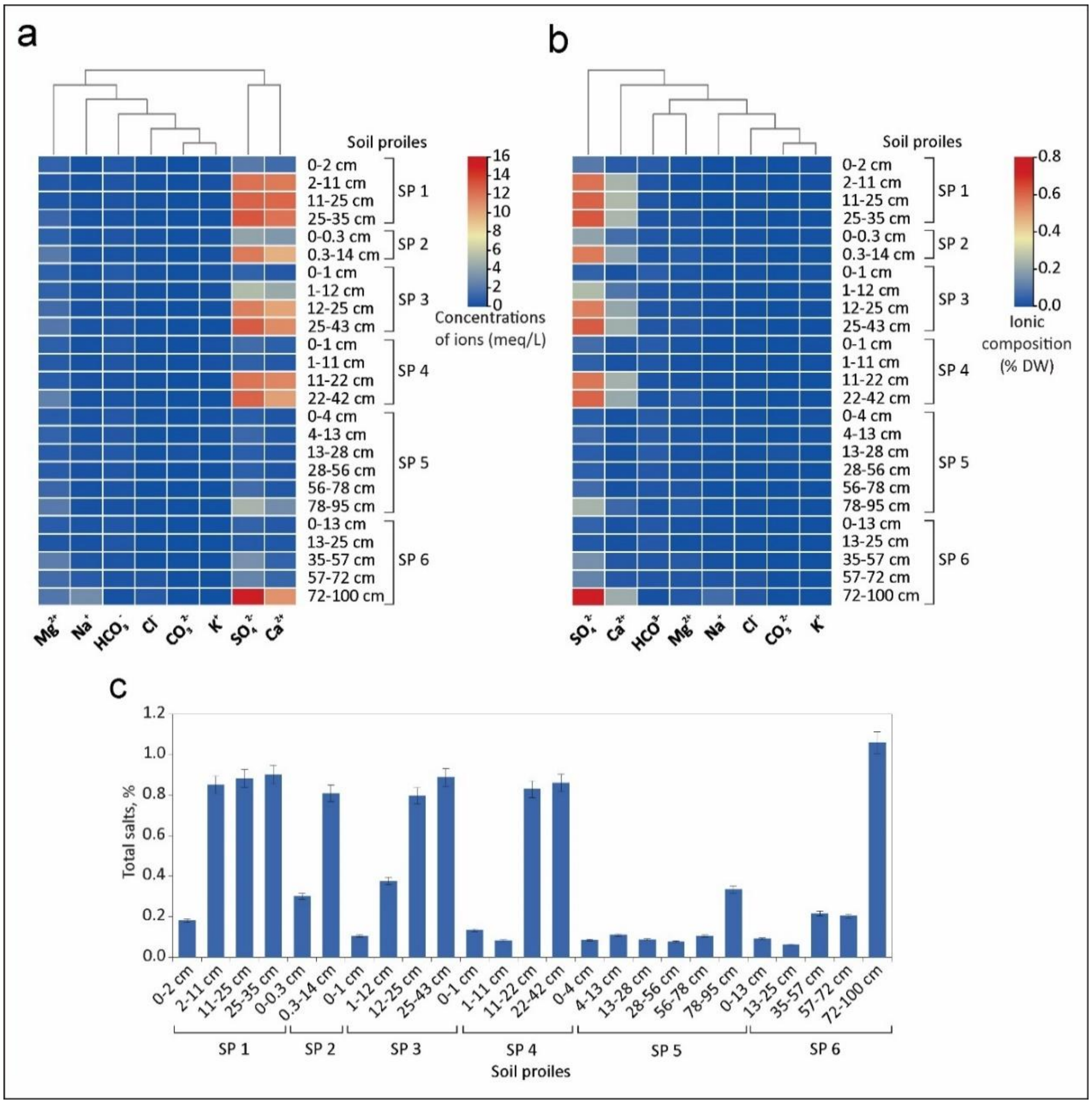

Fig. 3: Concentration of major salt ions in soils from the top, bottom, and surrounding areas of the dump. Note: (a) Concentrations of major salt ions; (b) Ionic composition of major salts expressed as a percentage of total dry weight (DW); (c) Total salt concentration across the soil profiles.

In SP 6, the highest total salt content was detected in the 72-100 cm range (1.1%), while the 13-25 cm layer contained only 0.1%. Notably, in SP 1 the salt concentration in the 2-35 cm depth range reached 0.85% (Fig. 3c).

In addition to gradual salt buildup with depth, surface salt efflorescence is a notable phenomenon on exposed mine tailings in arid environments.[55] After rare rain events, evaporating pore water can leave behind white crusts of salt on or near the surface. A case study in Sonora, Mexico documented extreme concentrations of ions and metals in evaporative crusts on copper mine tailings. There, the tailings had a moderate total Cu content (0.1% Cu), but evaporation led to efflorescent salts on the tailings surface containing up to 6.8% Cu (68,000 mg/kg) along with high levels of Zn, Mn, and other ions. This example highlights how the soluble weathering products can accumulate at the evaporation front, in this case at the surface, to levels far exceeding those in the bulk soil. The Akbakai soils likewise showed elevated SO_4^{2-} and Ca^{2+} in the upper layers of the tailings, suggesting periodic dissolution and re-precipitation of gypsum and related salts. Such salt encrustations pose challenges for revegetation, as they create intense osmotic stress and can be toxic (Fig. 3). Therefore, the observed ion accumulation with depth at Akbakai, alongside any surface efflorescence during dry seasons, is in line with salinization trends reported in other arid mining contexts, underlining the need for soil amendments or leaching interventions to mitigate salt build-up.

3.3. Potentially toxic elements analysis in soils

Total concentrations of metal(loid)s were determined for copper Cu, Zn, Cd, Pb, Co, Ni, Mo, Ag, and As across all soil profiles. The majority of profiles were contaminated with Pb, with the highest total Pb content observed in SP 1 (308 mg/kg at the surface and 284 mg/kg in the inner layer), while SP 5 and SP 6 exhibited comparatively lower Pb levels. Similarly, Zn was present at elevated concentrations, particularly in SP 1

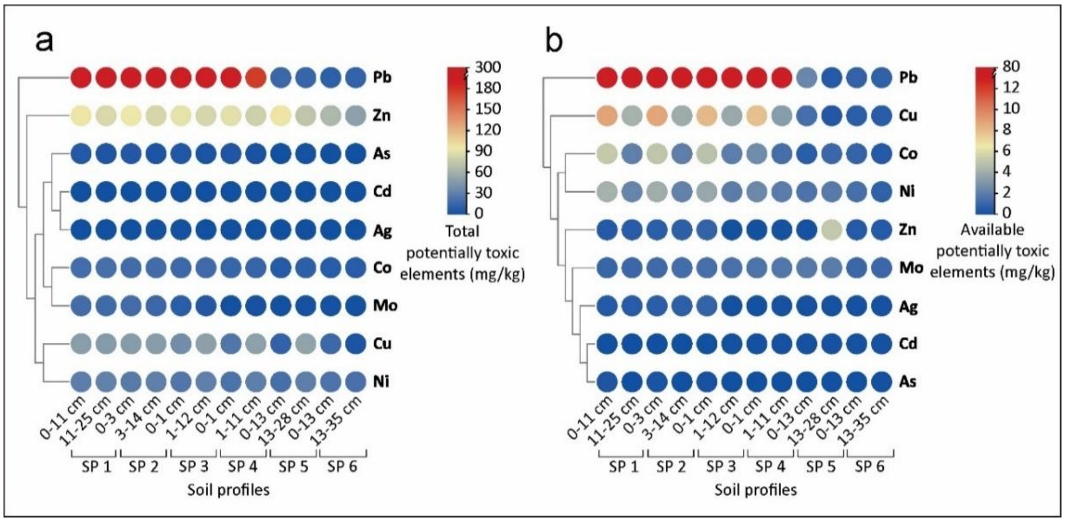

Fig. 4: Potentially toxic elements concentrations in soils from the top, bottom, and surrounding areas of the dump. Note: (a) Total content of potentially toxic elements; (b) Available content of potentially toxic elements.

and SP 2, whereas SP 6 consistently displayed the lowest Zn values. In all profiles, potentially toxic elements contents were generally higher in the surface horizons and gradually decreased with depth. Notably, Ni concentrations were about one-tenth of those of Pb but were still higher than levels of other trace elements, such as Ag, Mo, and Co, while cadmium did not exceed 0.15 mg/kg in any profile (Fig. 4a).

Measurements of the available potentially toxic element content further revealed that available Pb was approximately 80 mg/kg in SP 1 through SP 4, indicating significant metal mobility in surface layers. Available Cu values were roughly one-tenth of the total Cu, reaching a peak of 8.8 mg/kg in SP 1 and decreasing slightly in deeper parts. Additionally, available Co and Ni were found to be higher in SP 1 and SP 2 but dropped markedly in SP 5 and SP 6. Available As was close to zero in all profiles, and available Mo remained low, with total concentrations ranging from 5.34 mg/kg in SP 5 up to 18.12 mg/kg in SP 1 (Fig. 4b).

Soils in mining-affected zones commonly contain elevated total concentrations of potentially toxic elements, and the Akbakai region is no exception. Comparable studies in other semi-arid mining areas have found potentially toxic elements levels far exceeding natural background values and often above safety thresholds (Fig. 4). For example, at an abandoned sulfide mine in Morocco, the oxidation of pyrite-rich tailings lowered soil pH to 2, and nearby soils became severely contaminated with trace metals, cadmium, copper, lead, and zinc concentrations all surpassed guideline limits for agricultural soil.[56] In many affected locations, Zn and Pb in top soils reach hundreds or even thousands of mg/kg, well above typical background levels (Pb, 20-30 mg/kg). These high totals reflect inputs from mine waste material and deposition of metal-laden dust. At Akbakai, similarly, total metal assays showed enriched levels of elements like As, Cu, and Zn in the profiles influenced by mine waste. At Moroccan pyritic mine sites, oxidative weathering of tailings generates extreme acidity (pH ≈ 2) and mobilizes high loads of Cu, As, Zn and Pb into neighbouring soils. Soils sampled within 50 m of the Sidi Bou Othmane tailings exhibit Cd, Cu, Pb and Zn concentrations of 157.2 ± 8.8, 969.1 ± 38.7, 1640.7 ± 42.7 and 2846.8 ± 84.6 mg kg^{-1}, respectively, values that far exceed Moroccan and international guideline limits for agricultural land.[57] Likewise, at the semi-arid Klondyke Superfund tailings (Arizona, USA), arid-climate weathering promotes formation of soluble sulfate salts that accumulate in the surficial horizon, yielding a mobile, available Pb fraction 2-3× higher in surface layers than in the bulk material.[13,55]

Another mechanism affecting metal bioavailability in arid soils is the formation of soluble metal salts.[58] These salts readily dissolve in water, making their metal content immediately available to plants or to leaching. Thus, even if total metal concentrations in a profile decrease with depth or distance, the fraction that is available may concentrate at the surface where evaporation occurs. This is consistent with our Akbakai findings that available metal fractions were often highest in the upper layers of the tailings and technogenic soils. Similar arid-zone studies emphasize that total content of potentially toxic elements alone is an insufficient indicator of environmental risk.[13] One must consider speciation: metals sequestered in stable compounds contribute to long-term contamination but may pose lower immediate toxicity, whereas metals in soluble or available species are of greater ecological and health concern. The key implication is that remediation efforts at Akbakai should focus not only on reducing total metal levels, but also on immobilizing the available species.[59]

3.4. Potentially toxic elements analysis in natural soils of the area affected by technogenic pollution

Natural soils in areas affected by technogenic pollution were sampled at two representative points (Point 1 and Point 2) to assess both total and available content of potentially toxic elements concentrations (Fig. 1, Fig. 5a, b). In these soils, the available fractions of metals were generally lower than those

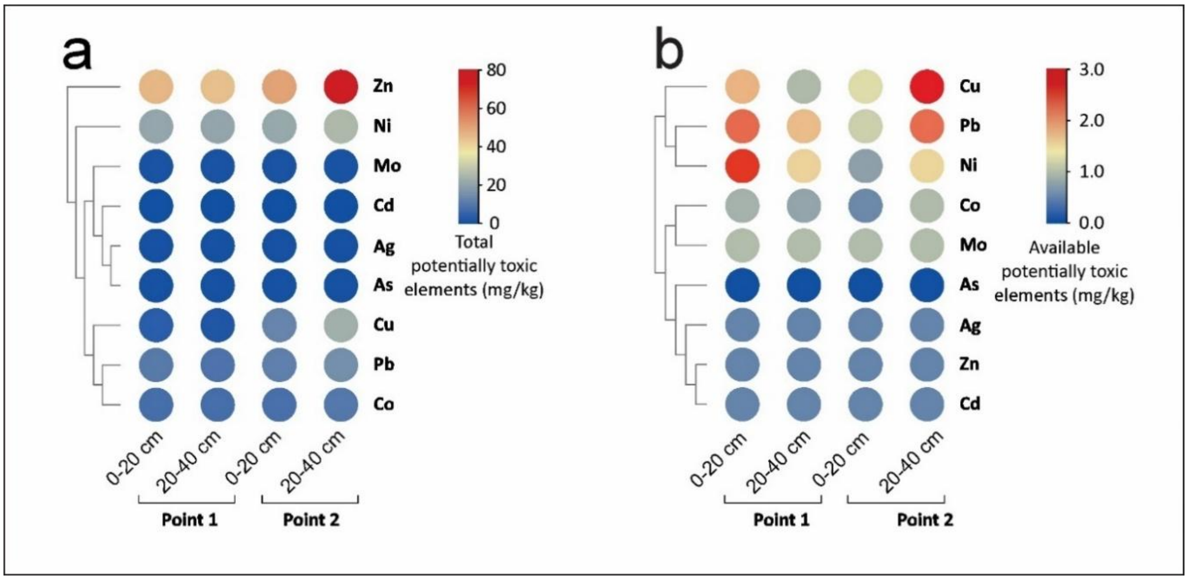

Fig. 5: Potentially toxic elements concentrations in natural soils outside the technologically disturbed areas. Note: (a) Total content of potentially toxic elements in natural soils outside the technologically disturbed area; (b) Available content of potentially toxic elements in natural soils outside the technologically disturbed area.

measured in dump areas.

Further analysis of the total metal content in these technologically disturbed soils revealed that Point 2 was notably more contaminated with Zn, registering total concentrations greater than 73 mg/kg compared to about 44 mg/kg at Point 1. In these areas, Cu, Pb, and Co concentrations generally ranged between 5 and 10 mg/kg and were slightly higher than those measured for Mo, Cd, Ag, and As. Additionally, the surface layers of these soils exhibited lower total metal contents than the corresponding deeper layers (Fig. 5a). In particular, the highest available Cu concentration was observed in Point 2 at the 20-40 cm depth interval, while available Pb and Ni reached approximately 2.1 mg/kg and 2.4 mg/kg, respectively. Concentrations of Ag, Zn, and Cd were consistently low, averaging around 0.5 mg/kg across all samples (Fig. 5b).

Next, we examined the soils in the tailings ponds and observed that they were categorized into gray, red, and black types, collected at two depth intervals (0-20 cm and 20-40 cm) (Fig. 6a-e). We hypothesized that these differently colored soils might contain varying potentially toxic elements concentrations, which we aimed to investigate.

Black tailings, primarily contaminated in the top 0-20 cm layer, showed particularly elevated Zn, with total concentrations of 133.7 mg/kg and available Zn reaching 5.03 mg/kg. Total Co, Pb, and Ni in these layers were 6.99 mg/kg, 56.5 mg/kg, and 10.1 mg/kg respectively, while total As was 15.8 mg/kg. In the 20-40 cm layer of black tailings, available Ni was 5.88 mg/kg, and total As remained at 15.8 mg/kg, with available Zn slightly elevated (Fig. 6a,b).

In gray tailings, the 0-20 cm layer showed a total Cu concentration of 138.11 mg/kg (with an available fraction of 3.75 mg/kg), along with total Zn at 127.9 mg/kg, Pb at 51.8 mg/kg, Co at 18.9 mg/kg (available fraction 6.5 mg/kg), and total Ni at 8.6 mg/kg; available As ranged between 8.8 and 17.6 mg/kg. In the 20-40 cm layer of gray tailings, although Cu and Zn levels slightly decreased (70.3 and 11.29 mg/kg, respectively), Pb (56.94 mg/kg), available Ni (8.4 mg/kg), and total As (20.71 mg/kg) remained high (Fig. 6a,b).

Red tailings exhibited substantial contamination as well. In the 0-20 cm layer, total Cu reached 85.3 mg/kg, Zn 167.1 mg/kg, Pb 72.6 mg/kg, and Co 22.4 mg/kg (with an available fraction of 5.97 mg/kg). Available Ni was recorded at 8.8 mg/kg and total As at 19.2 mg/kg. In the deeper 20-40 cm layer, the concentrations of Cu (6.89 mg/kg), Zn (114.2 mg/kg), Pb (35.79 mg/kg), available Ni (9.9 mg/kg), and total As (19.7 mg/kg) all remained above safe limits (Fig. 6a,b).

Exceedances of the maximum permissible concentration (MPC) were predominantly observed in technogenic sediments and tailings, specifically in both total and available species of Cu, Zn, Co, and Pb; the available species of Ni; and the total species of As. No such exceedances were observed in the outer areas of the technogenic zone. The key pollutants adversely affecting soil quality, plant growth, and food chains are Cu, Zn, Pb, Co, Ni, and As, with arsenic in the gray tailings exhibiting the highest levels.

In the bulk soil, As was the most problematic, exceeding its MPC in all six samples by 7.88-10.36 × (maximum at gray soil, 20-40 cm). Pb surpassed its limit in five of six samples (1.12-2.27 ×), peaking at red soil (0-20 cm). Zn also exceeded in five samples (1.13-1.67 ×), with the highest at red soil (0-20 cm). Cu was elevated above its threshold in three samples, up to 2.51 × at Gray (0-20 cm), while Co barely breached its MPC once (1.12 × at Red, 0-20 cm). Cd, Ni, Mo and Ag remained below their total MPC across all depths and sites (Fig. 6c). In the soil solution, Mo and Ag uniformly exceeded their mobile MPC by 10 × in every extract. As exhibited

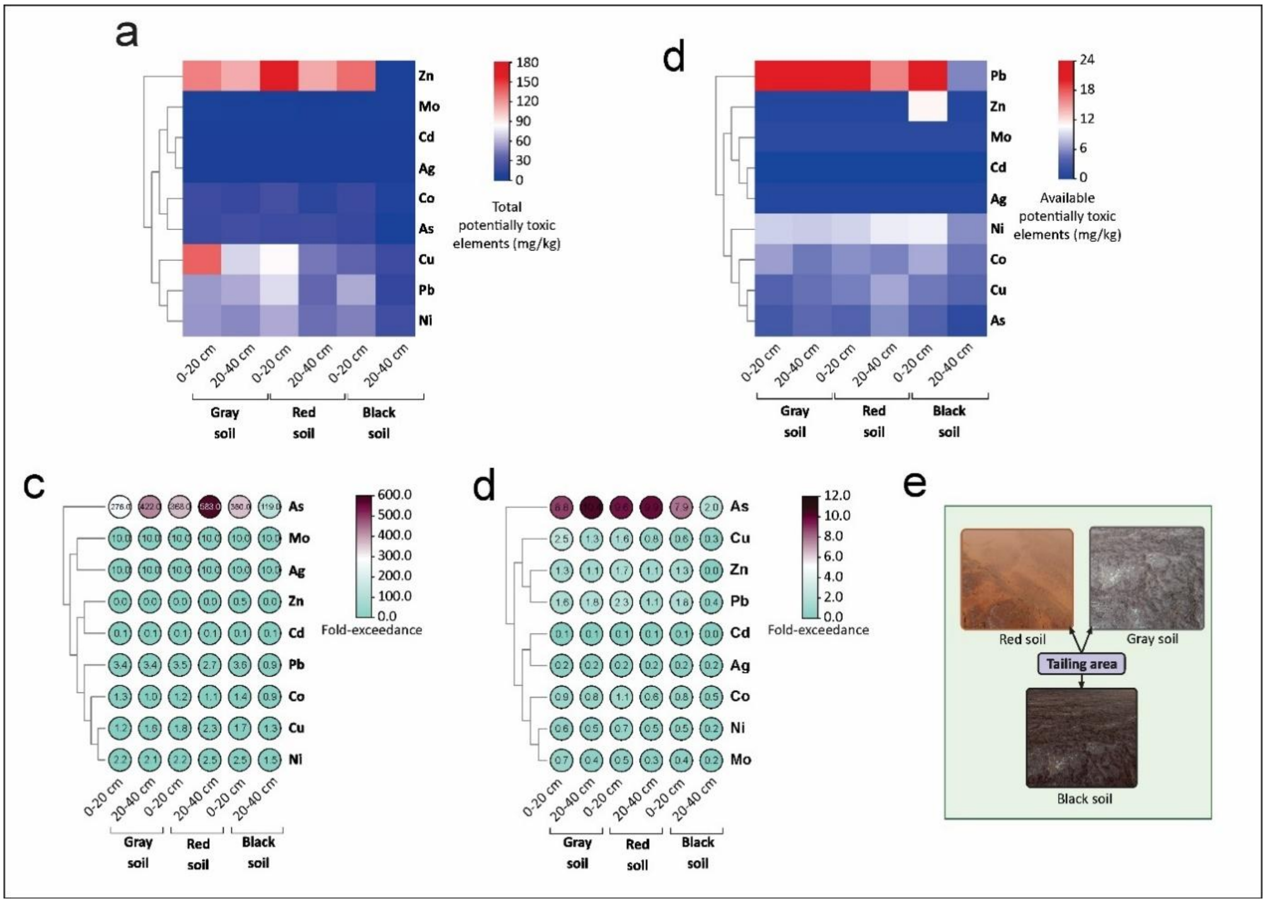

Fig. 6: Potentially toxic elements concentrations in natural soils outside the technologically disturbed and tailings areas. Note: (a) Total content of potentially toxic elements in soils from the tailings area; (b) Available content of potentially toxic elements in soils from the tailings area; (c) Fold-exceedance of total content of potentially toxic elements relative to mobile MPC across sites and depths; (d) Fold-exceedance of available content of potentially toxic elements relative to MPC across sites and depths; (e) Representative red, gray, and black soils in the tailings area.

extreme mobility, with dissolved concentrations 119-583 × above its limit (highest at red soil, 20-40 cm). Ni and Cu were mobilized in all samples, exceeding their thresholds by 1.47-2.52 × and 1.25-2.30 ×, respectively. Pb and Co surpassed their mobile MPC in five of six extracts (2.71-3.56 × and 1.08-1.40 ×), whereas Zn and Cd remained immobilized below their available limits throughout (Fig. 6d).

To contextualize the Akbakai results, it is useful to compare contamination across different land categories: the mine tailings themselves, adjacent technogenic zones (disturbed soils around the mine, including those mixed with waste rock or affected by deposition), and undisturbed natural soils farther away (Fig. 5,6). A consistent pattern reported in the literature is that tailings or mine waste piles exhibit the highest contamination, technogenic or reclaimed soils show intermediate levels depending on the degree of mixing and remediation, and natural background soils have the lowest (baseline) levels of contaminants.[60,61] For example, Li *et al.*, (2024) assessed heavy-metal ecological risk around an asbestos mine on an arid plateau and found that soils immediately bordering the waste-residue heap exhibited extremely high risk indices (RI ≥ 444), while soils just a few hundred meters away showed dramatically lower RI values, consistent with a sharp tailings-to-natural decline in contamination.[62] Likewise, Ni *et al.*, (2023) sampled tailings sand, nearby river-terrace soils, and more remote background sites downstream of the Dexing Copper Mine: Cu and associated heavy-metal concentrations peaked in the tailings sand, dropped to intermediate levels in the river-terrace soils, and reached baseline values in distant soils.[63] For instance, the abandoned tailings dump acted as a point source that massively elevated metal concentrations in the surrounding topsoil relative to uncontaminated soil.[56] Also, Kozybaeva (2007) showed that the exhausted dumps at the Zyryanovsk and Tishinka deposits in East Kazakhstan undergo rapid erosion and intense weathering, leading to pronounced enrichment of heavy metals (Pb, Cd, Cu, Zn) in the surface soils.[64] In the Central Zhezkazgan region, soils within ~5 km of copper smelters exhibit elevated concentrations of sulfuric copper, lead sulfide and zinc particulates, creating localized contamination hotspots. More recently, Paramonova *et al.*, (2025) reviewed nationwide patterns of soil pollution and erosion, emphasizing how seasonal precipitation and local geomorphology govern contaminant dispersal across Kazakh mining areas.[65]

Across bulk and solution phases, As, Mo, and Ag exhibit

Fig. 7: Spatial distribution of total potentially toxic elements and key nutrient concentrations at sampling locations. Note: Units for Pb, Zn, As, Mg and AN are mg/kg. AN = available nitrogen; TP = total phosphorus; TN = total nitrogen; TK = total potassium. For each nutrient, the highest concentration observed among all soil profiles is shown.

the highest risks (As up to 583× its mobile MPC and 10× total; Mo & Ag uniformly 10× in solution), while Cu, Ni, Pb, and Co exceed thresholds in most samples (1.1-3.6×); Zn and Cd remain below limits. These coupled abundance and mobility patterns demand integrated remediation – stabilizing total-bound metals and deploying barriers (pH adjustment, organic amendments) to curb leaching, safeguard groundwater, and limit plant uptake (Fig. 6c,d).

The pH of soils in the impact zone was also drastically lower compared to the neutral pH of native desert soils, underscoring how tailings-derived acidity and metals together degrade local soil quality (Fig. 7).

A risk assessment by Boularbah *et al.*, (2006) noted that without intervention, such pollution continues to spread outward via dust and water, gradually encroaching on soils that were originally unpolluted.[66] This scenario likely parallels the Akbakai site, where we observed the highest total metal loads and poorest soil health metrics in the tailings materials, moderate contamination in soils within the mine lease (affected by ore processing activities and dust fallout), and relatively low metal levels in the remote reference soils of the area.[67]

In parallel to the heavy-metal leaching observed in gold mining, petroleum extraction in arid regions such as Zhambyl and Kyzylorda employs enhanced oil recovery methods, chemical polymer and surfactant flooding as well as gas injection, to boost production. When well cementation or casing integrity is compromised, these injected agents and formation fluids can migrate upward, contaminating shallow soil horizons and groundwater with residual surfactants, polymers and hydrocarbons. Regional hydrogeological studies in South Kazakhstan identify oil and gas production complexes as significant non-point sources of aquifer pollution, reporting elevated levels of dissolved organic compounds and shifts in redox conditions in groundwater adjacent to aging well pads.[68] Sector-wide reviews further document that widespread discharge of produced waters and chemical additives has altered soil physicochemical properties, reducing permeability and changing microbial communities, in areas surrounding decommissioned oilfields.[69]

5. Conclusion

This study provides a comprehensive evaluation of the soil quality and contamination patterns at the Akbakai open-pit gold mine in southern Kazakhstan. Our analyses reveal a pronounced vertical stratification, with surface horizons enriched in organic matter and nutrients that sharply decline with depth, while subsoil layers exhibit increased accumulation of salts and base cations. These trends underscore the limited natural pedogenesis and the influence of arid environmental conditions on soil development. Soil salinization is a significant issue at the site, with ion concentrations, particularly Ca^{2+} and SO_4^{2-}, increasing with depth. This reflects the combined effects of limited rainfall, high evaporation, and the weathering of parent materials, leading to a gradual buildup of salts in the subsurface. The observed salt accumulation in these dry conditions aligns with similar trends reported in arid mining regions, reinforcing the challenges for natural restoration. Potentially toxic elements analyses further indicate that mining activities have resulted in elevated levels of contaminants, particularly Pb, As, Mg, and Zn, with the highest concentrations occurring in the surface horizons of tailings and technogenic soils. Although the available fractions are lower, they still present a significant risk for environmental exposure. Interventions such as tailings stabilization, organic amendments, and revegetation are recommended to improve soil structure, reduce salt and contaminant mobility, and promote long-term ecological recovery.

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Conflicts of Interest

The authors declare no conflicts of interest.

Supporting Information

Not applicable.

CRediT Statement

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