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Soil Quality Changes in Open-Pit Nickel Mining and Post-Mining Reclamation: Implications for Achieving SDG 15 (Life on Land)

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Abstract: Open-pit nickel (Ni) mining has expanded rapidly in Indonesia and has become one of the main drivers of land degradation. This review synthesizes scientific evidence on the impacts of open-pit Ni mining on soil properties and evaluates the application of the Soil Quality Index (SQI) as integrative tools for assessing soil degradation and reclamation success. The reviewed studies consistently report severe declines in soil quality following mining, including reductions in soil organic carbon (SOC) from approximately 40.2 g/kg in forest soils to as low as 2.29 g/kg in post-mining soils, increases in bulk density from around 0.88 g/cm to 1.37 g/cm, and substantial decreases in microbial biomass carbon 350 mg C/kg to below 110 mg C/kg in heavily disturbed areas. Sensitive indicators such as soil organic matter, pH, bulk density, microbial biomass carbon, soil respiration, and enzyme activities were identified as key variables responding rapidly to mining disturbance and reclamation measures. Reported SQI values range from very low in active mining areas (0.18–0.30), moderate in reclaimed lands (0.43–0.55), and high in forest ecosystems (0.70–0.81). These findings demonstrate that SQI provides a science-based framework for monitoring post-mining restoration and supports the achievement of SDG 15 (Life on Land), particularly land degradation neutrality targets.

Keywords: Literature review; Minimum data set; Nickle mining; Open-pit mining; Soil quality

Introduction

Nickel (Ni) is one of the potential products for Indonesia to strengthen its position in the global market and encourage economic growth, Indonesia earns revenue of U$ 30 billion from domestic Ni downstream activities (Radhica & Wibisana, 2023). Indonesia is the country with the most Ni reserves in the world, with 55.000.000 tons, and in 2021 Indonesia was able to produce 1 million metric tons of Ni, which accounts for 37% of the world's Ni production (U.S. Geological Survey, 2023). Massive Ni mining in Indonesia causes environmental degradation such as pollution, ecosystem damage, and biodiversity decline due to the deforestation of natural forests into active mines (Rehman et al., 2024). One of the provinces with the largest Ni mining concession area is Southeast Sulawesi. Ni mining permits for 252 companies in Southeast Sulawesi are estimated to have reached 510.282 ha out of 562.600 ha of total forest cover, with a total Mining Business Permit Area covering an area of 9.047 ha (WALHI Region Sulawesi, 2021).

Topsoil stripping is a crucial stage in laterite Ni mining activities because it directly removes the most fertile soil layer that serves as the main buffer of terrestrial ecosystems. The topsoil layer and vegetation cover that are lost result in post-mining Ni soils having a C-organic content of 2.29 g/kg which is much lower

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than the C-Organic content of 40.20 g/kg in forest areas (Prematuri et al., 2020). Excavation of the topsoil layer due to the Ni mine is the main factor in the change in soil characteristics. Loss of organic matter causes ex-mining land to have a bulk density of 1.37 g/cm^3 in the upper layer (0–30 cm), which indicates a denser soil condition than natural forests, which have a bulk density of 0.88 g/cm^3. The soil porosity in the ex-mining land has a value of 45%; this condition is much lower than that of forest areas with a soil porosity of 59% (Widjaja et al., 2025). Organic matter lost due to open pit mining causes soil structures to become denser in dry conditions, resulting in aeration and root penetration being hampered (Simon et al., 2025).

Mine reclamation is an obligation that must be carried out by all mining companies as written in Law No. 4/2009 Article 100 and Law No. 3/2020 Article 103 related to mining regulations. Mine reclamation aims to restore lost land and ecosystem functions, as well as being a form of responsibility to improve environmental services. Reclamation should be focused on improving sensitive and responsive soil functions so that the success rate of reclamation and soil quality restoration can be evaluated periodically. The results of the analysis of the most sensitive parameters representing changes in soil quality in the open pit mine area in Hequ, China from the 9 parameters analyzed, showed that only the three main parameters Soil Organic Matter (SOM), pH, and Bulk Density (BD)—contributed the most to the variation in soil quality index in the open and post-reclamation mine areas (Li et al., 2024).

Soil quality has become an internationally accepted science-based tool for assessment for land degradation issues. previous research has proven that if the analysis of sensitive parameters and SQI functions as a scientific evaluation tool, SQI can be the basis for decision-making in land restoration planning as well as long-term monitoring of the effectiveness of reclamation of ex-mining land (Damiba et al., 2024). The Soil Quality Index research on mining areas comparing forest conditions, active mines, and reclamation shows that forests have a very high SQI (0.81). This value is much higher than the poor active mining SQI (0.29), which indicates a very degraded soil condition, while reclaimed land has a moderate SQI (0.43). It shows that open system mining activities and reclamation efforts have an effect on the SQI (Arifin et al., 2025).

The concept of soil quality offers an integrative approach that is able to describe the ability of soil to carry out its ecological function, both in degraded conditions and during the recovery process through reclamation. Soil quality can be used as a tool to assess the level of degradation of mining land and evaluate the success of post-mining reclamation in a more objective and measurable manner.

In the context of global environmental commitments, land degradation caused by open-pit Ni mining is closely related to the achievement of Sustainable Development Goal (SDG) 15 (Life on Land), particularly Target 15.3 which emphasizes combating land degradation and restoring degraded land and soil. Post-mining landscapes represent one of the most critical forms of anthropogenic land disturbance, requiring science-based evaluation tools to ensure effective ecological restoration. The assessment of soil quality and the application of the SQI provide measurable and objective indicators to monitor degradation levels and reclamation progress. Therefore, integrating soil quality assessment into post-mining management strategies is essential to support sustainable land restoration and contribute to the implementation of SDG 15.

This review article aims to synthesize scientific findings related to the impact of Ni open pit mining activities on the physical, chemical, and biological properties of the soil, as well as evaluate the use of the SQI as a tool to rate degradation and reclamation after open-pit mining.

Method

This article was prepared using a narrative literature review method with a conceptual and analytical approach, which aims to collect scientific findings related to the impact of Ni mining activities of open mining systems on soil quality, as well as the use of the SQI as a tool to assess the level of degradation and post-mining soil recovery.

The literature search is carried out systematically through reputable scientific databases including Scopus, Web of Science, Google Scholar, and ScienceDirect. The search also includes scientific reference books, official statistical data from government agencies (Central Statistics Agency/BPS), institutional reports, grey literature relevant to mining and land degradation issues. The keywords used include a combination of terms: open-pit Ni mining, soil degradation, soil quality indicators, soil quality index, mine reclamation, post-mining land, and their equivalents in Indonesian.

The literature is explored in stages according to the focus of the discussion : (1) Ni open-pit mining activities and processes, (2) the impact of mining on the physical, chemical, and biological soil properties , (3) soil parameters that are sensitive and responsive to mining disturbances, and (4) the application of the SQI in assessing the degradation and success of mining land reclamation.

Literature Selection Criteria

The articles used in this study were selected based on several criteria, namely: (1) Scientific articles from accredited national journals or reputable international journals, (2) Relevant to the topics of open pit mining, soil quality, soil-sensitive indicators, and post-mining reclamation, (3) Present quantitative data or clear analysis results related to changes in soil characteristics, and (4) Published mainly in the last 10 years, while still including some of the classic literature that is the main reference of the concept of soil quality and SQI.

Literature Analysis and Synthesis Techniques

Literature analysis was carried out in a descriptive-critical manner, by comparing the results of the research between locations, types of mines, age of reclamation, and soil parameters used. Each soil parameter is analyzed based on its level of sensitivity to mining disturbances as well as its ability to represent changes in soil quality.

The results of the research were then synthesized to identify general patterns, current research trends, and research gaps related to the use of single indicators compared to the soil quality index approach. This synthesis is used to strengthen the argument that the SQI is an integrative, objective, and relevant evaluation tool for assessing the level of degradation and restoration of post-open mining soils.

Result and Discussion

Nickel (Ni) Reserves and Open-pit Nickle Mining

Ni is one of the metal elements in the periodic table with atomic number 28, which has strong characteristics, is resistant to corrosion, and is a good conductor of electricity, so it is widely used in stainless steel, metal alloys, and becomes a raw material for making electric batteries for vehicles. Ni ore is divided into 2 types, namely laterite ore and sulfide ore, where sulfide ore is easier to process because it can go through a beneficiation process to increase Ni levels to about 10–26% before smelting. Laterite ore cannot be enriched in this way, so it must be directly processed through smelting or hydrometallurgical processes with large volumes of raw materials. Most of the world's Ni reserves, which are more than 70%, are in the form of laterite Ni ores, while the rest is in the form of sulfide ores (Tamehe et al., 2024). The minerals olivine and pyroxene undergo intensive weathering, causing Ni to detach from their parent minerals and accumulate in the laterite profile layer (Puspita et al., 2022). The Ni laterite profile consists of a layer of topsoil, limonite zone, saprolite zone or an enrichment zone, and bedrock. An illustration of the latertite profile of Ni can be seen in Figure 1.

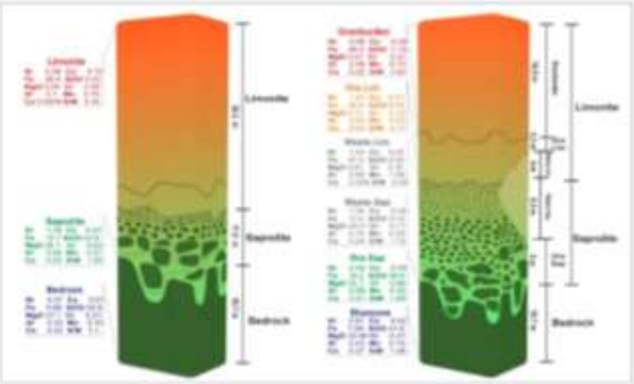

Figure 1. Distribution of the Ni latertite sediment profile layer (Prinaldi et al., 2025)

The Ni laterite deposits are generally composed of five layering zones, namely topsoil, limonite, transition zone, saprolite, and bedrock. The developed transition zone is limited to the northern part of Pomalaa as yellow limonite, which lies between red limonite and saprolite, and is composed of loose material with a sandy to clay texture, with a relatively high content of hydrated iron oxide and organic matter, reflecting the enrichment of residual iron due to advanced weathering. The saprolite zone is characterized by a greenish-brown colour and a fine to rough texture, formed from the weathering of parent rocks with secondary mineral development, and is the main zone of Ni enrichment with a thickness of about 10–15 m and a Ni level ranging from 1.8–3.0%. The profile of the Ni laterite deposits can be seen in Figure 2.

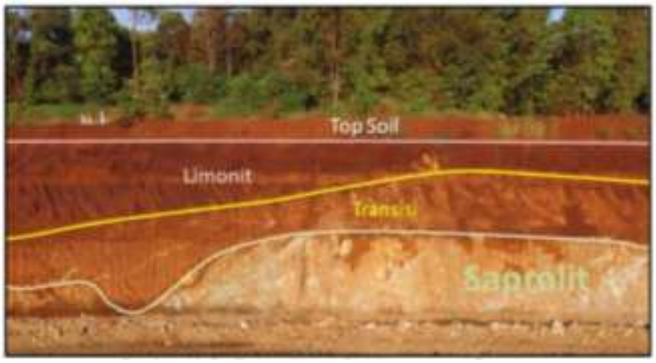

Figure 1. Latertite sediment profile of Pomalaa District (Kamaruddin et al., 2018)

The laterite profile develops clearly into zones of limonite, saprolite, and bedrock. The average Ni content is 0.96% in limonite and increases significantly to 2.08% in saprolites; even in saprolytic dunites it reaches 2.24% Ni, so that saprolyte is identified as the main Ni ore zone (Prinaldi et al., 2025). The limonite zone contains Ni oxide with lower levels of Ni but is rich in iron (Fe) and cobalt (Co). The study shows that the level of Ni enrichment is strongly influenced by the type of ultramafic rock that makes it up, the degree of serpentinization, and the Mg and Si leaching process, where ultramafic rocks rich in olivine minerals tend to produce higher Ni more potential than non-ultramafic rocks.

Open-pit Mining Process

Ni mining with an open-pit mining system begins from a survey and exploration process that aims to identify the distribution and potential reserves of Ni ore from ultra alkaline rock weathering, by sampling drilled results in the form of core samples placed in the core box, after which the results of the core samples were described in terms of layer thickness, material characteristics, and laterite zoning such as topsoil, limonite, and saprolite (Syahrul et al., 2023). The stage of opening and stripping clears vegetation and land cover in the mining area. The next stage is topsoil stripping; this topsoil is separated and stored in a special location so that its quality is maintained for reuse at the reclamation stage. The stripping is then continued with overburden removal, which is the removal of the overburden layer that is on top of the laterite Ni deposit, followed by the removal of the overburden layer using heavy equipment until the limonite ore and saprolite layers are exposed (Gunawan, 2025). Open-pit mining in the Ni mining area is generally carried out to a depth of 15-20 meters below the ground surface, where at greater depths Ni laterite ore is often found, namely in the saprolite layer or enrichment zone (Puspita et al., 2022).

Impact of Open-Pit Mining

Topsoil stripping is one of the most crucial stages in laterite Ni mining activities because it directly removes the most fertile soil layer that serves as the main buffer of terrestrial ecosystems. Stripping and land clearing have an impact on the increase in forest deforestation in Southeast Sulawesi; from 2019–2021, the rate of deforestation due to mining increased from 3,184 ha to 4,188 ha (BPS, 2024). Research on Obi Island with NDVI analysis based on Landsat 8 imagery shows that the area of non-vegetated areas increased from 5,174.06 ha in 2015 to 6,553.47 ha in 2025. This increase in open land is mainly concentrated in the core zone of the mine and within a radius of 1–3 km from the centre of mining activities; the area of non-vegetated area increases sharply to reach 1,886.96 ha by 2025 (Rakuasa et al., 2025). BPS data and NDVI analysis results clearly show that Ni mining activities with an open system cause a significant loss of topsoil and vegetation cover, which of course will cause problems of damage to the biological ecosystem around the mine. Clearing of forests in the Ni mine concession area in Halmahera also caused a loss of 2.04 million tons of CO_2 from around 5,331 ha of tropical forests, which accelerated greenhouse gas emissions (Shennum & Renaldi, 2022). The impact of Ni mining can be seen in Figure 4.

Figure 2. Impact of Ni mining open system (WALHI Reg Sulawesi., 2021)

Ni mining activities with an open system cause significant changes in land topography through open excavation activities and overburden accumulation, which cause surface runoff due to rainwater. Research in the Bahodopi watershed shows increased turbidity, total suspended solids (TSS), and discoloration of river water as strong indications of massive erosion and sedimentation from the Ni mine area (Nasution et al., 2024). The sediment from the erosion is deposited into river and estuary bodies, accelerating siltation and increasing the risk of flooding in the rainy season. Research in Kolaka and Pomalaa shows that changes in the contour of the land contributed to the overflow of the Oko-Oko River, which repeatedly inundated about 750 ha of area, including 450 ha of productive rice fields. The quality of surface and coastal water around the Ni mine has also suffered degradation. In the Oko-Oko River, Kolaka, hexavalent chromium (Cr) concentrations were detected in the range of 0.021–0.124 m/L (Ilham et al., 2017).

Open-pit mining causes the topsoil layer rich in organic C to be eroded, resulting in soil loss of up to >70–80% of organic matter content compared to pre-mining conditions (Zhang et al., 2020). Organic matter lost in the topsoil layer will reduce the soil's ability to form a solid aggregate, resulting in the soil structure being destroyed and being carried away by water flows. Post-Ni mining topsoil stripping led to a 98% decrease in N-total, 93% C-organic, 11% available phosphorus (P), 85% exchanged calcium, and 74% exchange sodium compared to natural forest soils (Prematuri et al., 2020). Ni mining activity has a contamination level (CF) of 1.96 – 2.96 in the soil layer and water flow around the mining area, which shows that the sedimentation of the residual Ni mining activity is moderately to severely polluted (Adidharma et al., 2023). Vegetated reclaimed areas showed a pH of 4.8 and a CEC of 17.89 me/100g, which was higher than unreclaimed former mining land with a pH of 4.4 and a CEC of 15.8 me/100g (Lulu et al., 2022).

Tailings come from the residual processing of saprolite and limonite ores that have undergone separation of the target metal; the tailings content generally carries a heavy metal content of Ni 0.5%, Co 0.36%, Fe 37%, and Cu 0.08% (Majalis et al., 2020). This heavy metal content makes Ni tailings a potentially toxic material for the soil and aquatic environment. Hydrometallurgical methods such as high pressure acid leaching (HPAL) involve smelting laterite ore using sulfuric acid at high temperatures and pressures to dissolve Ni and Co. Ni tailings generally contain significant concentrations of heavy metals, especially Fe, Cr, Ni, Co, Mn, and Al. Cr is the most valuable element, 1–2% by weight of tailings and being one of the most soluble materials in water (Delina et al., 2025).

The tailings produced from the hydrometallurgical process of Ni-Co ore also contain a fairly high amount of Cr. Cr is known to be dangerous if it is in the form of Cr (VI) because it is toxic and carcinogenic; about 39–61% of Cr is bound in hematite, which has the potential to dissolve into water. Soils exposed to Ni tailings showed a significant decline in physical and biological quality. The organic carbon content of soil (SOC) was recorded to be very low, at only 0.15–0.38%, compared to natural soil at 1.2–2.4%. Soil microbial biomass has also decreased drastically, with the value of microbial biomass carbon (MBC) only 45–110 mg C/kg, lower than natural soil which reaches 350–600 mg C/kg (Ye et al., 2022). The concentration of Ni in metal-tolerant plant tissues was recorded to reach 120–340 mg/kg, while Cr was in the range of 60–180 mg/kg, which has the potential to cause chronic toxic effects on organisms (Mustafa et al., 2022).

Sensitive Indicators of Soil Quality

Degree of Acidity (pH)

The degree of acidity or pH is one of the variables of the chemical properties of the soil used to determine the acidity or alkaline content in the soil. The level of acidity and alkalinity of a soil can be used as an indicator to assess soil quality. Soil pH conditions will affect the plant's ability to absorb nutrient ions needed by plants. In general, a good pH for plants is neutral, namely pH 6.5-7.5 because the pH is able to facilitate the dissolution of nutrients by water (Rukmana et al., 2019). The pH value indicates the amount of H^+ in the soil; the higher the H^+, the more acidic the soil. On the other hand, alkaline soils have a high OH^- content. Ni mining activities with an open system result in the lifting of subsoil layers rich in Fe and Al elements to the surface; this condition causes the soil to be acidic. Measurements using X-Ray Diffraction show that pH ranges from 5.4–5.9, and the high Fe content of the soil is reported to exceed 325 ppm (Jafar et al., 2022).

Soil Organic Carbon

SOC is the fraction of organic C in the soil that comes from organic matter, such as plant residues and microbes. SOC plays a role in the global C cycle, supporting soil fertility and plant growth. C sources are abundant in soil, with soil storing 1.100–3.150 PgC, a much higher amount than the amount of C in the atmosphere (Bekchanova et al., 2024). Proper rehabilitation strategies such as forest topsoil fertilization and revegetation with native species can significantly restore SOC and SOM content. Research on ex-mining land in areas that have been rehabilitated for 10 years shows that the SOC stock is 40 mg/ha, which is 10 times higher than the area that has not been rehabilitated, with a SOC stock of only 4.4 mg/ha, but still slightly below the SOC content of natural forest stock of 45 mg/ha (Ribeiro et al., 2022). Open-system Ni mining causes soil to lose SOC stock, as evidenced by the fact that the former Ni mining soil has a C-organic content of 2.29 g/kg, which is lower than the C-Organic content of 40.20 g/kg in forest areas (Prematuri et al., 2020).

Nitrogen

Nitrogen (N) is the main nutrient that plants need, especially in the vegetative phase for the formation of leaves, stems, and roots. Plants absorb N in the form of nitrates (NO_3^-) and ammonium (NH_4^+). Changes in N are caused by several factors such as leaching, denitrification, and activities that cause topsoil loss, such as soil excavation. Studies show that the N-total of 0.05–0.22% in ex-mining soil is classified as very low; this is due to the loss of the topsoil layer. This value is far below productive soil, which is usually >0.3–0.5% (Tobing et al., 2021). The N content in post-mining areas has a value of 0.09% (very low) and 0.17% (low) in post-mining 10 years old, which shows a slight recovery with the age of the land after mining, but this value is much lower than natural soil in forest areas (Lulu et al., 2022). Topsoil returns combined with compost and biochar were shown to contribute 165 kg/ha, able to raise the soil NH_4^+ to 5.5 µg/g and increase N fixation by centrosema by up to 50 kg/ha. Biochar provides a moderate increase with a fixation of 25 kg/ha through improved nutrient retention. The most effective treatment can be used a biochar–compost mixture that supplies 203 kg/ha, resulting in the highest N fixation of 73 kg/ha, soil NH_4^+ of 6.7 µg/g, and plant N absorption of 111 kg/ha (Maftukhah et al., 2023).

Phosphorus

P is an essential macronutrient that plants need in large quantities and is generally absorbed in the form of $H_2PO_4^-$. The availability of P in the soil is greatly influenced by pH and will be most optimal when the pH is in the range of 6.5–7.5 (Firnia, 2018). Ex-mining land shows a very low P content in the soil, ranging from only 3.45 to 11.25 mg/kg; this is because P will be bound by Al and Fe acid cations (Wang et al., 2024). Former Ni mine soils have low available P-content (1.84-10.10 ppm); even some samples of soil extracted with the Olsen reagent show very low P-potential content (3.36-6.53 mg P_2O_5/100g) (Iskandar et al., 2024). The use of P waste or tailings on reclaimed land combined with organic fertilizers is able to increase soil P content. As a result, soils in layers 0–20 cm have a total P-content of 952.82 mg/kg and P-available of 28.46 mg/kg (Geng et al., 2025). A study of post-mining soil restoration in former strip-mining areas of Australian tropical forests showed that the total P value in 0–10 cm of restored soil was reported to be 316 mg/kg, slightly larger than that of natural forest soils with a total P of 271 mg/kg, indicating that the increase in P in the topsoil layer was quite rapid (Tibbett et al., 2018).

Cation Exchange Capacity

Cation exchange capacity (CEC) is the level of soil's ability to exchange anions and cations, with cmol/kg units, which has a close relationship with soil fertility and nutrient absorption (Syachroni, 2019). The former Ni mine soil has a very low to low CEC of 1.67-16.89 cmol/kg at a depth of 0-60 cm; this condition is caused by the loss of organic matter in the topsoil layer (Iskandar et al., 2024). Experimental research on ex-Ni mine soils with a combination of biochar and calcite showed that the CEC value was 15-21 cmol/kg, higher than the pre-treatment soil that had only a CEC of <13 cmol/kg (Jayadi et al., 2022). The CEC is often associated with the total alkaline cations in the soil; the higher the CEC, the greater the potential for the total alkaline cations in the soil if there is no competition with acidic cations.

Ex-mine soils generally have low alkaline cation values due to the loss of organic matter-rich topsoil. The former Ni mining soil has Ca 1.41 cmol/kg, Mg 1.91 cmol/kg, K 0.28 cmol/kg, and Na 0.20 cmol/kg, which indicates that the soil is very poor in Ca and K; the high Mg value can be caused due to ultramafic bedrock. The 7.5% biochar treatment + 4.5 lime is proven to increase Ca to 4.16 cmol/kg, Mg to 5.32 cmol/kg, K to 0.51–0.52 cmol/kg, and Na 0.42 cmol/kg (Jayadi et al., 2022) Other studies on ex-mine acidic soils had Ca ±0.20–0.40 cmol/kg, Mg ±0.10–0.20 cmol/kg, K ±0.05 cmol/kg, and Na <0.05 cmol/kg; then after 2% biochar + lime treatment, the values increased to Ca 2.0 cmol/kg, Mg 1.0 cmol/kg, K 0.10–0.15 cmol/kg, and Na 0.05–0.07 cmol/kg (Becerra-agudelo et al., 2022). Reclamation of minelands shows that ultrabase soils are very poor in Ca <1 cmol/kg but rich in Mg >3 cmol/kg. Lime administration increases Ca by three–four times, lowers Al saturation, and raises K-available to 0.3–0.5 cmol/kg (Suswati & Denashurya, 2023). The return of topsoil combined with biochar and calcite or dolomite is able to increase Ca, Mg, K, and Na by improving CEC and reducing acidity; soil conditions again support plant growth (Widjaja et al., 2025).

Soil Porosity

The soil BD in the polyculture system mine rehabilitation area is 1.40 g/cm³, which is lower than the monoculture system rehabilitation area, which is 1.62 g/cm³. The lower soil BD in the polyculture system is due to the organic matter content of 1.08%, which is higher than monoculture reclaimed areas of only 0.66% (Bakri et al., 2025). A comparison of BD in the mining area shows that post-mining soil without restoration has a BD of 1.39 g/cm³, higher than the BD of 1.33 g/cm³ in the restoration area with topsoil arrangement and *Cenchrus ciliaris* (Castellanos-Barliza & León-Peláez, 2023). Ex-mining plantations have the lowest porosity of 56.11% due to intensive processing without the presence of organic C in the soil pore space; when compared to non-mined forest areas, they show the highest porosity of 70.44%, dominance of organic matter, and good soil aggregation (Rosita et al., 2023).

Microbial Biomass Carbon

Microbial biomass carbon (MBC) is the amount of C measured based on the activity of soil microbes including bacteria, fungi and pathogens. MBC can be used as one of the variables in the assessment of the soil quality index because it is one of the variables that is sensitive and related to the availability of organic matter in the soil and other variables. MBC in ex-mining soil has a value of 0.32 µg C/g, which is lower than reclaimed areas with monoculture revegetation of 0.58 µg C/g and agroforestry systems with an MBC value of 0.79 µg C/g (Fauziana, 2019). MBC in the mine tailings area has different content due to differences in heavy metal contamination; soils mixed with pure metal tailings material AS and Zn have an MBC of about 110–150 mg C/kg. In the dam zone that has mixed with natural soil and received vegetation litter, the MBC is higher, around 220–260 mg C/kg (Feketeov et al., 2021). Studies conducted on soils deliberately contaminated by multi-metals Cr, Cu, Cd, and Ni showed a much lower MBC of 90 mg C/kg compared to MBC in natural soils without metal contamination of 563 mg C/kg (Ji et al., 2021).

Soil Respiration

Soil respiration is an activity carried out by soil microorganisms of bacteria, fungi, algae, and protozoa that carry out gas exchange in metabolic processes, including the exchange of O_2 gases and the release of CO_2. Higher soil respiration values indicate that microbes are more active in decomposing organic matter in the soil; this activity can be influenced by different types of land use (Meena & Rao, 2021) qCO_2 indicates that microbes release a lot of CO_2 per unit of biomass, so their carbon use efficiency is low, indicating that microbes are under environmental stress because they emit more CO_2 than they use CO_2 for growth (Ashraf et al., 2022). In mine reclamation research, qCO_2 in mine-affected areas is much higher at 0.25 mg CO_2/g compared to natural forests at 0.1 mg CO_2/g, which indicates a high level of stress due to lack of vegetation (Goulart et al., 2025). Soil respiration from the activity of microorganisms can be one of the indicators in assessing soil quality.

β-glucosidase

The enzyme β-glucosidase becomes an important indicator for soil health and quality that is sensitive to land use changes, regulating the dynamics of organic matter (Adetunji et al., 2017). β-glucosidase activity tends to decrease if the soil is heavily metal-contaminated; in soil that is not polluted, β-glucosidase is around 1.10 µmol PNP g/h, higher than in lightly polluted soils where it is 0.45 µmol PNP g/h, and it is 0.20 µmol PNP g/h in soils with high pollution levels (Daunoras et al., 2024). The β-glucosidase content on reclaimed land with *Elymus nutans* and *Picea crassifolia* was higher at 28.66 and 28.68 µg PNP g/h compared to the soil before mine restoration with a β-glucosidase content of 14.12 µg PNP g/h, and the highest β-glucosidase content was in the natural forest area of 150 µg PNP g/h, which shows mining and restoration activities impact β-glucosidase (Hu et al., 2020).

Dehydrogenase

The enzyme dehydrogenase (DHA) is an intracellular enzyme that is only active in oxidation-reduction (redox) reactions during the respiration of microbial cells, especially in producing ATP and NADH, which are energy for the activity of soil microorganisms. The activity of this enzyme reflects the respiration rate of microbes and is used as an indicator of soil quality because it is sensitive to land use. Dehydrogenase (DHA) in natural forest areas at 34.8 µg TPF g/h is higher than in degraded land use, which is only 10.6 µg TPF g/h; this value is influenced by C-Organic and microbial biomass that correlate positively with DHA ($r = 0.91$ and $r = 0.88$, respectively) (Bandyopadhyay et al., 2020). Studies on post-mining land reclaimed soil showed that DHA activity was very low, but DHA increased from <1 mg TPF/kg/h to >4.5 mg TPF/kg/h after 3 years of reclamation, followed by an increase in microbial biomass from 0.12×10^9 CFU/kg to 2.4×10^9 CFU/kg (Joniec et al., 2021). The enzyme DHA is suitable as one of the indicators of soil quality because it is closely related to microbial activity.

Soil Quality Index

Soil quality is the ability of soil to maintain the physical, chemical, and biological properties of soil to support ecosystem stability that supports the growth of plants and microorganisms, human activities, and health (Kurniawan et al., 2021). Soil quality is the capacity of the soil to carry out its functions within the limits of natural or managed ecosystems, including the ability of the soil to support plant and animal productivity, maintain the hydrological and air cycles, and support all human activities and life (Natural Resources Conservation Service, 2001). The specific definition of soil quality is the ability of soil to provide essential macro and micro nutrients and maintain the stability of soil structure and the activity of soil organisms (Behairy et al., 2024).

Soil quality index (SQI) is an index in the form of numbers that reflects soil conditions as poor or good. SQI is widely used to assess the ability of soil to carry out its functions optimally, including supporting plant growth, maintaining environmental balance, and supporting human activities (Lenka et al., 2022). The concept of SQI has been modified by various methods such as PCA and VSA, which aim to simplify various complex soil parameters into a single value that is easy to understand and can be compared between locations or over time (Hermiyanto et al., 2025). SQI research on mining forests is generally used to assess the success rate of reclamation that has been carried out by comparing the age of reclamation or land use. Soil quality assessment in ex-mining land can be carried out using the SQI approach; several soil trait variables are collected and then reduced by the PCA method (Li et al., 2024).

The assessment of the SQI in 3 land uses, namely active mines, reclaimed mines, and secondary forests, obtained eight main indicators that affect the value of SQI. The eight indicators are soil pH, base saturation, BD, electrical conductivity (EC), CEC, available P, total N, and C-organic. CEC and total N contributed the most to the increase value of SQI. SQI value on 18-year reclaimed land (0.651) is higher than that of natural forests (0.575). A SQI value above 0.5 is considered a sustainable reclamation (Noviyanto et al., 2017).

Research conducted in the open-pit coal mining area of PT Bukit Asam, South Sumatra, shows that secondary forests have SQI 0.68, which reflects the optimal function of the soil ecosystem. Active mines show extreme degradation with SQI 0.18–0.20. Reclaimed land exhibited a higher SQI (0.50–0.53) than active mines, mainly due to increased C-organic and soil aggregate stability (Lulu et al., 2022). Research in Sawahlunto, West Sumatra showed, that the SQI value was found in forests, namely 0.70–0.72, due to the high content of organic matter and high microbial activity. Active mines have the lowest SQI value, which is 0.15–0.22, due to soil compaction caused by dredging of topsoil and overburden layers. Reclaimed land shows a medium-class SQI value (0.45–0.55), which indicates a restoration of soil quality, although it has not fully matched that of natural forests (Herman et al., 2025).

The research was conducted in the coal mining area in Ezhuang, China; the soil quality in the coal mine sinking area showed a range of SQI 0.46 in the reclamation area. The worst soils had very low SQI (0.10–0.20), which reflected the damaged soil structure and low fertility on the former mining land. The best locations within the reclaimed area reach SQI 0.77, approaching SQI 0.88 in undisturbed reference forests (Liu et al., 2025). Other studies in restored open system P mining areas showed a very low grade of SQI 0.30, while in restoration areas the SQI (0.40 – 0.55) was higher than land without restoration (Levi et al., 2021). Active or non-reclaimed mining land has a very low SQI (0.29–0.35), which indicates that the soil is not able to carry out the functions of the basic ecosystem optimally (Ribeiro et al., 2022). Reclaimed land shows a clear gradual recovery trend as the age of reclamation increases. Reclamation aged 4–7 years old, has a SQI (0.43–0.51). Reclamation 10–12 years has an SQI 0.6–0.7, close to forest conditions with a SQI 0.81. An SQI value of >0.5 indicates that reclamation has been successful even though it has not matched natural forest land (Arifin et al., 2025). A summary of the SQI research on the mining area can be seen in Table 1.

Table 1. Comparison of Soil Quality Index Values in 3 Land Uses

SQI Forest	SQI Not Reclamation	SQI Reclamation	Source
0.57	-	0.65	Noviyanto et al. (2017)
0.72	0.22	0.45–0.55	Herman et al. (2025)
-	0.30	0.55	Levi et al. (2021)
-	0.32	0.62	Nuriman et al. (2025)
0.90	-	0.70	Ribeiro et al. (2022)
0.81	0.29	0.43	Arifin et al. (2025)

Description: 0-0.19 (Very Poor), 0.20-0.34 (Poor), 0.35-0.59 (Medium), 0.60-0.79 (High), 0.80-1 (Very High)

Beyond the scientific evaluation of soil indicators and SQI values, these findings also have broader implications for sustainable land restoration and global environmental commitments. The documented decline in soil physical, chemical, and biological properties following open-pit Ni mining demonstrates a clear form of land degradation that directly challenges the achievement of SDG 15, particularly Target 15.3, which aims to combat desertification and restore degraded land and soil. The significant reductions in SOC, MBC, CEC, and SQI values in active mining areas indicate a loss of soil ecosystem functions, including nutrient cycling, structural stability, and biological activity. Although reclamation efforts improve several soil indicators and increase SQI values to moderate levels, full recovery toward forest-like conditions remains limited even after more than 10 years of rehabilitation.

These findings highlight that successful post-mining restoration requires long-term management strategies that prioritize topsoil conservation, organic matter amendment, revegetation with diverse species, and continuous monitoring of sensitive soil indicators. The application of the SQI provides a science-based and integrative framework for evaluating reclamation performance and tracking ecological recovery over time. Therefore, incorporating SQI into post-mining environmental management policies can strengthen sustainable land management practices and contribute directly to the implementation of SDG 15 by promoting measurable progress toward land degradation neutrality.

Conclusion

Open-pit Ni mining leads to pronounced alterations in soil chemical balance and nutrient dynamics, primarily driven by topsoil removal and exposure of subsoil materials. The reviewed literature consistently reports a decline in soil pH from near-neutral conditions (pH 6.2–6.8) in forest soils to strongly acidic conditions (pH 4.3–5.0) in active mining areas, which directly constrains nutrient availability and biological processes. Concurrently, CEC decreases markedly from values exceeding 20 cmol/kg in undisturbed soils to less than 8–10 cmol/kg after mining, indicating a substantial loss of soil buffering capacity. SQI reveals clear differentiation among land-use types, with low SQI values in active mining areas (0.18–0.30), moderate values in reclaimed lands (0.43–0.55), and high values in reference forest soils (0.70–0.80). These findings confirm that while reclamation improves soil quality, full recovery of soil functions remains limited. Therefore, the integration of sensitive soil indicators and the SQI into post-mining management strategies can strengthen sustainable land restoration practices and contribute directly to the achievement of SDG 15 (Life on Land), particularly in promoting measurable progress toward land degradation neutrality.

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