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Hydroseeding for Post-Mining Land Reclamation in Indonesia: Implications for Soil Restoration and Environmental Health

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Abstract

Post-mining land degradation in Indonesia causes severe declines in soil quality and ecosystem functions, potentially affecting environmental sustainability and public health. Therefore, environmentally friendly reclamation technologies are needed to accelerate vegetation establishment and restore ecological stability in degraded mining landscapes. Although hydroseeding has been widely applied for post-mining revegetation, comprehensive reviews evaluating its implications for soil restoration and environmental health in tropical ecosystems remain limited. This review aims to evaluate the effectiveness of hydroseeding for post-mining land reclamation in Indonesia and to identify current challenges and future improvement opportunities. A structured narrative review was conducted using relevant national and international scientific literature published between 2015 and 2025. The reviewed studies indicate that hydroseeding improves soil structure, increases organic carbon content, enhances nutrient availability, stimulates microbial activity, and accelerates vegetation establishment. Increased plant cover also contributes to erosion control and reduces heavy metal mobilization within the soil-plant-water system, thereby supporting environmental recovery. However, hydroseeding effectiveness remains inconsistent due to climatic and topographic variability, poor soil fertility, limited technical expertise, and restricted availability of adapted native plant species. This review highlights the importance of integrating hydroseeding with soil amendments, indigenous vegetation, and biological restoration approaches to support sustainable post-mining land management. These findings contribute to environmentally friendly reclamation strategies that improve soil restoration, ecosystem stability, and environmental health in tropical post-mining areas.

Keywords: carbon sequestration; ecological restoration; mine revegetation; sustainable reclamation; vegetation establishment

INTRODUCTION

Indonesia has extensive mining areas covering approximately 9.1 million ha nationwide (Ayudiana, 2024). However, mining activities contribute significantly to environmental degradation through deforestation, biodiversity loss, and soil and water pollution. In 2024, Indonesia lost approximately 175,000 ha of primary forest, equivalent to 14% of annual forest

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loss (The Jakarta Post, 2024). Mining activities also release trace metals such as chromium (Cr), nickel (Ni), lead (Pb), cobalt (Co), and zinc (Zn) into the environment (Pędziwiatr et al., 2018; Farrokhpay et al., 2019; Prematuri et al., 2020).

Heavy metal contamination decreases soil quality and health, induces plant toxicity, and reduces bacterial abundance and microbial biomass carbon (MBC) across various ecosystems (Briffa et al., 2020; Campillo-Cora et al., 2025). In addition, mining activities emit greenhouse gases, contributing approximately 4 to 7% of total anthropogenic emissions globally, thereby accelerating climate change (Setia et al., 2023; Diwasasri, 2025). Mining operations, such as blasting and drilling, also release particulate matter (PM) and toxic gases, including SO_2 and NO_2, which may negatively affect environmental and public health (Cao et al., 2022; Wahyono et al., 2024). Human exposure to mining-derived PM has been associated with cardiovascular disease, cancer, pneumonia, and respiratory tract infections (Annie et al., 2023). These impacts indicate that post-mining land degradation is not only an ecological issue but also closely related to environmental sustainability and public health concerns.

Land reclamation is therefore required to restore soil quality, recover ecosystem functions, and prevent further degradation (Hendrychová et al., 2020). However, degraded post-mining soils are characterized by low pH, poor nutrient availability, and unfavorable physical conditions that limit plant establishment and reduce reclamation success (Rahmi and Budiani, 2020). Hydroseeding is widely applied as a revegetation method for soil stabilization and erosion control (Anshari et al., 2018a). Nevertheless, hydroseeding effectiveness varies depending on substrate characteristics, seed composition, environmental conditions, and management practices (Baiti and Arisoesilaningsih, 2015; Mulyani, 2018; Pratiwi et al., 2021).

Previous studies on hydroseeding in Indonesia have primarily focused on technical revegetation performance and erosion control at specific mining sites. However, comprehensive reviews discussing the effectiveness of hydroseeding from the perspectives of soil restoration, environmental sustainability, and environmental health in tropical post-mining ecosystems remain limited. In addition, information on major constraints, ecological limitations, and future development opportunities for hydroseeding in Indonesia is still fragmented across individual case studies.

Therefore, this review aims to evaluate the effectiveness of hydroseeding for post-mining land rehabilitation in Indonesia by synthesizing findings from national and international studies. Specifically, it assesses vegetation establishment through hydroseeding and its role in restoring the physical, chemical, and biological properties of post-mining soils. Furthermore, it identifies current technical limitations, environmental constraints, and research gaps while highlighting the potential contribution of hydroseeding toward sustainable land management and environmental health improvement in tropical post-mining areas.

MATERIALS AND METHOD

This study employed a structured narrative review approach to synthesize scientific information on the application of hydroseeding for post-mining land rehabilitation, particularly in tropical ecosystems such as those in Indonesia. Relevant scientific literature published between 2015 and 2025 was collected primarily from Google Scholar using the keywords “hydroseeding”, “post-mining land reclamation”, “mine revegetation”, “soil restoration”, and “environmental recovery”.

The selected literature included national and international journal articles, conference proceedings, and scientific reports relevant to hydroseeding, revegetation, erosion control, and soil improvement in post-mining areas. Literature was selected based on the following inclusion criteria: (1) studies discussing hydroseeding or revegetation techniques in degraded or post-mining lands; (2) studies evaluating soil physical, chemical, or biological restoration; (3) studies related to vegetation establishment, erosion control, or environmental recovery; and (4) studies relevant to tropical or Indonesian post-mining conditions.

The collected literature was analyzed descriptively and critically to evaluate the effectiveness of hydroseeding, identify factors influencing reclamation success, and assess its role in soil restoration and environmental recovery. Particular attention was given to hydroseeding materials, seed composition, soil amendments, environmental constraints, vegetation performance, and ecological impacts reported across different mining landscapes.

Additionally, the selected literature was synthesized to identify current technical limitations, ecological constraints, and research gaps in hydroseeding applications for post-mining land rehabilitation, thereby providing a basis for future research and sustainable reclamation strategies.

RESULTS AND DISCUSSION

Overview of hydroseeding technology

Hydroseeding is a planting technique that involves mixing seeds, adhesive, mulch, fertilizer, and water to form a thick, porridge-like suspension. This mixture is then sprayed evenly over the entire soil surface (Yulianingsih and Arisoesilaningsih, 2015; Mulyani, 2018). Functionally, hydroseeding aims to stabilize the soil surface, prevent erosion, and accelerate the establishment of vegetation cover. The mulch layer plays a crucial role in minimizing evaporation, retaining moisture, suppressing weed growth, regulating soil temperature, and supporting soil microbial activity (Anshari et al., 2018a).

Mechanistically, hydroseeding (Figure 1), also known as hydraulic mulch seeding or hydro mulch, is performed by spraying a fiber-based slurry containing seeds and nutrients evenly across the target area (Verma et al., 2024). Once applied, the cellulose fiber mulch acts as an absorbent mat that retains sufficient moisture to facilitate rapid germination while also forming a cover layer that prevents soil erosion (Parsakhoo et al., 2018). The adhesive component in the slurry enhances seed adhesion to the soil surface, thereby reducing seed loss caused by wind or water erosion (Wersebeckmann et al., 2022).

Application of hydroseeding in post-mining land in Indonesia

Hydroseeding has been proven to be one of the most effective methods for accelerating vegetation growth on degraded land, such as former mines or roadsides (Clemente et al., 2016). Empirical studies in Indonesia provide strong evidence on the effectiveness of hydroseeding in restoring soil health in post-mining landscapes (Table 1). Hydroseeding can promote faster vegetation growth, accelerating ecological recovery and land stabilization. This technique has proven effective in post-coal-mining land in Kintap, Tanah Laut Regency, South Kalimantan (Figure 2). Hydroseeding applications with several pioneer species simultaneously increased soil cover within one month of application (Anshari et al., 2023).

The application of hydroseeding in a coal mining area at the West IPD site in Lati, East Kalimantan, with marginal soil at pH 3.7, increased the land cover value by up to 90%. The highest cover crop shown by *Centrosema pubescens*, *Calopogonium mucunoides*, and *Pueraria javanica* (Kirmi and Masyhuri, 2019). At the Tanjung Tabalong site in South Kalimantan, hydroseeding on former coal-mining land showed a higher plant density of 42.95% than conventional planting (Kissinger et al., 2019). Furthermore, the combination of hydroseeding with jute netting at the former Melak coal mine site in East Kalimantan reduced sediment accumulation by around 89.57% in the disposal

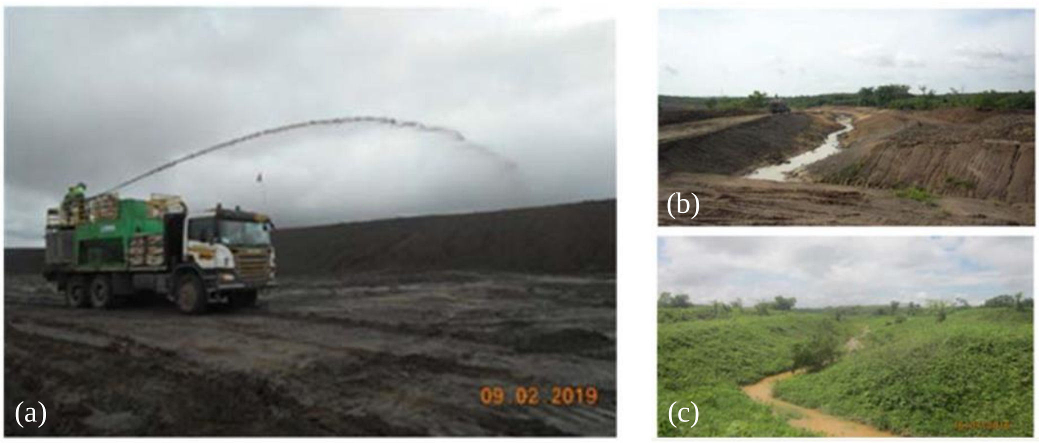

Figure 1. Hydroseeding application on ex-coal mining land, (a) during application, (b) before and (c) after five months of application (Pratiwi et al., 2021)

Figure 2. Hydroseeding trial plot on post-coal-mining land at Kintap, Tanah Laut, South Kalimantan, (a) before application and (b) one month after application (Anshari et al., 2023)

area and around 96.62% on the sloping mine slope (Bargawa et al., 2019).

Impact on vegetation establishment

The success of reclamation on former mining land is influenced by several factors, one of which is the selection of plants used. The selected plants should facilitate the process of natural succession and provide ecosystem services (Maiti et al., 2021), tolerate post-mining land conditions, produce high biomass, and establish quickly (Erfandi, 2016). Local plants from the families *Cyperaceae*, *Poaceae*, and *Leguminosae* have been shown to grow and thrive in greenhouse experiments using coal mine tailings (Rahma and Arisoesilaningsih, 2015; Azalia et al., 2016). Hydroseeding can reduce surface erosion in areas where vegetation and soil have been degraded, thereby supporting the regeneration of natural vegetation (Kolkos and Stergiadou, 2022). Plants from hydroseeding applications take 3 months to cover the surface of the steep post-mining slope with a growth percentage of up to 99.7% (Bargawa et al., 2019).

Vegetation growth using the hydroseeding method is much faster than conventional planting. The fast-growing pioneer species not only stabilize the soil surface but also improve microhabitat conditions and enable secondary plant species to inhabit the area. For example, the planting of pioneer crops in post-coal-mining revegetation areas in Tanjung Enim, Muara Enim Regency, South Sumatra Province, showed better results than in degraded natural forest areas (Yuningsih et al., 2021). Another study showed that pioneer plants hydroseeded were able to grow and survive in the post-coal-mining area in Kintap, Tanah Laut Regency, South Kalimantan. The *Poaceae* family used in that study showed rapid growth with shallow roots and good stolon development (Anshari et al., 2018a). This increased growth is due to the optimized nutrient delivery and moisture retention provided by the hydroseeding slurry, thus creating ideal germination conditions even in nutrient-poor growing mediums.

Hydroseeding plays a crucial role in restoring biodiversity and building ecosystem resilience in degraded post-mining landscapes. By incorporating native plant species into hydromulch formulations, hydroseeding enables the formation of diverse plant communities that support ecological balance and succession. The incorporation of local grasses (*Poaceae*), sedges (*Cyperaceae*), and legumes (*Fabaceae*) in the hydroseeding mixture ensures functional diversity, as these species contribute differently to nitrogen fixation, soil stabilization, and organic matter accumulation. Several species, such as *Cyperus eragrostis*, *C. brevifolius*, *C. odoratus*, *C. strigosus*, *Eleusine indica*, *Eulalia amaura*, *Paspalum conjugatum*, *Sorghum indicus*, *Cajanus cajan*, *Crotalaria pallida*, *Indigofera spicata*, *Desmodium triflorum*, and *Sesbania grandiflora*, have been shown to germinate and thrive in greenhouse experiments using former coal mine soil as a medium (Baiti and Arisoesilaningsih, 2015; Rahma and Arisoesilaningsih, 2015; Yulianingsih and Arisoesilaningsih, 2015; Azalia et al., 2016).

Further research on local species using former coal mine soil media showed that the highest germination rate was achieved by *Sesbania sesban*, while the fastest germination time was recorded for *C. pallida* and *S. sesban*, emerging within 2 days of sowing (Anshari et al., 2018b). The hydroseeding method applied in the coal mine reclamation area resulted in the fastest germination times for *Sorghum timorense*,

Table 1. Application of hydroseeding on several post-mining lands in Indonesia

No.	Mining type	Planted crops	Key soil findings	Time application	Source
1.	Coal mining (Site Tanjung Tabalong, South Kalimantan)	▪ *Acacia mangium* ▪ *Aquilaria malaccensis* ▪ *Neolamarckia cadamba (syn. Anthocephalus cadamba)* ▪ *Senna siamea (syn. Cassia siamea)* ▪ *Alstonia scholaris* ▪ *Falcataria moluccana (syn. Paraserianthes falcataria)*	▪ *A. mangium*, *S. siamea*, and *P. falcataria* have the highest tree dimensions among other species ▪ Hydroseeding results in tighter soil cover ▪ Erosion and weed disturbance decreased	2 months	Kissinger et al. (2019)
2.	Coal mining (Kintap, South Kalimantan)	▪ *Vigna unguiculata* ▪ *Sorghum* sp. ▪ *S. grandiflora* ▪ *S. sesban* ▪ *S. italica* ▪ *Adenanthera pavonina* ▪ *Aglaia* sp. ▪ *Koompassia* sp. ▪ *Macaranga* sp. ▪ *Polyalthia glauca* ▪ *Shorea lamellata* ▪ *Vatica* sp.	▪ Hydroseeding applications improved N-total, P-total, K-total, CEC, and bacterial diversity compared to 12-year-old manual monoculture cultivation ▪ Early hydroseeding planting results in a higher soil pH	▪ Old hydroseeding (5.5 years) ▪ Early hydroseeding (3 months)	Anshari et al. (2024)
3.	Coal mining (Kintap, South Kalimantan)	▪ *Sorghum* sp. ▪ *C. cajan* ▪ *Indigofera* sp. ▪ *S. sesban* ▪ *Themeda arundinacea*	Hydroseeding results in a higher soil pH and EC than forests	1 year	Anshari et al. (2023)
4.	Batu Kajang, East Kalimantan	▪ *Calopogonium pubescens* ▪ *C. mucunoides* ▪ *C. caeruleum* ▪ *S. grandiflora* ▪ *P. javanica* ▪ *Mucuna cochinchinensis*	Hydroseeding increases carbon sequestration by up to 21.8 tons ha^{-1}	3 years	Hadi and Amin (2025)
5.	Coal mining (West IPD, Lati, East Kalimantan)	▪ *C. mucunoides* ▪ *C. pubescens* ▪ *P. javanica* ▪ *Crotalaria usaramoensis*	▪ Reduces erosion rate by 79.62% ▪ pH value increased by 7.52% ▪ C/N ratio increased by 47.75% ▪ Covering area 90%	12–20 months	Kirmi and Masyhuri (2019)

Table 1. Continued

No.	Mining type	Planted crops	Key soil findings	Time application	Source
6.	Copper and gold mining (Batu Hijau, West Nusa Tenggara)	Hydroseeding: ▪ *Stylosanthes* sp. ▪ *Oryza sativa* ▪ *S. grandiflora* Fast-growing plants: ▪ *F. moluccana* ▪ *N. cadamba* ▪ *A. scholaris* ▪ *A. stipulata* ▪ *Melochia umbellata* ▪ *Lagerstroemia speciosa* ▪ *Syzygium polyanthum* ▪ *Parkia timoriana* ▪ *Sterculia foetida* ▪ *Albizia chinensis* ▪ *Albizia procera* ▪ *Tetrameles nudiflora* ▪ *Toona sureni*	▪ The density of the canopy increased so that the light intensity decreased by 323.84–686.43% ▪ Air humidity increased to 84.7% (natural forest 83.6%) ▪ Soil temperature 25.5 °C (slightly higher than forest soil temperature 24.7 °C)	8 years	Iskandar et al. (2019)

Note: CEC = Cation exchange capacity; EC = Electrical conductivity

Sorghum bicolor, *Setaria italica*, *C. cajan*, and *S. grandiflora*, which germinated within 1 day of planting. The species with the highest germination rates (≥ 50%) were *S. italica* (58 to 80%) and *S. bicolor* (50%). Based on seed germination rate, timing, and their properties, they are highly recommended for use in hydroseeding (Anshari et al., 2023).

Hydroseeding provides better vegetation cover and enrichment of target species than manual seed sowing. The use of fertilizers in hydroseeding on degraded and reclaimed land can enhance plant establishment (Wersebeckmann et al., 2022). Hydroseeding has been shown to improve seedling development and plant recovery in damaged desert grasslands by creating a suitable microenvironment and protecting seeds from extreme environmental conditions (Hakimovich and Alishovich, 2023). Hydroseeding treatments at Arch Coal's Birch River Operation in West Virginia resulted in a wider herbaceous cover (22 to 30%) compared to treatments without hydroseeding (3 to 12%). This suggests that hydroseeding is an important component of reclamation, as it significantly increases the total cover in hydroseeding areas when compared with non-hydroseeding areas (Thomas et al., 2015). Similarly, hydroseeding results in denser crown closure due to higher plant density compared to conventional methods (Kissinger et al., 2019).

Impact on soil restoration

Hydroseeding can accelerate landscape revegetation on slopes and marginal areas, such as post-mining tailings piles, within 3 to 5 years (Antonik et al., 2022). Studies in South Kalimantan show that hydroseeding mixtures of legumes, grasses, and shrubs effectively stabilize mine tailings piles, reduce surface erosion, and improve slope stability (Anshari et al., 2018a). Previous research has demonstrated that the use of hydroseeding for post-mining land rehabilitation can enhance soil fertility by improving its physical, chemical, and biological properties. A slurry mixture consisting of seeds, mulch, fertilizers, and organic matter alters the soil microenvironment by increasing water absorption, nutrient availability, and microbial activity. Organic mulch and soil conditioners serve as protective layers that reduce erosion, stabilize aggregates, and encourage the accumulation of organic matter. These processes collectively enhance the nitrogen cycle, improve soil porosity, and facilitate plant root penetration, thereby accelerating the overall reclamation process (Clemente et al., 2016).

The study showed that the application of hydroseeding in the West IPD coal mining area in Lati, East Kalimantan, also succeeded in reducing the erosion rate from 844.60 to 47.1 tons ha^{-1} year^{-1} after 1 year of revegetation. The pH value and C/N ratio increased from 3.90 to 4.22 and from 10.45 to 20.00, respectively, after 1 year and 8 months of application (Kirmi and Masyhuri, 2019). Hydroseeding with *A. mangium*, *S. grandiflora*, and *Calliandra* sp. resulted in higher soil nutrient content: total-N (0.25%), P_2O_5 (30.59 mg kg^{-1}), K_2O (14.65 mg kg^{-1}), soil pH (5.15), CEC (33.42 cmol kg^{-1}), and bacterial diversity (Shannon index = 9.46), compared to 12-year-old monoculture revegetation areas (total-N = 0.18%). This indicates simultaneous physical and biological restoration of soil systems (Anshari et al., 2024). Hydroseeding also promotes the development of root systems, which significantly increase aggregate stability and reduce soil bulk density (Durand et al., 2024).

The presence of plant roots can affect soil structure and increase macroporosity by up to 30%. In addition, plant roots can alter rhizosphere hydraulics by absorbing water and increasing moisture content at certain matrix potentials. Research shows that the presence of root hairs can reduce soil hardness by up to 50% and soil elasticity by up to 36%. This is due to the modification of the soil structure by the root hairs and the diffusion of exudates within the soil mass (Marin et al., 2022). Similar trends have also been observed internationally. At Arch Coal's Birch River Operation in West Virginia, the application of hydroseeding increased soil pH (5.5 to 7.7) compared to untreated plots (5.0 to 7.0). It significantly increased MBC (17.5 vs 8.7 mg kg^{-1}) and potentially mineralized nitrogen (PMN, 0.81 to 0.92 vs 0.22 to 0.35 mg kg^{-1}) (Thomas et al., 2015).

Implications for environmental health

Post-mining land rehabilitation through hydroseeding not only accelerates vegetation recovery but also contributes to climate change mitigation by enhancing carbon sequestration. Rapid vegetation growth reduces erosion and nutrient loss, while promoting soil stabilization and improving water quality (Vourlitis et al., 2022). As plant cover grows, biodiversity and carbon inputs into the ecosystem increase through litterfall, root turnover, and mulch decomposition (Anshari et al., 2018a). Aboveground plant growth promotes the development of substrates underground, which triggers microbial growth; a significant increase in biomass contributes to higher total nitrogen and soil organic carbon (SOC) (Ossanna et al., 2023). Leaf litter from planted vegetation is one of the main sources of SOC at reclaimed sites and, over time, is related to SOC accumulation (Misebo et al., 2022). Hydroseeding on reclaimed land in Riam Adungan Village, Kintap, Tanah Laut, South Kalimantan, also showed a significant increase in SOC with increasing revegetation age (Anshari et al., 2024).

A legume cover crop (LCC) planted using hydroseeding on reclaimed land in Batu Kajang, Paser, East Kalimantan can prevent erosion, increase the fertility of revegetation land, and enhance carbon stocks by 21.8 tons ha^{-1} (Hadi and Amin, 2025). In Melak, East Kalimantan, hydroseeding combined with hemp nets reduced sediment yield by 89.57% at coal mine disposal sites, thereby reducing the level of environmental pollution (Bargawa et al., 2019). The biochar used in hydroseeding mixtures not only changes the physicochemical properties of the former mine soil but also helps provide a source of carbon for microbes and fungi. In addition, the combination of hydroseeded cover crops and trees showed positive effects over the growing time. Multispecies blends result in better soil cover, which improves the microclimate around plants, reduces evaporation, and maintains soil temperature (Asmara et al., 2023).

Limitation and challenges

Low soil fertility

One of the main challenges in post-mining land reclamation is the low fertility and poor structural condition of the remaining soils. The alternative soil substrates commonly used for reclamation, such as overburden and mine spoil, often lack essential nutrients for seed germination, seedling establishment, and long-term vegetation growth (Kneller et al., 2018). Unlike vegetation recovery on contaminated soils, restoring soil quality is considerably more complex, as it requires the reestablishment of interrelated physical, chemical, and biological properties (Morató et al., 2017; Wang et al., 2021). In addition, mining operations frequently cause severe soil compaction and the disruption of natural soil horizons, which further reduce microbial activity and nutrient cycling. Moreover, large-scale land clearing during mining operations leads to habitat fragmentation and biodiversity loss, exacerbating the difficulty of restoring a functional ecosystem (Fernandes et al., 2024).

Open-pit mining causes severe and often irreversible damage to soil structure and ecosystem function, primarily through the removal of fertile topsoil and the disruption of natural succession process (Soliveres et al., 2021). Mining activities such as drilling, blasting, and road construction significantly alter soil structure, while the movement of heavy machinery induces compaction that reduces soil permeability and aeration, thereby inhibiting root penetration and water infiltration. Land clearing during mining increases soil susceptibility to erosion and surface runoff, followed by deterioration in soil quality. Runoff debris potentially leads to sedimentation in adjacent water bodies, which can harm aquatic ecosystems. Moreover, mineral processing frequently involves the use of chemical reagents that discharge hazardous pollutants into the environment. Mining waste, groundwater, and surface drainage often exhibit extremely acidic or alkaline pH levels and high metal concentrations (Leila et al., 2020).

Water used in the mineral refining process produces liquid waste containing heavy metals, acids, and other harmful compounds. Without adequate management, the processing or disposal of this wastewater can cause water contamination, disturb river ecosystems, and damage aquatic life (Duncan, 2020). The mineral refining process also generates solid waste, such as tailings or waste rock. Improper tailings management pollutes water and soil through the discharge of heavy metals or radioactive materials. In addition, large-scale tailings disposal can result in landslides and other major environmental harm (Kaninga et al., 2020).

In Indonesia, post-mining degraded soil is characterized by poor physical and chemical properties, severely limiting plant growth. Among these constraints, heavy metal contamination is also one of the most critical environmental challenges associated with mining activities in the country (Table 2). For instance, tin-bearing land in the Bangka Belitung region is characterized by sandy loam soil with a poorly structured (loose) profile due to low nutrient status, low organic carbon content, and low pH value. These soils are also known to contain high concentrations of heavy metals, such as Cu, Pb, and Hg (Sukarman and Gani, 2017; Wulandari et al., 2022). Former gold mining sites also have mercury-contaminated soil with very low pH values and low nutrient availability (Pambudi et al., 2017; Gusmini et al., 2024; Nuriman et al., 2025).

Similar constraints of soil fertility are found in post-coal mining sites (Pambudi et al., 2017; Gusmini et al., 2024; Thaharah et al., 2024; Nuriman et al., 2025). In contrast, post-nickel mining soils tend to exhibit relatively higher pH values. However, they remain acidic and are still characterized by low nutrient availability, with metal contaminants such as Fe, Mn, and Ni commonly detected (Akib et al., 2019; Iskandar et al., 2024).

The accumulation of heavy metals in post-mining soil leads to severe degradation of soil quality and biological health. Toxic metals impair microbial activity, inhibit plant growth, and reduce soil fertility (Briffa et al., 2020). Heavy metals can accumulate in the human body through the food chain or other exposure pathways, causing organ damage and triggering various diseases. Heavy metals can also accumulate in plants through bioaccumulation (Hu et al., 2024). At the plant level, heavy metal exposure induces chlorosis, suppresses photosynthesis, reduces biomass accumulation, and causes oxidative stress, leading ultimately to cell damage and mortality (Collin et al., 2022).

Climate variability

Indonesia, as a humid tropical country, experiences diverse climatic conditions, including heavy rainfall and prolonged dry seasons (Pratiwi et al., 2021). These climatic fluctuations influence the success of hydroseeding. Drought is a major limiting factor for plant growth, especially in tropical countries. It causes oxidative stress and inhibits root penetration due to hard soil. Prolonged drought disrupts protein synthesis, nitrogen assimilation, and cell membrane activity (Zia et al., 2021). Drought stress often becomes the primary cause of seedling mortality, necessitating supplemental irrigation during critical early growth stages. Water is considered a key regulator of germination because it plays a role in enzymatic reactions and the mobilization of lipid, carbohydrate, and protein reserves. Water deficiency inhibits the enzymes involved in starch

Table 2. Soil chemical and physical properties and heavy metal concentration in coal and mineral mining

Mining type	Soil properties after mining	Heavy metal concentration	Source
Tin (Bangka Belitung)	▪ Coarse material (20–30%) ▪ pH (4.3–5.3) ▪ Organic C (0.05–0.62%) ▪ Available P (0.98–16.91 mg kg^{-1}) ▪ Total K (0.64–1.75 mg kg^{-1}) ▪ CEC (1.19–4.03 cmol 100 g^{-1}) ▪ BS (15–64 %)	▪ Cu (0.43–0.94 ppm) ▪ Pb (0.65–37.84 ppm) ▪ Hg (0.01–0.82 ppm)	Sukarman and Gani (2017)
Tin (Sungailiat, Bangka Belitung)	▪ Sand percentage (87.83%) ▪ pH (4.97) ▪ Organic C (0.08%) ▪ Total N (0.02%) ▪ Available P (2.43 ppm) ▪ Exchangeable K (0.95 me 100 g^{-1}) ▪ CEC (0.79 me 100 g^{-1})		Wulandari et al. (2022)
Gold (Wonogiri, Central Java)		▪ Hg (1–80 ppm) ▪ Mn (80–1300 ppm) ▪ As (11–134 ppm) ▪ Pb (598 ppm)	Pambudi et al. (2017)
Gold (Nagari Padang Sibusuak, Sijunjung, West Sumatera)	▪ pH (3.90) ▪ Organic C (0.29%) ▪ Total N (0.06%) ▪ Available P (2.85 ppm) ▪ Exchangeable K (0.07%) ▪ CEC (7.44 cmol kg^{-1}) ▪ BS (0.43 cmol kg^{-1})	Hg (32.50 ppm)	Gusmini et al. (2024)
Gold (Bengkayang, West Kalimantan)	▪ pH (3.53) ▪ Organic C (0.91%) ▪ Total N (0.17%) ▪ Available P (13.04 ppm) ▪ Exchangeable K (0.07 cmol kg^{-1}) ▪ CEC (9.83 cmol kg^{-1}) ▪ BS (6.82%)	Hg (11.60 mg kg^{-1})	Nuriman et al. (2025)
Coal (Tanjung Redeb, Berau, East Kalimantan)	▪ BD (1.6 g cm^{-3}) ▪ pH (4.1) ▪ Organic C (0.53%) ▪ Total N (0.05%) ▪ Total K (10.7 mg kg^{-1}) ▪ CEC (1.98 cmol kg^{-1}) ▪ BD (1.51 g cm^{-3}) ▪ BS (33.9 %)		Iskandar et al. (2022)
Coal (South Kalimantan)	▪ pH (5.10) ▪ Total N (0.07%) ▪ Total P (6.42 mg 100 g^{-1}) ▪ Total K (1.95 mg 100 g^{-1})		Thaharah et al. (2024)
Nickel (Gag, Raja Ampat, Southwest Papua)	▪ pH (5.25–6.62) ▪ Organic C (0.23–1.77%) ▪ Total N (0.01–0.09%) ▪ Available P (1.84–10.10 ppm)	▪ Fe (2.2–4,188.4 ppm) ▪ Mn (25.4–84.1 ppm)	Iskandar et al. (2024)

Table 2. Continued

Mining type	Soil properties after mining	Heavy metal concentration	Source
	▪ Total P (3.36–6.53 mg 100 g^{-1}) ▪ Exchangeable K (0.01–0.20 cmol kg^{-1}) ▪ CEC (1.67–16.89 cmol kg^{-1}) ▪ BS (7.8–33.8%; 43.7–100%)	▪ Fe (2.2–4,188.4 ppm) ▪ Mn (25.4–84.1 ppm)	Iskandar et al. (2024)
Nickel (Sorowako, East Luwu, South Sulawesi)	▪ pH (5.62) ▪ Organic C (1.88%) ▪ CEC (9.63 cmol kg^{-1}) ▪ BS (69%)	Ni (1.42%)	Akib et al. (2019)
Gold (Lombok, West Nusa Tenggara)	▪ pH (7.26±0.11) ▪ Organic C (0.24±0.01%) ▪ Total N (0.034±0.00%) ▪ Available P (11.69±0.09 ppm) ▪ Available K (0.56±0.04 cmol kg^{-1})	Hg (23.19±0.03 mg kg^{-1})	Ustiatik et al. (2022)

Note: CEC = Cation exchange capacity; BD = Bulk density; BS = Base saturation

hydrolysis (Sghaier et al., 2022). Supplemental irrigation during these critical stages has been shown to maintain 60 to 75% of seedlings through the first year, emphasizing the need for water management strategies at reclamation sites (Antonik et al., 2022).

Climatic conditions also determine land suitability for specific plant species, meaning that a given location is only suitable for a limited range of crops or vegetation types. Land evaluation studies in Indonesia have demonstrated that agroclimatic factors, particularly rainfall distribution, temperature, and water availability, play a decisive role in determining land suitability and plant selection (Mujiyo et al., 2017). This principle is highly relevant to post-mining reclamation, where inappropriate species selection under unsuitable climatic conditions can result in poor revegetation performance and hydroseeding failure.

As an archipelagic nation, Indonesia is highly vulnerable to climate change. When rainfall is insufficient to meet crop water requirements and groundwater consumption, salt accumulation in the environment occurs, resulting in soil salinity (Oelviani et al., 2024). In coastal reclamation areas, low rainfall and high evapotranspiration rates promote salt accumulation in the soil, leading to salinity stress that inhibits seed germination. Under saline conditions, osmotic imbalance prevents water uptake by seeds, while excessive Na^{+} and Cl^{-} accumulations cause ion toxicity and oxidative damage in developing embryos (Atta et al., 2023). These conditions reduce the effectiveness of hydroseeding by limiting seed viability and early seedling establishment.

Conversely, reclamation sites in mountainous or high-rainfall regions face the opposite challenge, where intense precipitation can accelerate soil erosion and nutrient leaching (Song et al., 2025). Heavy rainfall can wash away hydroseeding substrates and disrupt vegetation establishment, while steep slopes further exacerbate surface runoff. Climate change amplifies these site-specific risks by increasing the frequency and intensity of extreme weather events, driven by phenomena such as the El Niño-Southern Oscillation (ENSO). The impact of ENSO is twice as high in tropical regions, including Indonesia. Geographically, several regions, such as North Maluku, Bali, North Kalimantan, South Kalimantan, East Kalimantan, and all provinces on Sulawesi Island, are most affected by ENSO (Malau et al., 2023). Extreme weather changes impact the success of hydroseeding techniques by increasing the risk of failure due to water scarcity and erosion (Sunandar and Prananda, 2020).

The success of hydroseeding in Indonesia is highly dependent on regional climatic characteristics. A uniform application strategy is unlikely to succeed across the Indonesian archipelago due to variations in temperature, rainfall, and seasonal patterns. Rising temperatures lead to increased evapotranspiration, decreased water availability, and intensify drought stress, thus disrupting plant growth (Nahazanan et al., 2021). Conversely, low soil temperatures reduce the production of phyto-siderophores and iron uptake, leading to chlorosis and nutrient deficiency. It also increases bicarbonate levels in the soil solution, which increases iron deficiency. Fluctuating precipitation patterns lead to changes in the behavior of plant pathogens and pests. For example, *Phytophthora capsici* thrives under high soil moisture (Elias et al., 2019), which potentially increases disease risk in reclamation areas. Hydroseeding experiments on former coal mine soils have also shown that excessive soil moisture and acidity can promote fungal growth, thereby reducing germination success and early plant growth (Anshari et al., 2018a).

Regional climate disparities further influence the effectiveness of hydroseeding. Eastern Indonesia, such as Nusa Tenggara and parts of Sulawesi, experiences a longer dry season than western Indonesia, including Sumatra, Kalimantan, and West Java (Rejekiningrum et al., 2022). This influences land management strategies and plant selection for hydroseeding. Regions with prolonged dry seasons require drought-tolerant species such as *Acacia* and *Sesbania*. Studies in agroclimatic regions of Indonesia have shown that species such as *S. sesban* and *Acacia* spp. can grow well in drylands and are suitable for the revegetation of critical land. Furthermore, local species can also be used for hydroseeding due to their greater adaptability to environmental conditions. The greater adaptability of endemic plants increases their survival and effectiveness in controlling erosion (Nasir et al., 2024).

Conversely, western regions such as Sumatra, Kalimantan, and West Java receive higher annual rainfall and demand stronger erosion control measures than eastern regions. The application of biodegradable materials such as coconut fiber netting, burlap, or palm fiber-based erosion control blankets is effective for stabilizing soil in areas with high rainfall (Jahja et al., 2024). Research shows that the application of hydroseeding with jute netting in Melak reduced erosion during the early observation period, but erosion rates increased as rainfall intensified (Bargawa et al., 2019). Therefore, integrating regional climate profiles, plant selection, and erosion-control design into hydroseeding planning is critical to achieving resilient and site-specific reclamation outcomes across Indonesia's diverse landscape.

Limited technical expertise

Effective hydroseeding implementation requires multidisciplinary expertise in soil science, hydrology, and plant ecology, which is currently limited in many mining areas in Indonesia (Pratiwi et al., 2021; Anshari et al., 2024). This shortage is caused by the lack of formal training and education programs specifically designed for hydroseeding technology. Local operators lack the technical understanding needed to select native species suited to specific microclimates, optimize seed mixtures, or assess soil properties, leading to suboptimal vegetation recovery. To address these limitations, recent studies have suggested the development of standardized species-selection protocols that utilize ecological modeling and software-based tools to identify native species functionally similar to those in undisturbed forests (Xu et al., 2024).

Without proper training, reclamation projects often fail to account for site-specific challenges, such as poor soil quality or slope instability. This further hampers the success of post-mining land reclamation. The application of hydroseeding at a former coal mine site in Paringin, South Kalimantan, showed that the installation of jute nets on the mine pit wall surface resulted in relatively high erosion prevention and geochemical stability. However, the net installation process has a high level of safety risks due to unstable wall conditions (Triwibowo et al., 2024). In Tanah Laut, South Kalimantan, hydroseeding application on former coal mining land showed the importance of proper formulation and mulch thickness for successful seed germination. Thinner hydroseeding mulch with a higher seed density resulted in better germination rates (Anshari et al., 2018a). In Sulawesi, the addition of compost to marginal soils with acidic pH improved the growth, yield, and survival of cocoa trees during the dry season (Mulia et al., 2019).

Beyond technical limitations, the dependency on foreign consultants underscores a broader capacity gap in Indonesia's reclamation sector. Multinational companies struggle to secure sufficiently skilled labor and often rely on foreign workers for complex projects. However, the involvement of these foreign experts is generally short-term and insufficient to build sustainable capacity among local workers (Boschee, 2023).

Furthermore, studies on Foreign Direct Investment (FDI) spillovers in Indonesia also show that knowledge transfer and local workers' capacity development remain suboptimal, despite the presence of foreign experts with advanced technology and expertise. Local companies still experience limited efficiency and productivity due to a lack of adequate training and human resource development, resulting in a high dependence on foreign workers (Fawait et al., 2024).

A self-sufficient restoration system is essential, incorporating socio-ecological aspects adaptively to encourage the participation and diversity of local workers. Restoration activities must be designed and implemented by local practitioners to achieve long-term sustainability. This also shows that reliance on foreign experts without strengthening the capacity of local workers can hinder the success of adaptation and restoration efforts (Frietsch et al., 2023).

The availability of adapted local seeds

The effectiveness of hydroseeding also depends on the selection of plant species that are adaptive to local environmental conditions. In Indonesia, however, obtaining fast-growing native seeds suitable for degraded mining areas remains a significant challenge. Native species have developed unique adaptations to regional environmental stressors and are crucial for ecological restoration (Rivière et al., 2022). Yet, the limited commercial availability of native seeds means the reclamation projects rely on alternative, generic, or non-native species, which often fail to thrive in Indonesia's diverse microclimates. This scarcity of native seed is primarily due to underdeveloped systems for seed collection, processing, and distribution, particularly in remote mining areas (Anshari et al., 2023). Without access to region-specific seeds, hydroseeding efforts struggle to establish resilient vegetation capable of stabilizing soils and restoring ecosystems.

Technical constraints in seed propagation further exacerbate this issue. Many native species in Indonesia have complex germination requirements. In Central Sulawesi, for example, nutmeg seeds (*Myristica fragrans* Houtt.) exhibit complex dormancy and require special treatments such as full scarification to increase germination rates to 96.66% (Dharma et al., 2015). Similarly, *Dictyoneura acuminata* Blume from Kalimantan demonstrates light-dependent germination patterns (Wardani and Latifah, 2016). This adds to the complexity of native plant seed propagation. Another study conducted in East Kalimantan showed that the successful growth of native species planted on post-coal mining reclamation land is influenced by seed visibility. Furthermore, the limited availability of natural populations also hampers large-scale revegetation (Lestari et al., 2019). *Macaranga* spp. often grows in post-mining areas and is part of revegetation efforts. However, low soil pH and poor nutrient availability, coupled with low potential seed viability and small natural populations, make the use of this species less effective (Fikriah et al., 2024).

The reliance on non-native species as substitutes presents additional ecological risks. The use of non-native species can cause "genetic pollution," leading to ecological incoherence and disruption of ecosystem functioning. It can also lead to the spread of plant pathogens, fungi, or predatory insects that can harm native species (Rivière et al., 2022). For example, the widespread introduction of *A. mangium* has triggered a rapid biological invasion and has become an invasive plant in Asia, including Indonesia, as well as in South Africa and South America. Its high adaptability to marginal soils makes *A. mangium* often used for the conservation of degraded ecosystems. Planting *A. mangium* can help improve N and C cycling in the soil, and increase P availability. However, the species is increasingly showing its invasiveness. This poses a threat to biodiversity, particularly due to its high competitiveness with native trees (Koutika and Richardson, 2019).

Moreover, non-native plants frequently fail to provide habitat for local wildlife, diminishing the ecological functionality of restored sites. They can cause hydrological damage by altering physiological services, behavior, and species interactions. This is exacerbated when non-native species function as ecosystem engineers or transformers. Non-native plant invasions can alter seasonal patterns of water availability (Catford, 2017). Inappropriate use of species leads to a decline in local species biodiversity, ecosystem services, and carbon sequestration potential.

Local plants have higher survival rates than exotic plants. However, the success of using local species in hydroseeding remains limited due to low germination rates and limited availability (Anshari et al., 2018).

Fragmented seed supply chains further limit accessibility. In Indonesia, the government has begun establishing a seed industry with the support of the World Bank and has introduced regulations for a seed certification system. Seed quality is a crucial factor that influences crop production. Seed availability and easy access directly impact seed viability (Qadir et al., 2024). Reclamation, as mandated by Law No. 4 of 2009 on Mineral and Coal Mining and Government Regulation No. 78 of 2010 on Reclamation and Post-Mining, aims to restore environmental and ecological functions (Karyono and Santiago, 2018). However, the limited availability of high-quality native seeds often delays project implementation and undermines compliance with post-mining restoration requirements. Strengthening national seed networks, promoting native seed research, and developing regional seed banks are therefore essential steps toward improving the sustainability and effectiveness of hydroseeding-based reclamation in Indonesia.

CONCLUSIONS

Hydroseeding serves as a vital and established reclamation technique for post-mining land rehabilitation in Indonesia. Supported by existing regulatory frameworks–including Law No. 3 of 2020 on Mineral and Coal Mining, Government Regulation No. 78 of 2010, Minister of Energy and Mineral Resources Decree No. 111.K/MB/04.02/2024, and the 2015 Ministry of Public Works and Housing Guidelines–it effectively accelerates early vegetation establishment and significantly reduces erosion in degraded landscapes. The application of hydroseeding goes beyond surface revegetation; it actively contributes to the restoration of the soil's physical, chemical, and biological properties, thereby enhancing surface stability, moisture retention, and nutrient availability. This vegetative establishment further supports critical microbial development and rhizosphere recovery, which are necessary for long-term soil function and environmental health. However, this review also highlights several ongoing limitations, including occupational safety risks, constraints in native seed and nutrient availability, heavy metal toxicity, and extreme climate variability. Additionally, the characteristic uniform seed distribution of hydroseeding can increase interspecific plant competition and limit overall vegetation diversity. Because current studies are still heavily dominated by evaluations of superficial vegetation performance, future research must shift toward assessing soil biological recovery and holistic ecosystem functions. It is highly recommended that subsequent studies also cover broader sectors related to public health impacts and the economic evaluation of hydroseeding applications to ensure sustainable and safe post-mining land management.

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DECLARATION OF GENERATIVE AI USE

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