The effect of mining-derived tailings on soil physicochemical properties and ecological recovery potential in northwestern Romania

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Abstract. Soil contamination resulting from historical mining activities represents one of the major environmental constraints in northwestern Romania, affecting soil quality, vegetation recovery, and ecosystem stability. This study aimed to evaluate the physicochemical characteristics of soils collected from tailings ponds, former mining areas, and an uncontaminated control zone to assess the degree of degradation and the potential for natural ecological recovery. A total of 66 soil samples were collected from 22 locations across three study zones and analyzed for pH, moisture content, cation exchange capacity (CEC), organic matter (OM), electrical conductivity (EC), bulk density (Db), and texture, following ISO standardized methods. Results revealed pronounced spatial variability among zones. Soils from tailings ponds (Zone I) exhibited acidic pH (5.42±0.28), low OM (1.12±0.33%), and reduced CEC (8.7±1.9 cmol(+)/kg), indicating strong chemical degradation and limited fertility. Mining-area soils (Zone II) showed intermediate values, suggesting partial natural recovery through vegetation establishment and organic input. In contrast, control soils (Zone III) displayed near-neutral pH (6.82±0.22), higher OM (3.96±0.72%), and increased CEC (17.5±3.1 cmol(+)/kg), reflecting well-developed pedogenic conditions and stable agroecosystem functioning. Statistical analysis (one-way ANOVA, $p<0.05$) confirmed significant differences across all parameters, with pH, CEC, and OM emerging as key indicators of soil degradation and recovery potential. The results demonstrate that soil physicochemical parameters are reliable diagnostic tools for assessing the impact of mining activities and monitoring ecological restoration progress. Natural attenuation was evident along the contamination gradient, suggesting that rehabilitation strategies—such as organic amendment and phytostabilization—can further accelerate ecosystem recovery in post-mining landscapes.

Key Words: cation exchange capacity, ecological recovery, mining contamination, organic matter, Romania, soil physicochemical parameters.

Introduction. Mining activities impose a profound disturbance on soil systems, leading to both chemical contamination and physical degradation. Globally, current and former mining sites cover over 57000 km^2 of land (Voșgan et al 2021; Kosheleva et al 2022). These landscapes are often hotspots of heavy metal accumulation, where soils contain elevated levels of toxic elements like lead, arsenic, and cadmium that pose long-term ecological and health risks (Voșgan et al 2021; Kosheleva et al 2022). For instance, soils near a Romanian mining area were found to have lead concentrations exceeding regulatory thresholds decades after mine closure (Voșgan et al 2021). Such contamination can disrupt plant communities and enter food chains, underscoring the need for rigorous assessment of mined land soils (Mir et al 2020). In parallel, the removal of vegetation and topsoil during mining initiates severe erosion and habitat loss, compounding the environmental impact.

Mining fundamentally alters soil physicochemistry by stripping away the fertile topsoil and leaving behind technosols – soils with anthropogenic substrates and disturbed profiles. Open-pit excavation and heavy machinery compaction destroy soil structure, often resulting in barren, compacted surfaces with minimal organic matter (Miu et al 2022). These denuded mine soils are typically nutrient-depleted and microbiologically inactive due to the lack of organic carbon and nitrogen inputs (Miu et al 2022). Consequently, natural revegetation is extremely slow; even pioneer plants struggle to establish on mine spoils with poor fertility and extreme conditions. Additionally, mine waste tailings stored in ponds or dumps present a chronic source of pollution. Tailings materials, often finely ground and sulfide-rich, can generate acid mine drainage (AMD) when exposed to air and water. The oxidation of sulfide minerals (e.g. pyrite) produces sulfuric acid, leading to severely acidified soils ($pH<3$ in extreme cases). This acidic runoff leaches further into surrounding soil and water, mobilizing heavy metals in the process (Liao et al 2016). Low pH conditions greatly increase the solubility and mobility of metal cations, as demonstrated by studies linking acidic soils to elevated extractable metals (Zeng et al 2011). The result is a toxic substrate where aluminum, iron, zinc, and other metals become readily available to biota, often at concentrations lethal to plants and soil organisms. Heavy metal stress in such soils manifests as stunted plant growth, root browning, and suppressed microbial activity (Ningombam et al 2024). Thus, post-mining landscapes commonly exhibit a combination of acidification, metal toxicity, organic matter loss, and compaction, all of which contribute to a hostile environment for life.

In order to evaluate soil degradation and guide rehabilitation efforts, it is critical to monitor key physicochemical parameters that reflect soil health and contaminant dynamics. The present study focuses on six interrelated indicators – pH, organic matter (OM), cation exchange capacity (CEC), moisture content, electrical conductivity (EC), and bulk density – which together provide a comprehensive picture of soil quality in post-mining contexts. Each parameter is closely tied to soil functions and metal mobility:

- pH: Soil pH governs nutrient availability and metal solubility. Mining-impacted soils often exhibit low pH due to sulfide oxidation, which enhances heavy metal release and bioavailability (Liao et al 2016). Even a modest increase in acidity can dramatically increase the leaching of cadmium, zinc, and other metals into the soil solution. Conversely, remediating pH through liming has been shown to immobilize metals and improve plant growth (He et al 2021). Monitoring pH is therefore essential, as it is a primary control on toxicity and soil fertility.
- OM: OM is the cornerstone of soil ecological function, influencing structure, nutrient cycling, and pollutant binding. Mine soils are often extremely low in OM due to the lack of vegetation and microbial inputs. This loss of humus reduces soil aggregation and deprives the soil of binding sites for metals, increasing metal mobility (Miu et al 2022). Conversely, higher OM content can sequester heavy metals through complexation and improve soil moisture retention and CEC. Indeed, adding organic amendments (compost, manure, biochar) to mine tailings raises OM levels, which in turn has been observed to elevate pH and stabilize metals (Miu et al 2022). Thus, OM is a key indicator of soil recovery – rising organic carbon typically signals returning fertility and biological activity.
- CEC: CEC measures the soil's ability to retain and exchange nutrient cations (Ca^{2+}, Mg^{2+}, K^{+}, etc.) as well as heavy metal ions. It is largely governed by clay minerals and OM content. In degraded mine soils with sandy textures or low OM, CEC tends to be low, indicating poor nutrient-holding capacity. A low CEC also

means fewer adsorption sites to bind metal ions, potentially leaving contaminants in more labile forms (Young et al 2015). Improvement in CEC over time – for instance, through natural clay formation or humus accumulation – often accompanies ecosystem recovery, as it enhances the soil's buffering capacity against acidification and metal leaching. Thus, CEC serves as an integrative index of soil chemical health and pedogenic development in post-mining landscapes.

- Moisture content: Soil moisture regulates a host of ecological and geochemical processes, from plant water availability to microbial respiration and leaching of soluble pollutants. Mine tailings and wastes often show extreme moisture regimes: coarse waste materials may drain quickly and become drought-prone, whereas compacted or fine-textured tailings may trap water and create anoxic conditions. Low moisture content can limit revegetation success by inducing drought stress in seedlings, while excessive moisture can facilitate metal mobility via runoff or seepage. Monitoring gravimetric moisture content (and related properties like water holding capacity) helps determine if rehabilitated soils are improving in structure and porosity. Typically, increasing soil OM leads to better water retention, alleviating harsh dry-down cycles in reclaimed soils (Paz-Ferreiro & Fu 2016). A balanced moisture regime – neither too dry nor waterlogged – is a hallmark of a functional, recovered soil.
- EC: EC is a proxy for soluble salt content in soil pore water. In mining contexts, elevated EC often indicates salinization or high concentrations of dissolved metals and sulfates from mineral weathering. Acid mine drainage-affected soils, for example, can exhibit very high EC due to the presence of sulfate salts and metal ions. Leiva et al (2021) note that mine tailings are characteristically low in pH and high in salinity, reflecting the abundance of ionic contaminants. High EC levels are deleterious to plants, causing osmotic stress and ion toxicity in roots. Thus, tracking EC provides insight into the intensity of contamination: a downward trend in EC over time would suggest leaching of salts or successful attenuation of pollution, whereas persistently high EC flags ongoing chemical stress in the soil.
- Bulk density (Db): Db is an indicator of soil compaction and porosity. Severe disturbance by heavy machinery can leave mine soils highly compacted, with bulk densities often above 1.5 g cm^{-3}, which is enough to restrict root penetration and reduce gas exchange. In healthy soils, lower bulk density (typically 1.0–1.4 g cm^{-3}, depending on texture) corresponds to greater pore space, better infiltration, and a more hospitable rooting environment. Reclaimed mine soils tend to show a gradual decrease in bulk density as OM builds up and bioturbation by roots and soil fauna restores structure. Values of Db are therefore closely watched in restoration projects – declining bulk density is a positive sign of soil physical recovery, whereas stubbornly high Db may indicate the need for soil ripping, subsoiling, or additional organic amendments to alleviate compaction (Harris et al 2020). In short, bulk density links directly to soil aeration and root growth potential, making it a critical physical quality metric for post-mining soil health.

Collectively, these physicochemical parameters serve as sentinels of soil health in post-mining landscapes. They not only reflect the legacy of mining-induced degradation (acidification, contamination, compaction), but also chart the trajectory of natural attenuation or remediation. Importantly, they are interrelated: for example, acidic pH and high EC often co-occur in sulfide-rich tailings, while increasing OM tends to lower Db and increase CEC, fostering improved nutrient status. By quantitatively monitoring these indicators, scientists and land managers can assess how far a degraded soil has progressed towards a functional state and identify which limiting factors remain. In practice, soil monitoring is indispensable for guiding restoration and land management on former mine lands. Regular measurements of pH, nutrients, and contaminants allow for adaptive management – if pH remains low, liming can be applied; if organic carbon is deficient, amendments or planting of nitrogen-fixing cover crops can be introduced (He et al 2021). Moreover, tracking parameters like CEC and metals over time can inform risk assessments, ensuring that reclaimed sites do not continue to leach toxins into groundwater or pose hazards to local communities (Adnan et al 2022). In essence, soil quality indices that integrate these parameters have been proposed as tools to evaluate reclamation success (Mukhopadhyay et al 2016; Paz-Ferreiro & Fu 2016). A rise in soil pH and OM alongside a drop in EC and bioavailable metal fractions, for example, would indicate that ecological conditions are improving and that the soil is recovering its productive capacity. On the other hand, stagnation of these metrics might signal the need for more intensive remediation interventions.

Given the importance of these soil attributes, the present study investigates physicochemical soil degradation and incipient recovery in a post-mining landscape, using data from three representative zones: (i) an active tailings pond (severely contaminated substrate), (ii) a former mining site undergoing natural rehabilitation, and (iii) an off-site control area with undisturbed soils. By comparing key parameters (pH, OM, CEC, moisture, EC, Db) across this gradient, we aim to contextualize the extent of mining-induced degradation and the efficacy of natural reclamation processes. This introduction has outlined the environmental impacts of mining on soils and the relevance of each measured parameter to soil health and metal dynamics. In the sections that follow, we build on this foundation to analyze the empirical data from the three zones, with reference to peer-reviewed benchmarks, in order to draw conclusions about soil degradation and potential pathways to recovery in temperate post-mining ecosystems. Ultimately, a better understanding of this soil indicators will support more effective restoration strategies and sustainable land management for landscapes scarred by mining.

Material and Method

Description of the study site. Soil samples were collected from a variety of locations across three distinct study zones in northwestern Romania: Bozânta Mare, Săsar, Nistru, Herja, Ilba, Șuior, and Tîrlișua. Zones I and II include areas historically impacted by mining and ore-processing operations, such as the former tailing’s ponds of Bozânta Mare, Săsar, and Nistru, as well as the abandoned mining sites of Herja, Ilba, Șuior, and the UP Central Flotation area. In these contaminated zones, soils are affected by the deposition of tailings dust, surface runoff, and infiltration of metal-bearing waters from mining residues, leading to pronounced spatial variability in the concentrations of Pb, Zn, Cu, and Cd.

Zone III represents the control area at Tîrlișua, situated outside the influence of mining or industrial activities, and serves as a reference for background soil conditions. Sampling points were selected to represent both surface and subsurface horizons (0–20 cm), covering areas with varying degrees of anthropogenic and natural influence within each zone. All soil samples were collected in triplicate using acid-washed polyethylene tools, air-dried at room temperature, homogenized, and sieved (<2 mm) prior to physicochemical and elemental analysis in the laboratory.

Soil samples. Soil samples (n=66) were collected from three study zones located in northwestern Romania: Zone I (Bozânta Mare, Săsar, and Nistru), Zone II (Herja, Ilba, Șuior, Nistru, and UP Central Flotation), and Zone III (Tîrlișua – control area). Zone I encompassed the areas surrounding the former tailings ponds of Bozânta Mare, Săsar, and Nistru, while Zone II included soils from the vicinities of former mining and ore-processing sites such as Herja, Ilba, Șuior, and UP Central Flotation. Zone III represented the uncontaminated reference site at Tîrlișua, located outside any mining or industrial influence (Table 1).

Table 1

Detailed inventory of soil samples, including site, owner, and collection date

Sample code	*Sample type*	*Zone/The main sources of pollution*	*Owner*	*Collection date*	*Observations*
Zone I encompasses the areas of the former tailings ponds at Bozânta Mare, Săsar, and Nistru					
S-TMBTP-O1	Soil	TMBTP	O1	March 12, 2025	Slightly yellow soil
S-RS-O1	Soil	RS	O1	March 12, 2025	Slightly yellow soil
S-TMN-O1	Soil	TMN	O1	March 12, 2025	Slightly yellow soil
Zone II includes the areas of the former mines: Herja, Ilba, Șuior, Nistru, and UP Central Flotation					
S-TMH-O1	Soil	TMH	O1	March 12, 2025	Slightly yellow soil, friable
S-TMH-O2	Soil	TMH	O2	March 12, 2025	Slightly yellow soil, moist
S-CI-O1	Soil	CI	O1	March 7, 2025	Dark grey soil, slightly compact
S-CI-O2	Soil	CI	O2	March 7, 2025	Slightly yellow soil, friable
S-CȘ-O1	Soil	CȘ	O1	March 7, 2025	Dark grey soil, moist
S-CȘ-O2	Soil	CȘ	O2	March 7, 2025	Greyish soil, compact
S-CȘ-O3	Soil	CȘ	O3	March 7, 2025	Slightly yellow soil, friable
S-TNN-O1	Soil	TNN	O1	March 7, 2025	Slightly yellow soil, sandy texture
S-UPCFBM-O1	Soil	UPCFBM	O1	March 7, 2025	Slightly yellow soil, dry surface
Zone III includes the control area					
S-T-O1	Soil	Tîrlișua	O1	March 7, 2025	Slightly yellow soil, friable
S-T-O2	Soil	Tîrlișua	O2	February 10-11, 2025	Slightly yellow soil, moist
S-T-O3	Soil	Tîrlișua	O3	February 10-11, 2025	Yellowish-brown soil, friable
S-T-O4	Soil	Tîrlișua	O4	February 10-11, 2025	Slightly yellow soil, sandy texture
S-T-O5	Soil	Tîrlișua	O5	February 10-11, 2025	Slightly yellow soil, dry surface
S-T-O6	Soil	Tîrlișua	O6	February 10-11, 2025	Light brown soil, compact
S-T-O7	Soil	Tîrlișua	O7	February 10-11, 2025	Slightly yellow soil, friable
S-T-O8	Soil	Tîrlișua	O8	February 10-11, 2025	Slightly yellow soil, moist
SE-T-O9	Soil	Tîrlișua	O9	February 10-11, 2025	Light brown soil, sandy texture
SE-T-O10	Soil	Tîrlișua	O10	February 10-11, 2025	Slightly yellow soil, friable

Note: S - soil; TMBTP - Tăuții-Măgherăuș / Bozânta Mare tailings ponds; RS - Recea / Săsar; TMN - Tăuții-Măgherăuș / Nistru; TMH - Tăuții-Măgherăuș / Herja; CI - Cicârlău / Ilba; CȘ - Cavnic / Șuior; TNN - Tăuții-Măgherăuș / Nistru (tailings ponds area); UPCFBM - UP Central Flotation / Bozânta Mare; T - Tîrlișua (control area). O1 - Owner number 1; O2 - Owner number 2; O3 - Owner number 3; O4 - Owner number 4; O5 - Owner number 5; O6 - Owner number 6; O7 - Owner number 7; O8 - Owner number 8; O9 - Owner number 9; O10 - Owner number 10. Zone I n=9 (soil samples); Zone II n=27 (soil samples); Zone III n=30 (soil samples). Sample code format: S–[Site Code]–[Owner ID].

At each of the 22 sampling locations, three subsamples were taken within a 10 m radius, homogenized, and composited into a single analytical sample representing the upper 0–20 cm soil layer. Sampling sites were selected to capture local heterogeneity across pasture areas, hay-producing meadows, and control grasslands. Soils were collected using a stainless-steel auger, stored in acid-washed polyethylene bags, air-dried at room temperature, gently disaggregated, and sieved through a 2 mm mesh prior to chemical analysis. Soil sampling was conducted under stable weather conditions (no recent precipitation) to avoid variability caused by soil moisture. Air temperature during sampling ranged between 10–18°C, and relative humidity between 55–70%.

Sampling and sample preparation procedures followed ISO 10381-1:2002 and ISO 11464:2006 standards for soil quality sampling and pretreatment, and ISO 11466:1995 following general ISO procedures for soil quality assessment. Field observations noted color and texture variations among the sites, ranging from slightly yellow and friable to dark grey and compact, reflecting both natural soil heterogeneity and anthropogenic influence.

Sample preparation and analytical determination of soil physicochemical parameters. Soil samples were air-dried at room temperature for 72 h, gently disaggregated, and sieved through a 2 mm nylon mesh to remove coarse particles, roots, and plant residues. The <2 mm fraction was homogenized and used for the determination of physicochemical parameters according to standardized ISO methods. All measurements were performed in triplicate, and analytical precision was maintained within ±5%.

The soil pH was determined in a 1:2.5 (w/v) soil-to-water suspension using a calibrated pH meter (ISO 10390:2005). Moisture content (%) was measured gravimetrically (ISO 11465:1993) by oven-drying at 105 °C until constant weight. Cation exchange capacity (CEC) was assessed according to ISO 23470:2018, using ammonium acetate as the exchange solution. OM content (%) was quantified using the Walkley–Black dichromate oxidation method (ISO 14235:1998). Electrical conductivity (EC) was measured in the soil–water extract (1:5 w/v) with a conductivity meter, following ISO 11265:1994. Soil texture was determined by the pipette (sedimentation) method according to ISO 11277:2009, classifying soils into sand, silt, and clay fractions. Bulk density was measured gravimetrically using the core method, relating dry soil mass to core volume. These parameters were selected to evaluate key soil properties influencing the mobility, retention, and bioavailability of metals in mining-impacted and control zones.

Quality assurance and quality control (QA/QC). All analyses were performed in triplicate to ensure reproducibility. Analytical instruments were calibrated daily, and standard reference materials were analyzed periodically to verify method accuracy. Reagent blanks and duplicate samples were included in each analytical batch. Data consistency was verified by cross-checking against reference soil standards where available.

Reagents and equipment. All chemicals used in this study were of analytical grade or higher. Ultrapure deionized water (resistivity ≥18.2 MΩ·cm) was obtained using a Milli-Q purification system (Merck Millipore, Darmstadt, Germany) and was used for all dilutions and sample preparations. For the pH determination (ISO 10390:2005), a 1:2.5 soil-to-water suspension was prepared using deionized water and measured with a Mettler Toledo SevenCompact S220 pH meter, calibrated daily with standard buffer solutions (pH 4.01, 7.00, and 9.21, Merck). Moisture content was determined gravimetrically (ISO 11465:1993) using an electronic analytical balance (±0.001 g precision) and a Binder FD 53 drying oven (Darmstadt, Germany) set to 105°C.

CEC was measured according to ISO 23470:2018, using 1 M ammonium acetate (NH_4OAc) solution at pH 7 as the exchange reagent. All reagents (NH_4OAc, CH_3COOH, NH_4OH) were supplied by Sigma-Aldrich (St. Louis, MO, USA). OM content was quantified by the Walkley–Black method (ISO 14235:1998), employing potassium dichromate

($K_2Cr_2O_7$, 1 N) and concentrated sulfuric acid (H_2SO_4, 98%) as oxidation reagents, and ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2{\cdot}6H_2O$) for titration. EC was measured in a 1:5 soil–water extract following ISO 11265:1994, using a Hanna Instruments HI 2315 conductivity meter equipped with a temperature-compensated probe.

Soil texture was determined by the pipette (sedimentation) method (ISO 11277:2009), using sodium hexametaphosphate ($(NaPO_3)_6$, 0.05 N as a dispersing agent. Db was assessed gravimetrically using the core method, with stainless-steel cylinders of known volume and precision balances for mass determination. All glassware and plastic containers were pre-cleaned by soaking in 10% HNO_3 for 24 h and rinsed thoroughly with deionized water before use to prevent contamination.

Ethical considerations. The clinical protocol entitled "Combined Effects of Environmental and Dietary Factors on Heavy Metal Bioaccumulation in Horses and Health Risk Assessment" was approved by the Bioethics Committee of the University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca (Decision No. 491/21.01.2025).

Statistical analysis. Descriptive and inferential statistics were performed using IBM SPSS Statistics v29.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism v10.0 (GraphPad Software, San Diego, CA, USA). Data were first tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. Depending on distribution, inter-zone and inter-matrix differences in metal concentrations were analyzed by one-way ANOVA followed by Tukey's post-hoc test or, for non-parametric data, by the Kruskal–Walli's test with Dunn's multiple comparisons. Relationships between environmental and biological matrices were evaluated using Pearson's or Spearman's correlation coefficients. Results are expressed as mean ± standard deviation (SD), and statistical significance was accepted at $p<0.05$.

Results and Discussion

Soil reaction (pH). The soil pH values revealed marked differences among the three study zones, reflecting both the intensity of anthropogenic disturbance and natural pedogenic processes. Soils from Zone I (tailings ponds) were distinctly acidic (5.42±0.28), a condition commonly attributed to sulfide oxidation and acid mine drainage resulting from the exposure of pyrite (FeS_2) and other metal sulfides to air and moisture. The low pH in these sites significantly enhances the solubility and mobility of toxic metals such as Pb, Cd, and Zn, thereby increasing their bioavailability and ecological risk. In contrast, Zone III (control soils) displayed near-neutral pH values (6.82±0.22), typical of undisturbed pasture soils rich in base cations and organic matter. The slightly acidic conditions in Zone II (6.11±0.34) suggest a gradual natural buffering effect driven by vegetation recovery and organic inputs, indicative of incipient ecological stabilization in former mining areas.

Table 2

Physicochemical parameters of soil samples from the three study zones

Parameter	*Unit*	*Method / ISO standard*	*Zone I (Tailings ponds) Mean ± SD*	*Zone II (Mining areas) Mean ± SD*	*Zone III (Control area) Mean ± SD*	*Ecological significance / Observations*
pH (soil reaction)	pH units	ISO 10390:2005	5.42±0.28	6.11±0.34	6.82±0.22	Acidic soils in tailings areas due to sulfide oxidation; low pH enhances Pb, Cd, and Zn mobility.
Moisture content	%	Gravimetric / ISO 11465:1993	12.4±2.1	16.8±3.5	20.3±3.2	Lower moisture in contaminated soils due to coarse texture and sparse vegetation cover.
Cation Exchange Capacity (CEC)	cmol(+)/kg	ISO 23470:2018	8.7±1.9	12.3±2.4	17.5±3.1	Indicates soil ability to retain metal cations; lowest in tailings-affected zones.
Organic Matter (OM)	%	Walkley–Black / ISO 14235:1998	1.12±0.33	2.34±0.47	3.96±0.72	Organic matter enhances metal complexation; lowest values found in degraded soils.
Electrical Conductivity (EC)	µS/cm	ISO 11265:1994	478±96	385±84	162±45	Higher EC in contaminated zones reflects increased soluble ions and potential salinization.
Soil Texture (average composition)	–	Pipette / ISO 11277:2009	Sandy loam (61% sand, 25% silt, 14% clay)	Loam (48% sand, 32% silt, 20% clay)	Clay loam (35% sand, 33% silt, 32% clay)	Finer textures in control soils promote metal retention; coarse tailing soils favor leaching.
Bulk Density (Db)	g/cm³	Gravimetric method	1.54±0.07	1.43±0.06	1.28±0.05	Lower density in control soils due to higher OM and better aggregation.

Note: mean ± standard deviation (SD) of triplicate determinations. Soils from Zone I (tailings ponds) exhibited acidic pH, low organic matter, and reduced cation exchange capacity (CEC), typical of substrates affected by pyrite oxidation and long-term heavy metal exposure. Zone II (mining areas) displayed intermediate values, suggesting partial recovery through vegetation cover and organic inputs. In contrast, control soils from Zone III (Tîrlișua) showed near-neutral pH, higher CEC, and increased organic content, reflecting well-developed pedogenic processes and stable agroecosystem conditions.

Soil moisture. Moisture content followed a clear gradient across the zones, increasing from tailings sites (12.4±2.1%) to control areas (20.3±3.2%). The lower moisture in contaminated soils is likely a consequence of coarse texture, limited vegetation cover, and poor aggregate stability, all of which reduce water retention capacity. Conversely, the higher moisture levels in Zone III reflect well-structured, humus-rich soils capable of sustaining biological activity and maintaining balanced hydric conditions. These findings are consistent with the idea that long-term contamination and physical degradation of mining soils lead to hydrological dysfunction, reducing the capacity for vegetation regrowth and natural remediation.

Cation exchange capacity (CEC). CEC values showed significant spatial variability, from 8.7±1.9 cmol(+)/kg in Zone I to 17.5±3.1 cmol(+)/kg in Zone III. The reduced CEC in tailings-affected soils indicates depletion of clay minerals and humic colloids, both essential for cation retention. This depletion limits the soil's buffering ability against heavy metals, allowing for greater metal mobility and leaching into groundwater. Intermediate CEC values in Zone II (12.3±2.4 cmol(+)/kg) reflect the partial reestablishment of exchange sites through organic matter accumulation and secondary clay formation. The strong correlation between CEC and OM across all zones underlines the functional coupling between chemical fertility and organic quality in post-mining soils.

Organic matter (OM) content. The OM content varied threefold between contaminated and control sites, from 1.12±0.33% in Zone I to 3.96±0.72% in Zone III. Such low OM levels in tailings areas are typical of physically disturbed, biologically inactive substrates where organic inputs from vegetation are minimal and microbial decomposition is suppressed by high metal toxicity. The moderate OM content in Zone II (2.34±0.47%) supports the hypothesis of progressive ecological recovery, as pioneering plants contribute litter and root biomass that gradually improve soil aggregation and nutrient cycling. Enhanced OM in the control zone indicates mature pedogenesis, promoting complexation and immobilization of heavy metals through humic functional groups.

Electrical conductivity (EC). EC decreased from 478±96 µS/cm in Zone I to 162±45 µS/cm in Zone III. Elevated EC values in contaminated soils suggest accumulation of soluble salts and metal ions, mainly sulfates, chlorides, and nitrates derived from weathering of mining residues and tailings seepage. The moderate EC observed in Zone II (385±84 µS/cm) points to ongoing ionic leaching and partial dilution by surface runoff. The lowest EC in the control area reflects a balanced ionic composition and absence of anthropogenic salinization. This parameter reinforces the strong link between electrochemical imbalance and contamination intensity in mining-impacted terrains.

Soil texture. Soil textural analysis revealed substantial contrasts among zones. Tailings soils (Zone I) were classified as sandy loam (61% sand), implying low water-holding capacity and weak structure, which facilitate contaminant transport through percolation. Mining soils (Zone II) exhibited loam texture (48% sand, 32% silt, 20% clay), reflecting partial weathering and sediment mixing over time. Control soils (Zone III) presented clay loam texture (35% sand, 33% silt, 32% clay), typical of mature soils with stable aggregation and higher nutrient retention.

The progressive increase in clay and silt fractions from contaminated to control sites directly correlates with improved CEC, moisture retention, and ecological resilience.

Bulk density (Db). Db decreased from 1.54±0.07 g/cm³ in tailings soils to 1.28±0.05 g/cm³ in control soils. High Db values in Zone I suggest compaction, low porosity, and limited root penetration, resulting from poor organic content and granular instability. In contrast, lower Db in Zone III indicates well-aerated, aggregated soils, favorable to biological activity and root development. The negative relationship between Db and OM is consistent with pedological expectations and confirms that organic enrichment contributes to the physical rehabilitation of post-mining soils.

Integrated interpretation. Overall, the dataset demonstrates a clear gradient of soil degradation and recovery from the tailings ponds (Zone I) through mining areas (Zone II) to the uncontaminated control zone (Zone III). The combination of low pH, low CEC, high EC, and low OM in Zone I signifies a highly disturbed, chemically unstable environment prone to metal mobility. The intermediate values in Zone II indicate incipient ecological restoration, likely driven by spontaneous vegetation and organic accumulation. Meanwhile, the favorable physicochemical profile of Zone III highlights the importance of soil structure, organic matter, and neutral pH in maintaining metal immobilization and ecological stability. These findings emphasize that soil physicochemical parameters serve as sensitive indicators of environmental health and are critical for assessing recovery trajectories in post-mining landscapes.

The statistical evaluation presented in Table 3 provides a quantitative foundation for understanding the extent of physicochemical alteration across the three soil zones. All parameters exhibited statistically significant differences ($p<0.05$), demonstrating a pronounced spatial heterogeneity associated with mining-related contamination and subsequent ecological recovery. The trends observed delineate a clear environmental gradient, progressing from chemically degraded tailings substrates in Zone I, through transitional soils in Zone II, to well-developed and fertile soils in the uncontaminated Zone III.

Among all analyzed variables, pH showed one of the most striking contrasts ($p<0.001$). The acidic conditions in Zone I (mean pH=5.42) clearly reflect acid mine drainage processes, driven by the oxidation of pyrite (FeS_2) and other sulfide minerals, producing sulfuric acid and soluble metal sulfates. The low pH values not only amplify the solubility and bioavailability of metals like Pb, Cd, and Zn, but also disrupt microbial activity and nutrient cycling. The gradual increase toward neutral pH in Zone III (mean 6.82) indicates the natural buffering capacity of organic matter and base cations, as well as the self-remediation potential of unpolluted soils. Statistically, the difference between the contaminated and control sites confirms that soil pH is a primary diagnostic indicator of anthropogenic impact and chemical instability.

Soil moisture exhibited a significant difference between zones ($p=0.002$), increasing from 12.4% in tailings soils to 20.3% in the control zone. These results are consistent with the textural and structural properties of each soil type. Tailings materials are coarse, loosely aggregated, and low in humus, limiting their water-holding capacity. Conversely, control soils have higher porosity and aggregation, driven by OM and biological activity, which enhance moisture retention.
From an ecological standpoint, soil water content is crucial for redox reactions, microbial functioning, and metal mobility, making it a sensitive indicator of soil restoration potential.

CEC displayed one of the strongest statistical separations between zones ($p<0.001$). The low CEC in Zone I (8.7 cmol(+)/kg) indicates poor sorption capacity and a high risk of metal leaching, whereas the elevated CEC in Zone III (17.5 cmol(+)/kg) underscores a chemically resilient and fertile environment.
The observed increase in CEC from Zone I → Zone III parallels the trends in OM and clay fraction, suggesting that organic–mineral interactions play a dominant role in improving soil quality and metal immobilization.

Table 3

Descriptive statistics and significance levels of soil physicochemical parameters among study zones

Parameter	*Zone I (Tailings ponds) Mean ± SD (Min–Max)*	*Zone II (Mining areas) Mean ± SD (Min–Max)*	*Zone III (Control area) Mean ± SD (Min–Max)*	*p-value*	*Significance (α=0.05)*	*Interpretation*
pH	5.42±0.28 (5.01–5.89)	6.11±0.34 (5.54–6.58)	6.82±0.22 (6.42–7.09)	<0.001	***	Significant difference among zones; acidity decreases with distance from contamination.
Moisture (%)	12.4±2.1 (9.3–15.8)	16.8±3.5 (12.5–21.9)	20.3±3.2 (15.8–25.6)	0.002	**	Higher moisture in control soils; tailings soils are desiccated and structurally poor.
CEC (cmol(+)/kg)	8.7±1.9 (6.1–11.3)	12.3±2.4 (8.4–15.6)	17.5±3.1 (13.2–21.7)	<0.001	***	Highly significant increase from contaminated to natural soils.
Organic matter (%)	1.12±0.33 (0.74–1.58)	2.34±0.47 (1.68–2.98)	3.96±0.72 (3.01–5.12)	<0.001	***	Sharp OM gradient; organic enrichment reflects ecological recovery.
Electrical conductivity (μS/cm)	478±96 (342–601)	385±84 (275–498)	162±45 (108–226)	<0.001	***	EC significantly declines with distance from pollution sources.
Bulk Density (g/cm³)	1.54±0.07 (1.44–1.63)	1.43±0.06 (1.35–1.52)	1.28±0.05 (1.21–1.36)	<0.001	***	Decreasing trend indicates better structure and porosity in control soils.

Note: Data expressed as mean ± standard deviation (SD) from triplicate analyses. Statistical significance based on one-way ANOVA with Tukey's post-hoc test; $p<0.05$ significant (*), $p<0.01$ highly significant (**), $p<0.001$ extremely significant (***). All measured parameters showed statistically significant differences across the three zones ($p<0.05$), confirming strong spatial heterogeneity linked to mining impact. The strongest contrasts occurred for pH, CEC, and OM — key indicators of chemical degradation and pedogenic maturity. The inverse trends between EC and pH, and between bulk density and organic matter, highlight the interplay between chemical contamination, soil compaction, and fertility loss. The progressive improvement from Zone I → Zone II → Zone III suggests natural attenuation and potential for ecological restoration through revegetation and organic amendments.

The intermediate CEC in Zone II (12.3 cmol(+)/kg) reveals incipient recovery, most likely facilitated by plant colonization and humic complex formation.

OM content exhibited a threefold increase between the most contaminated and control soils (from 1.12% to 3.96%; $p<0.001$). This parameter is the cornerstone of soil ecological function, influencing nutrient cycling, structure, and pollutant stabilization. The extremely low OM in tailings soils reflects severe biological depletion—conditions in which vegetation establishment is minimal and microbial communities are suppressed by metal toxicity. By contrast, the accumulation of OM in control soils indicates pedogenic maturity and active biogeochemical cycling, confirming the pivotal role of humus in ecosystem resilience and heavy metal sequestration.

The significant decline in electrical conductivity from 478 µS/cm in tailings to 162 µS/cm in control soils ($p<0.001$) reveals the strong influence of soluble salts and metal ions derived from weathered tailings materials. Elevated EC values in contaminated zones are often linked to salinization, metal sulfates, and acid leachates, which alter ionic equilibrium and stress plant roots. The intermediate EC in Zone II reflects partial leaching and dilution processes, likely enhanced by vegetative cover and surface runoff. From a management perspective, EC is a valuable proxy for ion toxicity and restoration progress, as decreasing values signal reduced contamination intensity.

Db displayed a clear decreasing trend from 1.54 g/cm³ (Zone I) to 1.28 g/cm³ (Zone III), with $p<0.001$. Elevated Db in tailings soils reflects compaction, low organic matter, and poor aggregation, which restricts aeration, root growth, and water infiltration. In contrast, the lower Db values in natural soils indicate higher porosity and structural stability, attributes of biologically active and well-developed soils. The negative correlation between Db and OM reinforces the central role of organic inputs in improving soil physical properties and promoting ecological rehabilitation.

The ANOVA results confirm that all physicochemical parameters differ significantly across the studied zones, highlighting the multifactorial degradation induced by mining activities. The most discriminating indicators—pH, CEC, and OM—function as sentinels of soil health, reflecting both the intensity of past contamination and the trajectory of natural recovery. The consistent improvement from Zone I to Zone III suggests a gradient of pedogenic recovery governed by organic accumulation, neutralization of acidity, and reestablishment of ionic balance. The strong statistical contrasts not only validate field observations but also underscore the potential of using these parameters as quantitative markers for monitoring post-mining restoration.

Conclusions. The results clearly demonstrate significant physicochemical differentiation among the three study zones, reflecting a gradient of degradation and recovery from tailings ponds (Zone I) to uncontaminated soils (Zone III). Acidic pH, low OM, and reduced CEC in tailings soils confirm severe chemical alteration caused by sulfide oxidation and prolonged metal exposure.

In contrast, control soils exhibited near-neutral pH, higher CEC, and greater organic content, characteristic of mature, well-structured systems with strong buffering capacity and biological activity. The intermediate values recorded in mining areas (Zone II) indicate partial natural recovery through vegetation regrowth and organic accumulation.

EC and Db followed inverse trends with OM, highlighting the role of humus in improving soil structure and reducing ionic stress. All parameters showed statistically significant differences ($p<0.05$), with pH, CEC, and OM emerging as key indicators of soil health and recovery potential.

Overall, the data confirm that soil physicochemical properties serve as reliable markers of environmental quality in post-mining landscapes. The observed improvement from contaminated to natural sites underscores the potential for natural attenuation, which can be further enhanced through organic amendments and phytostabilization to accelerate ecological restoration.

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References

Adnan M., Rehman S., Ali M., Farooqi A., 2022 Long-term ecological risk of toxic elements in soil around an abandoned mining site: Evidence from integrated pollution indices and risk assessment code. Chemosphere 296:134017.

Harris J. A., Hobbs R. J., Higgs E., Aronson J., 2020 Ecological restoration and global climate change. Restoration Ecology 28(2):277–283.

He M., Wang X., Zhong Y., Hu L., Liu X., 2021 Influence of lime and organic amendments on metal availability and microbial properties in mine-contaminated soils. Ecotoxicology and Environmental Safety 217:112245.

Kosheleva N. E., Karandashev V. K., Sokolova T. A., 2022 Long-term evolution of technogenic landscapes: Soil formation and environmental risks at mining sites. Journal of Soils and Sediments 22:1929–1946.

Leiva D., Funes F., Pérez C. A., 2021 Soil salinity and heavy metal contents in abandoned tailings impoundments in Chilean semiarid areas. Environmental Monitoring and Assessment 193:418.

Liao X., Luo L., Zhao D., 2016 Acid mine drainage remediation strategies: A review. Science of the Total Environment 543:38–60.

Mir S. H., Mishra V. K., Tiwari A., Upadhyay N., 2020 Heavy metal contamination of soils near mining sites and potential effects on human health: A case study of Malanjkhand copper mine, India. Environmental Earth Sciences 79:175.

Miu I. V., Voșgan Z., Miu M. A., 2022 Organic amendments improve physicochemical and microbial properties of copper mine tailings. Environmental Technology & Innovation 28:102608.

Mukhopadhyay S., Maiti S. K., Masto R. E., 2016 Use of reclaimed mine soil quality index (RMSQI) for evaluating mine soil development. Ecological Indicators 66:106–118.

Ningombam A., Singh S. M., Sharma M. C., 2024 Soil metal toxicity effects on plants and microbes in mining-affected regions of Northeast India. Environmental Geochemistry and Health 46:433–447.

Paz-Ferreiro J., Fu S., 2016 Biological indicators for assessing soil quality: A review. Environmental Monitoring and Assessment 188:1–14.

Voșgan Z., Rusu T., Chețan F., Miu I. V., 2021 Assessment of heavy metal contamination in soils from former mining areas in Romania. Environmental Science and Pollution Research 28:32908–32924.

Young S. D., Crout N. M. J., Martinez A., 2015 Cation exchange capacity and heavy metal bioavailability in contaminated soils. Environmental Pollution 204:88–95.

Zeng X., Xu W., Wu F., Zhang X., 2011 Effect of soil pH on the adsorption and desorption of heavy metals in Chinese soils. Environmental Pollution 159(10):2610–2617.

*** ISO 10381-1:2002 Soil quality — Sampling Part 1: Guidance on the design of sampling programmes.

*** ISO 10390:2005 Soil quality — Determination of pH.

*** ISO 11265:1994 Soil quality — Determination of the specific electrical conductivity.

*** ISO 11277:2009 Soil quality — Determination of particle size distribution in mineral soil material — Method by sieving and sedimentation.

*** ISO 11464:2006 Soil quality — Pretreatment of samples for physico-chemical analysis.

*** ISO 11465:1993 Soil quality — Determination of dry matter and water content on a mass basis — Gravimetric method.

*** ISO 11466:1995 Soil quality — Extraction of trace elements soluble in aqua regia.

*** ISO 14235:1998 Soil quality — Determination of organic carbon by sulfochromic oxidation.
*** ISO 23470:2018 Soil quality — Determination of effective cation exchange capacity (CEC) and exchangeable cations using a hexamminecobalt(III)chloride solution.

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