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ASSOCIATIONS AMONG TEXTURE, BULK DENSITY AND SOIL MOISTURE DURING POST-MINING SOIL RECOVERY IN SEMI-ARID CONDITIONS

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Abstract. Post-mining phosphorite landscapes in semi-arid regions often retain physical constraints that limit vegetation establishment and slow soil recovery. We assessed soil physical recovery at the Zhanatas phosphorite deposit (southern Kazakhstan) by comparing three site types: (i) a reclaimed dump (technical reclamation in 2012, biological reclamation in 2013; ~2 ha; ~50 cm loam substrate; 70–75% plant establishment), (ii) a dump undergoing passive self-recovery since mine closure in 1984 with sparse vegetation cover (~9.5–10%), and (iii) an undisturbed reference soil. During May–September 2025, three soil profiles were excavated per site and sampled by genetic horizons. Across sites, materials were sand-dominated, but the fine fraction (<0.01 mm) differed strongly among recovery pathways. The reclaimed site showed stable near-surface texture (<0.01 mm = 31.97–34.93% at 0–40 cm), comparable to the upper horizons of the naturally revegetated dump (28.60–30.34% at 0–70 cm). In contrast, a deep layer of the naturally revegetated dump (70–110 cm) was extremely coarse (sand 89.89%; <0.01 mm 8.87%), indicating a persistent textural discontinuity. The undisturbed soil had the highest fine fraction (<0.01 mm = 34.57–45.05%). Moisture ranged from 2.09% (reclaimed 0–10 cm) to 11.69% (dump 70–110 cm). PCA differentiated site types and revealed the greatest heterogeneity in the naturally recovering dump. Reclamation improved near-surface physical conditions, but full convergence to reference soil remains incomplete due to strong textural contrasts within the profile.

Keywords: phosphorite mining; land reclamation; natural revegetation; soil texture, PCA.

INTRODUCTION

Mining is among the most intensive land-use disturbances, typically removing natural soil profiles and leaving heterogeneous overburden materials with poor structure, low organic matter, and altered hydrological functioning. As a result, post-mining landscapes often exhibit reduced infiltration, limited plant-available water, enhanced erosion risk, and constrained root development, which together slow ecosystem recovery unless effective reclamation practices are implemented [1-3].

In semi-arid regions, soil recovery can be particularly challenging because low precipitation and high evaporative demand constrain vegetation establishment and organic matter accumulation - the key drivers of aggregation and structural development. In arid to semi-arid mine settings, reclamation success depends strongly on reconstructing a growth medium that can store water, reduce mechanical impedance, and support early plant cover [4, 5]. These constraints are relevant for southern Kazakhstan, where large phosphorite deposits have been mined for decades and extensive dumps and disturbed surfaces remain in need of ecological rehabilitation [6, 7].

Soil physical properties are central to post-mining recovery because they regulate water flow and retention, aeration, and root penetration. Among these, particle-size distribution (texture), bulk density, and soil moisture are widely used as sensitive indicators of disturbance and rehabilitation progress [5, 8, 9]. Bulk density is a direct proxy for compaction and pore space reduction; excessive compaction limits infiltration, gas exchange, and root elongation, and is a common legacy of grading and heavy machinery during technical reclamation [10, 11]. In reclaimed mine soils, bulk density often remains higher than in adjacent undisturbed soils for years, with recovery depending on material placement, biological activity, and vegetation development [11, 12].

Texture provides a stable "baseline" property that shapes the trajectory of structural and hydrological recovery. Fine-textured fractions (silt and clay) can increase water-holding capacity but may also predispose reconstructed soils to crusting or poor aeration when structure is weak, whereas coarse textures can reduce available water under semi-arid climates. Pedotransfer and soil-hydrologic studies consistently show that moisture retention and plant-available water are tightly linked to texture and organic matter, with bulk density influencing the pore-size distribution that controls water storage and movement. Therefore, the joint assessment of texture–bulk density–moisture relationships can provide an integrated view of whether reclaimed substrates are developing toward functional soil conditions [11, 12].

A key question in mine rehabilitation is whether technical reclamation accelerates recovery compared with passive/natural revegetation, and how both compare to an undisturbed reference. Classic restoration concepts emphasize that natural succession can rebuild soils over time, but trajectories are strongly site-dependent and may be slow or arrested under harsh physical constraints. Comparative studies across reclaimed and spontaneously revegetated mine lands report mixed outcomes: while reclamation may speed up early stabilization, it can also increase compaction and reduce microsite heterogeneity, sometimes limiting long-term soil development relative to unmanaged (ungraded) substrates [10–13]. In practice, evaluating these trade-offs requires side-by-side measurements of key physical indicators across contrasting site types within the same climate and geological setting [11-13].

For phosphorite mining landscapes in southern Kazakhstan, the peer-reviewed evidence base is still relatively limited compared with coal or metal-mine systems. Existing work in the Zhambyl region has documented that reclaimed or disturbed phosphorite-mine substrates can be highly unfavorable for plants due to immature "human-transported materials" and weak soil-forming processes, highlighting the need for targeted monitoring of soil quality and recovery [14, 15]. More recent regional research on phosphorite dump reclamation in Kazakhstan's semi-desert zone underscores the scale of disturbance and the importance of selecting sensitive indicators to evaluate reclamation outcomes [16]. However, detailed comparisons focusing specifically on soil physical recovery-especially using a three-way design (reclaimed vs naturally revegetated vs undisturbed)-remain scarce for the Zhanatas phosphorite deposit and analogous semi-arid mine settings.

Although the methods applied in this study are standard in soil science, the present work addresses an important gap by focusing on an understudied phosphorite-mining landscape in southern Kazakhstan and by directly comparing three contrasting recovery pathways within the same semi-arid environment. The integration of horizon-based data on particle-size distribution, bulk density, and gravimetric soil moisture across reclaimed, naturally revegetated, and undisturbed reference soils provides a site-specific basis for assessing soil physical recovery trajectories and profile-scale heterogeneity at the Zhanatas deposit, where such comparative evidence is still scarce.

Multivariate statistics can help interpret post-mining soil recovery where properties co-vary and responses differ among site types. Correlation analysis is useful for diagnosing linkages between texture fractions and bulk density or moisture, while ordination methods such as principal component analysis (PCA) can summarize the dominant gradients differentiating reclaimed, naturally revegetated, and undisturbed soils. Such approaches are increasingly applied in mine-soil assessment to identify the most informative indicators and to visualize recovery trajectories relative to reference conditions [17-20].

In this study, we assess soil physical recovery after phosphorite mining in the semi-arid zone of southern Kazakhstan by comparing three site types: (i) a technically reclaimed dump area (reclamation conducted in 2011–2013), (ii) a disturbed area undergoing natural revegetation/self-recovery, and (iii) an adjacent undisturbed reference site. We focus on soil texture (particle-size distribution), bulk density, and soil moisture as core physical indicators of post-mining recovery.

MATERIALS AND METHODS

Study area. The study was conducted at the Zhanatas phosphorite deposit located near the town of Zhanatas, Sarysu district, Zhambyl region, southern Kazakhstan. The deposit belongs to the Zhanatas phosphorite basin, a major phosphate-rock mining area in Kazakhstan.

The region is situated within the semi-arid to semi-desert climatic zone of Kazakhstan, characterized by low and irregular precipitation and high evaporative demand. According to national climate descriptions, annual precipitation in the semi-desert zone typically ranges approximately within 134–330 mm, while independent regional assessments report mean annual precipitation around ~250 mm for the broader Zhambyl region.

Site selection and recovery pathways. Three site types representing contrasting disturbance and recovery pathways were selected within the same landscape setting: Reclaimed site (RN): a post-mining dump area reclaimed in 2011–2013 (total reclaimed area ~2 ha). Reclamation involved placement of a loam substrate (~50 cm) as a growth medium, followed by multi-layer sowing of plant species representing different strata and life forms. Plant establishment/survival was reported as ~70–75%. The reclamation works were implemented as technical reclamation in 2012 and biological reclamation in 2013.

Naturally revegetated site (NO): a disturbed dump area where mining/dumping activities ceased in 1984; the site has been undergoing passive self-recovery since closure (≈ 41 years by the 2025 field campaign). Current vegetation cover is low, with reported ground cover of approximately 8.5–9%. Undisturbed reference site (NP): a nearby area not affected by mining operations, representing local baseline soil physical conditions under natural vegetation (figure 1).

Soil profile excavation and sampling design. Field investigations were carried out during the growing season (May–September 2025). At each site type (RN, NO, NP), three replicate soil profiles were excavated. Each profile was morphologically described, and genetic horizons were identified in the field.

Soil samples were collected horizon-wise from each described horizon. For each horizon, disturbed samples were taken for particle-size distribution, and fresh samples were collected for gravimetric moisture determination. Undisturbed core samples for bulk density were collected from the mid-part of each horizon using metal cylinders of 100 cm^3 volume.

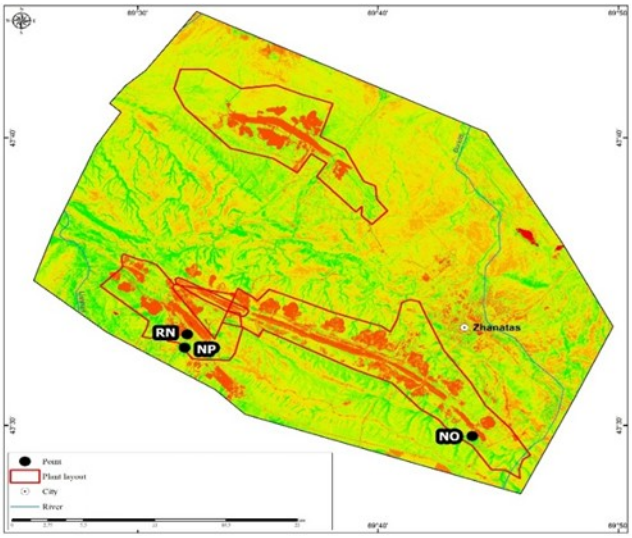

Figure 1 – Study area

Laboratory analyses. Particle-size distribution (Kachinsky method)

Particle-size distribution was determined using the Kachinsky pipette sedimentation method. Briefly, samples were prepared by removing coarse fragments (>2 mm) and visible plant residues; the fine earth fraction was dispersed following standard Kachinsky-type 3 in the Kachinsky fractionation system, and then summarized into texture-related groups for interpretation in an international context [21, 22].

Bulk density. Bulk density (ρb) was determined by the core method using 100 cm^3 cylinders. Samples were oven-dried at 105°C to constant mass and weighed. Bulk density was calculated as:

$$\rho_b = \frac{M_{dry}}{V_{core}}$$

where M_{dry} is dry soil mass (g) and V_{core} is core volume (cm^3). Results are reported in g cm^{-3}. The procedure follows standard guidance for dry bulk density determination by a known-volume core [23].

Gravimetric soil moisture. Gravimetric soil moisture content was determined on field-moist subsamples by oven-drying at 105°C to constant mass [24]. Moisture content (θg) was calculated as:

$$\theta_g(\%) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100$$

where M_{wet} and M_{dry} are wet and dry soil masses, respectively.

Statistical analyses. Because the number of replicates per site was limited, statistical inference was treated conservatively. Data are presented as mean ± SD. Differences among the three site types were tested using the Kruskal–Wallis test with appropriate post-hoc pairwise. Associations among texture fractions, bulk density, and moisture were examined using Pearson correlations.

To explore multivariate differentiation among site types, principal component analysis (PCA) was performed on standardized variables, including particle-size groups, bulk density, and moisture. PCA results were interpreted using score plots and loadings.

RESULTS AND DISCUSSIONS

Particle-size distribution and the fine fraction (<0.01 mm) across sites. Across the three site types, particle-size distribution was generally dominated by sand fractions, while the proportion of the fine fraction (<0.01 mm; "physical clay" in the Kachinsky system) showed clear site- and depth-related differences. Because the <0.01 mm fraction strongly controls water retention and related hydrophysical behavior, its variation provides a useful indicator of post-mining soil physical recovery under semi-arid conditions.

Reclaimed site (RN). In the reclaimed dump, the soil material exhibited a relatively stable texture within the sampled layer. Total sand content varied narrowly (63.49–66.53%) across 0–40 cm, whereas the fine fraction <0.01 mm ranged from 31.97 to 34.93%. The clay-sized fraction (<0.001 mm) was 7.29–8.50%. This comparatively consistent granulometric pattern is consistent with the reclamation practice of placing a loam substrate layer, which creates a more homogeneous near-surface growth medium.

Naturally revegetated site (NP). In the upper part of the naturally recovering dump (0–70 cm), total sand content remained similar to the reclaimed site but slightly higher overall (68.72–69.68%), and the <0.01 mm fraction ranged from 28.60 to 30.34%. However, at 70–110 cm the profile became markedly coarser: total sand increased sharply to 89.89% and the <0.01 mm fraction dropped to 8.87%. This strong textural discontinuity indicates that deeper dump materials remain highly sandy and weakly developed, which likely limits deep moisture storage and can constrain rooting and vegetation persistence in a semi-arid environment.

Undisturbed reference (NO). The undisturbed soils were generally finer-textured than both disturbed sites. The <0.01 mm fraction ranged from 34.57 to 45.05%, while total sand ranged from 53.25 to 60.71%. The clay-sized fraction (<0.001 mm) was also higher than in the reclaimed and naturally revegetated sites (8.06–15.02%), reflecting a more developed natural soil matrix with greater fine material (figure 2).

Overall, the reclaimed site showed fine-fraction contents (approximately 32–35% <0.01 mm) close to those in the upper horizons of the naturally revegetated site (approximately 29–30%), indicating that reclamation successfully created a functional near-surface texture compared with the coarse dump substrate. In contrast, the undisturbed site maintained the highest proportion of fine particles throughout the profile, representing the local baseline for soil physical condition. The pronounced decrease in fine material in deeper horizons of the naturally revegetated dump highlights a persistent physical limitation of technogenic deposits and underscores the importance of constructing or conserving a fine-textured surface layer to support long-term soil recovery in semi-arid post-mining landscapes.

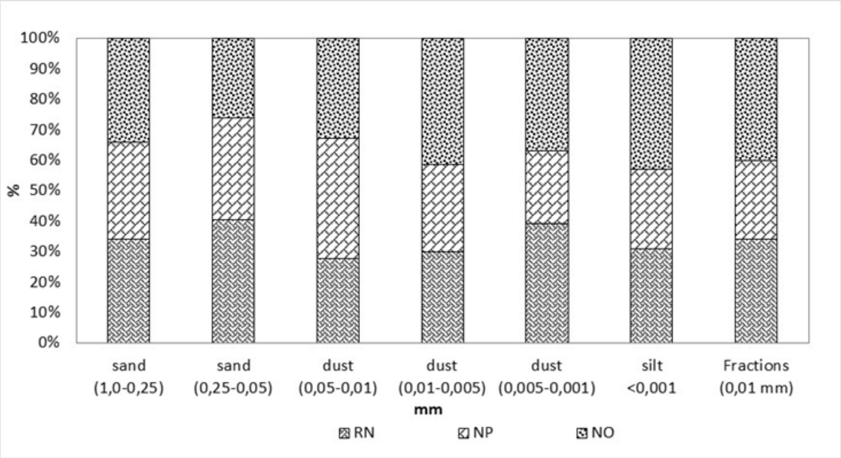

Figure 2 - Particle-size distribution across study area (RN, NP, NO)

Bulk density across sites and depths. Bulk density differed clearly among the three site types and showed contrasting depth patterns. In the reclaimed site (RN), bulk density in the surface layer (0–10 cm) was 1.253 g cm^{-3}, indicating a moderately compacted but workable reconstructed top layer. In the naturally revegetated dump (NP), bulk density was the lowest among sites and increased with depth from 1.099 g cm^{-3} (0–11 cm) to 1.325 g cm^{-3} (11–28 cm), consistent with a loose, coarse-textured technogenic substrate near the surface and progressive consolidation downward. In contrast, the undisturbed reference (NO) displayed substantially higher bulk density values, reaching 1.661 g cm^{-3} in the upper layer (0–18 cm) and increasing to 1.765 g cm^{-3} at 18–40 cm.

These results emphasize that bulk density in post-mining landscapes should be interpreted together with texture and profile organization. Lower bulk density on the dump (NP) does not necessarily indicate better physical quality; it can reflect unconsolidated, sand-dominated material with limited fine fraction and low water-holding capacity. Conversely, the higher bulk density in the undisturbed reference (NO) likely reflects a naturally denser, finer-textured mineral matrix and/or higher packing density under semi-arid conditions. The reclaimed site (RN) showed intermediate compaction status, suggesting that placement of a loam substrate layer created a more soil-like near-surface physical condition compared with the dump material.

Gravimetric soil moisture (field moisture) across sites and depths. Gravimetric soil moisture measured during the May–September 2025 field season varied with both site type and depth, reflecting the combined influence of recent weather, evaporative demand, infiltration, and substrate properties. The reclaimed site (RN) showed a pronounced vertical gradient: moisture was extremely low in the surface layer (2.09% at 0–10 cm) but increased sharply with depth to 6.21% (10–25 cm) and 7.19% (25–40 cm). This pattern indicates strong surface drying, consistent with high evaporative losses and limited surface water retention during the warm season.

In the naturally revegetated dump (NP), moisture in the upper profile was relatively stable, ranging from 6.91 to 7.85% across 0–70 cm. However, at 70– 110 cm, moisture increased markedly to 11.69%, suggesting that water percolation and reduced evaporative influence at depth allow moisture accumulation even in coarse dump substrates. This is important ecologically: deep moisture storage may exist, but the coarse texture and low fine fraction at depth can still constrain plant-available water and rooting effectiveness, especially if the main root zone is limited to upper layers.

The undisturbed reference (NO) showed a non-monotonic moisture pattern: relatively high moisture at 0–3 cm (7.96%), a drier layer at 3–18 cm (4.50%), followed by higher moisture at 18–40 cm (6.45%) and a maximum at 40–50 cm (9.01%). Such variability is typical for semi-arid soils where short-term surface wetting events, crusting/structure, and horizon-specific infiltration pathways can produce contrasting moisture conditions within the upper profile.

Overall, average moisture in the upper part of profiles (approximately the top ~ 40–50 cm, depending on site sampling intervals) followed the order NP (≈7.50%) ≥ NO (≈6.30%) > RN (≈5.16%), with the reclaimed site showing the strongest surface desiccation.

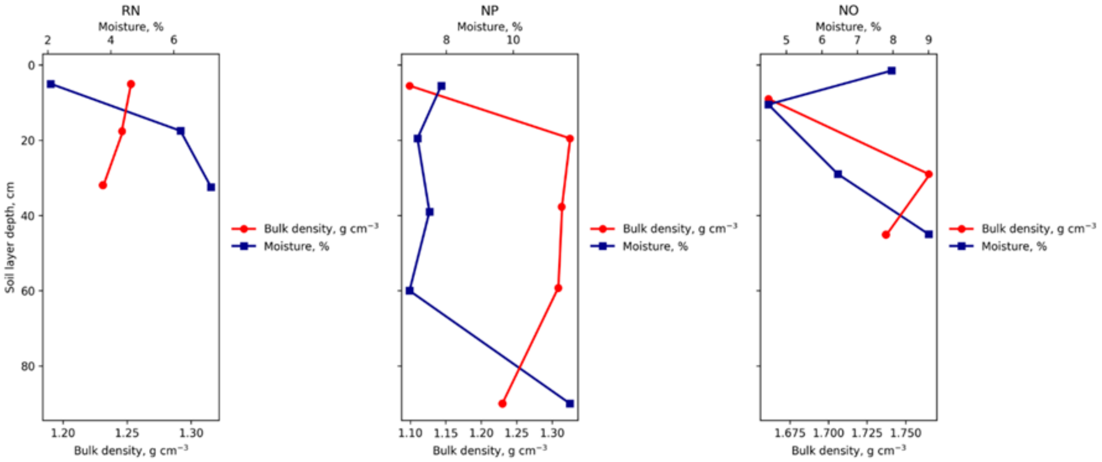

Figure 3 - Soil moisture content (%) and bulk density (g cm^{-3}) distribution along the soil profile in RN, NP and NO sites

Texture–bulk density–moisture associations. Figure 4 presents the Pearson correlation matrix for all granulometric fractions (Kachinsky system) together with gravimetric soil moisture (%) and bulk density (g cm^{-3}). The analysis was performed only for depth intervals where all three data blocks (granulometry–moisture–bulk density) were available simultaneously ($n=5$). For intervals with mismatched layer boundaries, granulometric fractions and moisture were harmonized to the bulk density interval using thickness-weighted averaging across overlapping horizons.

Several strong correlations occurred among granulometric fractions themselves, reflecting that fractions are compositional (they sum to ~100%) and therefore covary by definition. The two sand fractions were positively related ($r = 0.71$), while the sand fraction 0.25–0.05 mm showed a strong negative association with the silt fraction 0.01–0.005 mm ($r = -0.89$, $p < 0.05$). Fine fractions were mutually positively related: Fine fraction <0.01 mm correlated strongly with Clay <0.001 mm ($r = 0.86$) and with Silt 0.005–0.001 mm ($r = 0.73$), showing that an increase in the fine fraction is accompanied by a coordinated rise of the finest particle-size classes.

Bulk density exhibited the clearest associations with granulometry. The strongest relationship was a negative correlation with sand 0.25–0.05 mm ($r = -0.93$, $p < 0.05$), indicating lower packing density in coarser, sandier materials. Bulk density also tended to increase with finer material (positive correlations with Fine <0.01 mm, $r = 0.86$, and Clay <0.001 mm, $r = 0.67$) (figure 3).

Soil moisture showed no linear relationship with bulk density ($r = -0.05$), suggesting that during the May–September sampling period the instantaneous moisture content was not controlled by compaction alone. Instead, moisture was strongly positively associated with Silt 0.05–0.01 mm ($r = 0.87$) and strongly negatively associated with Silt 0.005–0.001 mm ($r = -0.83$). Moisture correlations with the “integrated” fine indices were moderate to weak (Moisture vs Fine <0.01 mm: $r = -0.41$; Moisture vs Clay <0.001 mm: $r = -0.12$) (figure 4).

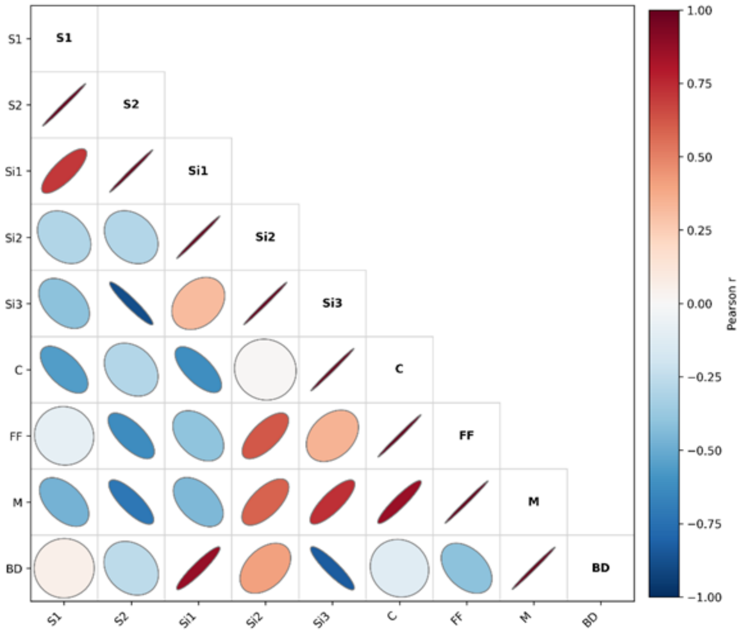

Figure 4 - Pearson correlation heatmap (r) for granulometric fractions (Kachinsky method), gravimetric soil moisture (%) and bulk density (g cm^{-3}) across the Zhanatas phosphorite sites

Note: S1 – Sand 1.0–0.25 mm; S2 – Sand 0.25–0.05 mm; Si1 – Silt 0.05–0.01 mm; Si2 – Silt 0.01–0.005 mm; Si3 – Silt 0.005–0.001 mm; C – Clay <0.001 mm; FF – Fine fraction <0.01 mm; M – Moisture; BD – Bulk density

Bulk density as an indicator of physical recovery. The correlation pattern supports a straightforward physical interpretation: in these post-mining soils/substrates, bulk density largely tracks the textural gradient from coarse to fine materials. Coarse sand-dominated dump or reworked materials commonly show lower bulk density because of looser packing and larger pores, whereas finer materials can pack more densely (especially when aggregation and organic binding agents are still weak during early-to-mid recovery). Therefore, differences in bulk density among reclaimed, naturally recovering, and undisturbed soils should be discussed together with their granulometric composition-bulk density alone can be misleading if the underlying material differs strongly in texture.

The absence of a moisture–bulk density relationship is expected under semi-arid field conditions because gravimetric moisture is highly dynamic and depends on recent rainfall, evaporation, plant water uptake, and depth. A compacted layer can reduce infiltration and increase runoff, but moisture at sampling dates may still be driven more by depth-controlled evaporation gradients and episodic wetting than by bulk density per se. This is consistent with your profiles where moisture often increases with depth even when the substrate is coarse. In other words, field moisture during the growing season behaves more like a “state variable” (current hydrological status) than an inherent capacity indicator.

These opposite associations suggest that field moisture responded more strongly to the balance among silt subfractions than to the integrated fine fraction alone, which is consistent with the profile-specific and seasonally dynamic nature of soil moisture under semi-arid conditions.

Principal component analysis (PCA) based on the full set of granulometric fractions (Kachinsky system) and gravimetric soil moisture separated the three site types in the PC1–PC2 space. The first two components explained 80.8% of the total variance (PC1=57.6%, PC2=23.2%). In the score plot with 95% confidence ellipses, the undisturbed reference (NO) formed a distinct cluster primarily along PC2, whereas the reclaimed site (RN) occupied predominantly negative PC2 scores. The naturally revegetated dump (NP) showed the broadest dispersion and was shifted mainly along PC1, indicating higher internal heterogeneity of the dump material and moisture regime compared with RN and NO (figure 5).

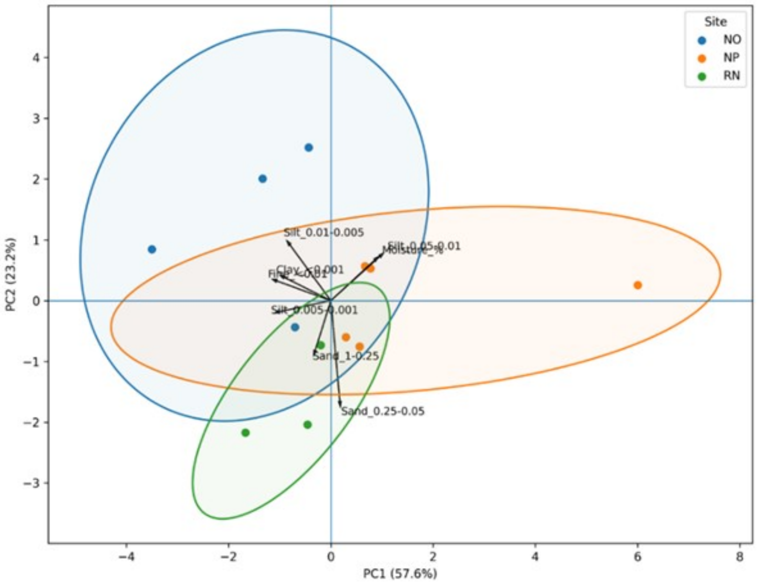

Figure 5 - PCA score plot (PC1 vs PC2) based on granulometric fractions (Kachinsky system) and gravimetric soil moisture for reclaimed (RN), naturally revegetated (NP) and undisturbed (NO) sites. Ellipses represent 95% confidence regions for each site type

The separation along PC1 reflects a dominant granulometric–moisture gradient associated with dump heterogeneity: NP includes layers with strongly contrasting textures and moisture conditions, which expands its ellipse and shifts some NP points to the positive PC1 region. This pattern is consistent with the presence of a deep, coarse layer in the naturally recovering dump that differs sharply from the upper layers and from the reference soil. In contrast, RN samples are more compact in PCA space, indicating that placement of a loam substrate layer produced a more uniform near-surface physical medium compared with the naturally recovering dump. The reference soil (NO) separates from disturbed substrates because of its more developed natural particle-size structure and comparatively stable pedogenic organization, which is captured by the PC2 gradient and results in a clearly displaced ellipse.

CONCLUSION

This study evaluated post-mining soil physical recovery at the Zhanatas phosphorite deposit in the semi-arid zone of southern Kazakhstan using granulometric fractions (Kachinsky system), bulk density, and gravimetric soil moisture across three site types: a reclaimed dump (technical reclamation in 2012 and biological reclamation in 2013), a naturally revegetated dump undergoing passive self-recovery since 1984, and an undisturbed reference soil.

Overall, the reclaimed site exhibited a comparatively stable near-surface particle-size distribution, with a fine fraction (<0.01 mm) close to that of the upper layers of the naturally revegetated dump, indicating that the placement of a loam substrate layer successfully formed a functional growth medium at the surface. In contrast, the naturally revegetated dump showed strong vertical heterogeneity, including a deep coarse-textured layer characterized by very low fine material, which represents a persistent physical limitation for water retention and rooting in semi-arid conditions. The undisturbed reference soil consistently contained the highest proportion of fine particles and clay-sized material, reflecting the local baseline of soil physical condition.

Multivariate analysis supported these patterns: PCA clearly differentiated site types and highlighted higher internal variability in the naturally recovering dump compared with the reclaimed site. Correlation analysis indicated that bulk density was primarily linked to texture (coarse fractions tending to lower density), whereas field moisture during the growing season showed weak and inconsistent linear associations with density, emphasizing the dynamic nature of moisture under semi-arid climate and the importance of interpreting it together with depth and texture.

From a reclamation management perspective, the results suggest that successful restoration of phosphorite mine dumps in semi-arid environments should focus not only on surface stabilization, but also on reconstruction of a physically functional root zone. In practical terms, this means prioritizing the placement and preservation of a sufficiently thick fine-textured growth layer, minimizing abrupt textural discontinuities between surface and subsurface materials, and avoiding excessive compaction during grading and substrate handling. Because the reclaimed site showed improved near-surface physical conditions but still strong surface drying during the warm season, post-reclamation monitoring should include repeated measurements of bulk density and seasonal soil moisture to evaluate whether reconstructed substrates are developing toward more stable hydro-physical functioning.

Future studies should include repeated seasonal measurements of soil moisture and related hydrophysical properties to better characterize the hydrological regime and improve assessment of post-mining soil recovery trajectories.

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ТҮЙІН

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ЖАРТЫЛАЙ АРИДТІ ЖАҒДАЙДА КЕН ӨНДІРУДЕН КЕЙІНГІ ТОПЫРАҚТЫҢ ҚАЛПЫНА КЕЛУІ БАРЫСЫНДА ГРАНУЛОМЕТРИЯЛЫҚ ҚҰРАМ, КӨЛЕМДІК ТЫҒЫЗДЫҚ ЖӘНЕ ТОПЫРАҚ ЫЛҒАЛДЫЛЫҒЫ АРАСЫНДАҒЫ БАЙЛАНЫСТАР

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Жартылай аридті аймақтардағы фосфорит өндіруден кейінгі ландшафттарда өсімдік жамылғысының орнығуын қиындататын және топырақтың қалпына келуін баяулататын физикалық шектеулер ұзақ сақталады. Біз Оңтүстік Қазақстандағы Жанатас фосфорит кен орнында топырақтың физикалық қалпына келуін үш учаске түрін салыстыру арқылы бағаладық: (i) рекультивацияланған үйінді (2012 ж. техникалық, 2013 ж. биологиялық рекультивация; аумағы шамамен 2 га; құмбалшық субстратының қабаты ~50 см; өсімдіктердің орнығуы 70–75%), (ii) 1984 жылы жабылғаннан кейін табиғи түрде өздігінен қалпына келіп жатқан үйінді (өсімдік жамылғысы төмен, ~9,5–10%), және (iii) бүлінбеген эталондық (бақылау) учаске. 2025 жылдың мамыр–қыркүйек айларында әр учаскеде үш топырақ қимасы қазылып, генетикалық горизонттар бойынша үлгілер алынды. Барлық учаскелерде құм фракциялары басым болды, бірақ ұсақ фракцияның (<0,01 мм) үлесі қалпына келу жолына қарай айқын өзгерді. Рекультивацияланған учаскеде үстіңгі қабаттың текстурасы тұрақты болды (<0,01 мм=31,97–34,93% 0–40 см), бұл табиғи қалпына келу учаскесінің жоғарғы горизонттарымен ұқсас (28,60–30,34% 0–70 см). Алайда табиғи қалпына келіп жатқан үйіндінің терең қабаты (70–110 см) өте ірі түйірлі болып шықты (құм - 89,89%; <0,01 мм - 8,87%), яғни техногендік субстратта тұрақты текстуралық контраст сақталған. Бүлінбеген топырақта ұсақ фракция ең жоғары болды (<0,01 мм = 34,57–45,05%). Ылғалдылық 2,09%-дан (рекультивация 0–10 см) 11,69%-ға дейін (үйінді 70–110 см) өзгерді. PCA талдауы учаскелерді айқын ажыратып, ең жоғары ішкі әртектілік табиғи қалпына келіп жатқан үйіндіде екенін көрсетті. Рекультивация үстіңгі қабаттың физикалық жағдайын жақсартады, бірақ эталондық топыраққа толық жақындау профильдегі күшті текстуралық контрасттармен шектеледі.

Түйінді сөздер: фосфорит өндіру, жерді рекультивациялау, табиғи қайта өсу, гранулометриялық құрам, PCA талдауы.

РЕЗЮМЕ

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ВЗАИМОСВЯЗИ МЕЖДУ ГРАНУЛОМЕТРИЧЕСКИМ СОСТАВОМ, ОБЪЁМНОЙ МАССОЙ И ВЛАЖНОСТЬЮ ПОЧВЫ В ПРОЦЕССЕ ПОСТГОРНОДОБЫЧНОГО ВОССТАНОВЛЕНИЯ ПОЧВ В ПОЛУЗАСУШЛИВЫХ УСЛОВИЯХ

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Постгорнодобывающие фосфоритовые ландшафты в полузасушливых регионах часто сохраняют физические ограничения, которые затрудняют закрепление растительности и замедляют восстановление почв. Нами проведена оценка физического восстановления почв на фосфоритовом месторождении Жанатас (Южный Казахстан) в сравнении трех типов участков: (i) рекультивированный отвал (техническая рекультивация в 2012 г., биологическая - 2013 г.; площадь ~2 га; слой суглинистого субстрата ~50 см), (ii) отвал на естественном самовосстановлении после закрытия в 1984 г. с низким растительным покровом (~9,5–10%), и (iii) ненарушенный контрольный участок. В мае–сентябре 2025 г. на каждом участке было заложено по три почвенных разреза и выполнен отбор проб по генетическим горизонтам. На всех участках преобладали песчаные фракции, однако доля тонкой фракции (<0,01 мм) существенно различалась. На рекультивированном участке гранулометрический состав верхней толщи был стабильным (<0,01 мм=31,97–34,93% на 0–40 см) и сопоставим с верхними горизонтами участка самовосстановления (28,60–30,34% на 0–70 см). Напротив, глубокий слой самовосстанавливающегося отвала (70–110 см) был крайне грубозёмистым (песок - 89,89%; <0,01 мм - 8,87%), что указывает на устойчивую текстурную неоднородность. В ненарушенной почве доля тонкой фракции была максимальной (<0,01 мм=34,57–45,05%). Влажность варьировала от 2,09% (рекультивация 0–10 см) до 11,69% (отвал 70–110 см). Анализ PCA разделил типы участков и показал наибольшую неоднородность на отвале, находящегося на естественном самовосстановлении. Рекультивация улучшает физическое состояние верхнего слоя, однако полное сближение с фоновыми почвами ограничивается выраженными текстурными контрастами в профиле.

Ключевые слова: фосфоритовая добыча; рекультивация земель; естественное зарастание; гранулометрический состав; анализ главных компонент (PCA).

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