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Mining-Driven Soil Degradation and Its Linkages with Nutrient Dynamics in Jharkhand's Mining and Non-Mining Agroecosystems

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Abstract:
This research compares the physicochemical properties and nutrient status of soils from open-cast coal mining areas and adjacent non-mining sites in Jharkhand to understand mining-induced degradation and its implications for land productivity. Mining soils showed wider and often higher pH values, elevated electrical conductivity, depleted organic carbon, and reduced available nitrogen and phosphorus relative to non-mining soils, reflecting severe disturbance, salinisation, and disruption of natural nutrient cycling. Macronutrient and micronutrient analyses, supported by correlation matrices and principal component analysis, revealed strong positive linkages between organic carbon, nitrogen, and key micronutrients, as well as mining-associated co-mobilisation of metals such as Fe, Cu, and Mn and their pH-dependent bioavailability. These patterns indicate that open-cast mining drives soil acidification or alkalisation, organic matter loss, nutrient imbalances, and metal contamination, collectively lowering soil fertility, water-holding capacity, and crop-supporting potential. The study recommends targeted remediation strategies—pH correction, organic amendments, re-vegetation, and microbial restoration—to rebuild soil function, recover ecosystem services, and promote sustainable land use in mining-affected landscapes.

Keywords: Mining, Nutrients, physicochemical properties, Jharkhand

Introduction

Soil represents the foundational matrix for terrestrial ecosystems, governing plant growth, nutrient cycling, microbial activity, carbon sequestration, and agricultural productivity across global biomes (Binkley & Vitousek, 2000). As a dynamic interface between lithosphere, hydrosphere, and biosphere, healthy soils sustain biodiversity, regulate water flows, and underpin food security for billions. However, open-cast coal mining—one of the most destructive forms of resource extraction—fundamentally disrupts this critical resource through systematic topsoil stripping, overburden dumping, chemical leaching, acid mine drainage, and irreversible landscape fragmentation (Frouz et al., 2008). These operations expose subsurface materials to atmospheric weathering, generating extreme physicochemical conditions that persist for decades and severely impair ecological recovery, land rehabilitation, and sustainable land use.

In Jharkhand, India—where coal mining constitutes over 80% of the state's mineral economy and supports millions of livelihoods—the Jharia coalfields in Dhanbad district exemplify these

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transformative impacts (Prach & Tolvanen, 2016). As one of India's oldest and most intensively exploited coal basins, Jharia features extensive open-cast operations that have created a degraded mosaic of mine pits, overburden dumps, subsidence zones, and fire-affected lands juxtaposed against remnant non-mining agroecosystems, village common lands, and forest fragments. Mining-induced soil changes include pH extremes (acidification from pyrite oxidation or alkalinisation from lime-rich tailings), elevated electrical conductivity from soluble salts and heavy metals, catastrophic organic carbon depletion, macronutrient deficiencies, and accumulation of potentially toxic elements such as iron, copper, manganese, and zinc (Ryu & Spuller, 2021). These alterations not only constrain vegetation establishment and primary productivity but also pose contamination risks to adjacent farmlands, groundwater, and human health through dust deposition and runoff.

The ecological and socioeconomic stakes are particularly high in Jharia, where mining infrastructure encroaches upon densely populated agricultural landscapes that millions depend on for subsistence rice-wheat systems and horticulture (Holomb et al., 2024). Degraded mine soils with low fertility, poor water-holding capacity, and chemical toxicity hinder reclamation efforts, perpetuate land wastage, and exacerbate rural poverty despite coal's economic contributions. Moreover, soil degradation cascades through food webs, impairing microbial communities, soil fauna (e.g., earthworms, dung beetles), and higher trophic levels while diminishing critical ecosystem services such as nutrient recycling and carbon storage (Nichols et al., 2008).

This study systematically compares soil physicochemical properties and nutrient status across actively mined sites (Anna, Kusunda) and reference non-mining sites (Karmatand, Dhangi Basti along Sindri–Baliapur road) in the Jharia coalfields. Non-mining soils typically exhibit moderately acidic pH optima, higher organic carbon content, balanced macronutrients (N, P, K, S), and moderate micronutrient levels that support robust plant productivity and microbial function. In contrast, mining soils display wider pH variability, salinisation (high EC), organic matter depletion, macronutrient deficiencies, and elevated bioavailable metals from ore weathering and industrial inputs (Badewa et al., 2023). Comprehensive correlation analyses further elucidate organic carbon as a "master variable" strongly linked to nitrogen availability ($r \approx 0.97$) and micronutrient dynamics, while principal component patterns reveal mining-specific fingerprints of Fe-Cu-Mn co-mobilisation. By quantifying these differences and their interrelationships, the research identifies diagnostic indicators of degradation and prioritises restoration interventions—pH correction, organic amendments, microbial inoculation—to rebuild soil function and ecosystem services in coal-affected landscapes of eastern India.

Methodology

Soil sampling followed standard protocols across four sites: two open-cast mining areas (Anna, Kusunda) and two non-mining reference sites (Karmatand, Dhangi Basti) in Jharia coalfields (Binkley & Vitousek, 2000). At each site, five composite samples were collected from the 0–15

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cm depth layer using a soil auger, air-dried, sieved (2 mm), and analysed for physicochemical properties.

Soil pH and electrical conductivity (EC) were measured in 1:2.5 soil:water suspensions using a pH/EC metre (Ryu & Spuller, 2021). Organic carbon (OC) was determined by the Walkley-Black wet oxidation method. Available macronutrients—nitrogen (N, alkaline permanganate distillation), phosphorus (P, Olsen method), potassium (K, ammonium acetate extraction), and sulfur (S)—followed standard agronomic protocols (Holomb et al., 2024). Micronutrients (Zn, B, Fe, Cu, Mn) were extracted with DTPA and quantified via atomic absorption spectroscopy.

Data were summarised as means ± standard errors per site type. Differences between mining and non-mining soils were tested using independent t-tests or Mann-Whitney U tests based on normality (Shapiro-Wilk). Correlation matrices and pairplots explored interrelationships among parameters, with Pearson coefficients indicating strength and direction of associations ($r > 0.7$ strong, 0.3–0.7 moderate). Multivariate analyses (principal component analysis) identified dominant gradients driving soil variation. Analyses used R software (v4.2+), with significance at $\alpha = 0.05$.

Results and Discussion

Physicochemical properties. Mining soils exhibited significantly wider pH ranges (5.25–7.80) compared to non-mining soils (5.44–6.36), reflecting heterogeneous influences of acid-generating pyrite oxidation in some pits and alkaline tailings/lime dust deposition in others (Ryu & Spuller, 2021). This pH variability impairs micronutrient solubility—high pH reduces Fe, Zn, Cu availability through hydroxide precipitation, while acidic zones promote Al toxicity and P fixation. Electrical conductivity was markedly elevated in mining sites (0.08–0.51 dS/m vs. 0.02–0.33 dS/m non-mining), indicating salinisation from mine runoff, sulfate-rich acid mine drainage, and weathering of sulfide minerals that impose osmotic stress on germinating seeds and young plants (Holomb et al., 2024).

Organic matter and fertility. Organic carbon depletion represented mining's most profound impact, with mining soils averaging 0.02–0.43% versus 0.16–1.35% in non-mining areas—a 70–90% reduction attributable to topsoil removal, vegetation loss, and suppressed litter inputs (Badewa et al., 2023). This OC crash undermines soil aggregation, water retention, cation exchange capacity, and microbial biomass, creating a self-reinforcing degradation cycle where poor structure accelerates erosion and further OC loss.

Macronutrients. Available nitrogen was critically low in mining soils (3.2–190.4 kg/ha) compared to non-mining (61.6–392.0 kg/ha), reflecting mineralisation failure from OC depletion and microbial suppression by metals/salts (Holomb et al., 2024). Phosphorus availability suffered similarly (mining: 3.6–26.8 kg/ha; non-mining: 4.0–54.4 kg/ha), constrained by both low OC and suboptimal pH-P relationships that promote fixation as insoluble phosphates. Potassium remained relatively adequate in both (mining: 18.0–784.0 kg/ha; non-mining: 25.2–1124.0 kg/ha) due to mineral weathering, though bioavailability declined with compaction and leaching. Sulfur showed wide variability in mining soils (0.2–52.0 ppm), likely from sulfide oxidation products with uncertain plant availability.

Micronutrients and contamination. Mining dramatically elevated potentially toxic metals: Fe (6.2–94.2 ppm vs. 4.4–66.2 ppm), Cu (0.2–5.4 ppm vs. 0.1–5.0 ppm), and Mn (0.2–28.2 ppm vs. 0.2–16.2 ppm), reflecting co-mobilisation from iron-rich coal measures and sulfide ores (Fe-Cu r=0.84; Cu-Mn r=0.89; Fe-Mn r=0.79). Zinc showed slight elevation with high variability (0.1–8.4 ppm mining vs. 0.1–7.5 ppm), while boron declined (0.1–4.4 vs. 0.2–5.4 ppm), creating deficiency-toxicant imbalances.

Correlation structure. Organic carbon emerged as the central fertility driver, showing near-perfect correlation with N (r=0.97), strong positive links with Cu (r=0.76) and Mn (r=0.66), and moderate associations with S and Zn, confirming OC's role as nutrient reservoir and metal chelator (Balian et al., 2008). Negative pH-micronutrient correlations (pH-Fe r=-0.70; pH-Cu r=-0.65) highlighted bioavailability trade-offs, while EC-sulfate linkage (r=0.57) signalled salinity risks. These patterns mirror global coal mining impacts and provide diagnostic fingerprints for contamination source attribution (Frouz et al., 2008).

These transformations create infertile, hostile substrates that thwart reclamation, reduce agricultural carrying capacity, and threaten food security in Jharkhand's coal belt. Targeted interventions—lime/gypsum for pH, compost for OC/N, phytoremediation for metals—offer restoration pathways (Prach & Tolvanen, 2016).

Conclusion

Open-cast coal mining in Jharia profoundly degrades soil quality, depleting organic carbon and macronutrients while elevating salinity and metal contamination, severely limiting agricultural and ecological recovery (Prach & Tolvanen, 2016). Non-mining reference soils demonstrate optimal conditions for productivity, underscoring mining's transformative effects. Strong OC-nutrient correlations and metal co-mobilisation provide diagnostic fingerprints for monitoring degradation (Nichols et al., 2008). Remediation must prioritise organic amendments, pH correction, and revegetation to rebuild fertility and ecosystem services, ensuring sustainable land use in Jharkhand's coal landscapes.

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