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## MINE LAND RECLAMATION AND RESTORATION: A REVIEW

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### ABSTRACT

Mining operations seriously degrade soil ecosystems, resulting in decreased fertility, a decline in biodiversity, and ecosystem instability by altering the physical, chemical, and biological characteristics of soil. Mine land reclamation has therefore become crucial in order to restore soil productivity and ecological sustainability in degraded mining sites. This review examines the effects of mining on soil ecosystems in addition to summarizing traditional reclamation techniques such as soil amendment, nitrogen management, microbial restoration, and revegetation strategies for enhancing soil quality and ecosystem recovery. Recent developments in restoration approaches are also covered, including the use of biochar, microbial biotechnology, remote sensing-based monitoring, and nature-based solutions, which improve restoration effectiveness and long-term sustainability. The review further discusses major challenges, such as severe soil degradation, sluggish biological process recovery, and restrictions on long-term monitoring of reclaimed ecosystems. Reclamation of mine land contributes to sustainable land management, having components including promotion of environmental resilience, increased land-use efficiency, and restoration of ecosystem services. Integrated restoration techniques are required for achieving ecological stability and sustainable post-mining landscapes.

**Key words:** Mining, reclamation, soil management, physical, chemical, and biological properties

### Introduction

Mining is crucial to the world economy, as it supplies vital raw materials for numerous sectors, such as manufacturing, infrastructure development, and energy generation. However, large-scale mining activities are the indirect causes of organic matter degradation and environmental contamination, including soil erosion, loss of agricultural land, deforestation, decreased soil moisture, depletion of water resources, decreased microbial activity, and ground subsidence in mining regions (Feng *et al.*, 2019; Skousen *et al.*, 2017). These disturbances limit ecosystem functioning and long-term land productivity and release soil carbon, contributing to climate change (Gregorich *et al.*, 1989; Tordoff *et al.*, 2000; Xu *et al.*, 2025).

Large-scale mine spoils and overburden dumps are produced worldwide by mining operations, and their successful reclamation is necessary to restore ecosystem

services and environmental sustainability. The necessity for sustainable restoration solutions is highlighted by the rapid expansion of mining activities in India, which has further escalated land degradation.

While land reclamation aims to improve disturbed land to reach a stable and productive condition comparable to its pre-disturbed state through soil reconstruction, vegetation establishment, and nutrient cycling processes (University of Alberta, 2005), ecological restoration refers to the recovery of ecosystems that have been degraded or damaged by human activities (Society for Ecological Restoration, 2004). Both strategies seek to restore ecosystem functionality and long-term environmental stability, despite their differing scopes.

Soil is an essential part of mine land restoration since it controls ecosystem processes, nitrogen cycling, and plant establishment. Mining activities hinder vegetation growth and ecological recovery by altering microbial populations, reducing fertility, and disrupting soil structure

(Sheoran *et al.*, 2010; Mao *et al.*, 2024). Therefore, restoring the physical, chemical, and biological characteristics of soil through suitable management techniques is necessary for sustainable reclamation.

Vegetation establishment plays a fundamental role in restoring degraded mine lands by stabilizing soil, boosting organic matter buildup, increasing nutrient availability, and promoting microbial activity. Effective revegetation aids in erosion prevention and ecosystem recovery by creating stable nutrient cycles (Singh *et al.*, 2002; Wong, 2003; Skousen *et al.*, 2017).

In recent mine land reclamation strategies, integrated ecological restoration frameworks that encompass soil management, vegetation development, microbial processes, and environmental monitoring technologies have replaced traditional engineering approaches (Xu *et al.*, 2025; Chen *et al.*, 2024). However, challenges with soil deterioration and long-term ecosystem sustainability persist, underscoring the need for a thorough understanding of restoration procedures and cutting-edge technologies.

This review discusses current knowledge on the effects of mining on soil ecosystems and assesses major approaches for mine soil reclamation and restoration, with a focus on emerging technologies, challenges, research gaps, and future directions for sustainable management of degraded mine lands.

### Impacts of Mining on Soil Ecosystems

Mining operations significantly change soil ecosystems by disrupting soil structure, chemistry, and biological processes. Surface mining produces large volumes of waste rock and overburden materials with coarse fragments, no developed horizons, and poor physical structure. These disturbed substrates are often characterised by low organic matter, high bulk density, reduced water-holding capacity, and high metal concentrations, thereby constraining plant establishment and ecosystem recovery (Feng *et al.*, 2019; Xu *et al.*, 2025).

### Physical Degradation of Mine Soils

Mining operations significantly alter soil texture, aggregation, and compaction. High percentages of coarse pieces (>50%) are commonly found in overburden dumps, which decrease nutrient availability and moisture retention. According to Skousen *et al.* (2017), heavy machinery traffic during excavation and spoil deposition increases soil compaction, which results in reduced aeration, restricted root penetration, and elevated bulk density (>1.7 Mg m<sup>-3</sup>). Further, slope instability and erosion concerns are exacerbated in compacted mine soils due to low

infiltration rates and higher surface runoff.

Also, topographic alterations, such as steep slopes and unstable landforms, worsen soil erosion and sediment transport. Acid mine drainage (AMD), which is caused by the oxidation of sulphide minerals, can intensify physical degradation by speeding up weathering processes and destabilizing soil aggregates. As a result, mine soils frequently continue to be structurally brittle and extremely vulnerable to environmental stress (Gregorich *et al.*, 1989).

### Chemical Alterations and Nutrient Imbalance

The chemical characteristics of soil, especially pH and nutrient availability, have been substantially altered by mining-induced soil disturbance. According to Tordoff *et al.* (2000), oxidation of pyritic materials can cause soil pH to drop to extremely acidic levels (pH < 4), which increases metal solubility and plant toxicity. On the other hand, alkaline conditions in carbonate-rich spoils may restrict the availability of micronutrients (Gitt and Dollhopf, 1991). Since topsoil and organic matter are removed, mine soils are usually lacking in important macronutrients, including nitrogen (N), phosphorus (P), and potassium (K). Low quantities of organic carbon restrict microbial-mediated mineralization processes and hinder nutrient cycling (Maiti and Ghose, 2005; Mao *et al.*, 2024). Depending on pH and redox circumstances, elevated amounts of heavy metals, including Fe, Mn, Zn, and Cu, may further impede plant growth (Feng *et al.*, 2019).

Leaching and drainage from acid mines can contaminate nearby soils and waterways, endangering ecological health and agricultural systems. Therefore, in mined landscapes, chemical deterioration severely limits soil productivity and ecological resilience (Maiti and Ghose, 2005)

### Biological Disruption and Loss of Soil Function

Mining severely disrupts soil biological communities, which are crucial for preserving soil structure, nutrient cycling, and plant-soil interactions. Removal and stockpiling of topsoil decrease microbial biomass, enzyme activity, and functional diversity. Arbuscular mycorrhizal fungi (AMF), which are essential for nutrient uptake and plant establishment, are among the symbiotic relationships that are disrupted by soil disturbance (Edgerton *et al.*, 1995; Gould *et al.*, 1996).

Decreased microbial activity delays nutrient cycling and ecosystem recovery by slowing the breakdown of organic matter and the mineralization of nitrogen. Studies have shown that while vegetation may reappear in a few years, soil microbial communities and functional processes frequently take much longer to recover (Franklin *et al.*,

2012; Xu *et al.*, 2025).

Reduced aggregate stability and decreased soil resilience are the outcomes of physical compaction, chemical stress, and loss of soil biodiversity. Consequently, biological degradation represents one of the most persistent challenges to effective mine land restoration (Edgerton *et al.*, 1995).

### **Conventional Mine Soil Reclamation Techniques**

In order to promote vegetation establishment and ecosystem recovery, mine soil reclamation entails restoring the physical structure, chemical fertility, and biological functioning of the soil. Conventional reclamation approaches primarily emphasize soil amendment, nutrient management, revegetation, and ecological stabilization of damaged mine substrates (Franklin *et al.*, 2012; Skousen *et al.*, 2017).

### **Restoration of Soil Physical Structure**

Reconstruction of soil physical properties is an essential step in mine land reclamation. Mining operations often lead to compacted substrates. Compacted substrates with poor aggregation, low porosity, and restricted water-holding capacity (Swamy *et al.*, 2025). Mechanical loosening, grading, and replacement of suitable growth media are commonly carried out to reduce compaction and improve soil structure. By replacing exchangeable sodium with calcium, the application of soil amendments such as gypsum improves aggregation, increases water infiltration, and decreases sodicity (Ghose, 2005).

Restoring soil productivity requires effective topsoil management. Replacement of recovered topsoil improves soil structure, moisture retention, and microbial activity. However, prolonged stockpiling of topsoil may lower nutrient availability and biological activity, thereby limiting its effectiveness during reclamation (Sheoran *et al.*, 2010). In reclaimed lands, soil stability is enhanced, and erosion is further reduced by stabilizing slopes and reshaping damaged landforms (Jeldes *et al.*, 2013).

### **Amendment of Soil Chemical Properties**

Mine soils usually have extremely high pH levels and nutrient deficits due to the removal of topsoil and oxidation of sulphide minerals. (Maiti and Ghosh, 2005). Calcium carbonate and other liming minerals are frequently used to improve plant growth conditions by neutralizing soil acidity and lowering metal toxicity. On the other hand, to increase nutrient availability, alkaline mine spoils may require the inclusion of organic matter or acidifying additives to improve nutrient availability (Gitt and Dollhopf, 1991; Tordoff *et al.*, 2000).

The application of organic and inorganic amendments,

such as fertilizers, compost, and organic wastes, improves soil organic carbon and nutrient availability and restores soil fertility. The establishment of nitrogen-fixing legumes is usually practised to enhance nitrogen supply and promote long-term nutrient cycling in reclaimed soils (Singh and Raghubanshi, 2002). The development of an organic matter pool is especially required for improving phosphorus availability and sustaining soil productivity (Arneeth *et al.*, 2021).

### **Restoration of Soil Biological Function**

Reclamation practices also prioritize restoring soil biological activity, which regulates soil aggregation, organic matter decomposition, and nutrient cycling. Ecosystem recovery is accelerated by the addition of organic amendments and topsoil, which increase microbial biomass and enzyme activity. Re-establishment of beneficial microorganisms, including nitrogen-fixing bacteria and arbuscular mycorrhizal fungi, increases soil fertility and improves plant nutrient uptake (Gould *et al.*, 1996; Mao *et al.*, 2024).

However, recovery of soil biological processes is often slow due to low organic carbon content and unfavourable chemical conditions in mine spoils (Song *et al.*, 2024). Therefore, management techniques that promote microbial activity and rhizosphere development are essential for the long-term sustainability of reclaimed ecosystems.

### **Revegetation and Ecological Stabilization**

Revegetation is an essential component of mine land reclamation since plant cover stabilizes soil, lessens erosion, and promotes the buildup of organic matter (Franklin *et al.*, 2012; Song *et al.*, 2024). For restoration to be successful, stress-tolerant plant species that can endure in nutrient-poor and metal-contaminated environments must be chosen. Native species are typically encouraged due to their adaptability to local environmental conditions and their contribution to ecosystem resilience (Caravaca *et al.*, 2002; Skousen *et al.*, 2017).

Legumes and grasses are frequently employed as pioneer plants to improve soil structure, speed up ground cover, and increase nitrogen cycling. Leguminous plants foster nitrogen enrichment through biological nitrogen fixation, thereby improving soil fertility and facilitating the succession of other plant species (Singh and Raghubanshi, 2002). The establishment of tree species further enhances soil quality through increased microbial interactions, root activity, and litter deposition (Ghose, 2005).

**Forestry Reclamation Approach (FRA)**

The Forestry Reclamation Approach (FRA) is a widely accepted strategy for re-establishing forest ecosystems on reclaimed mine lands. This strategy includes loose grading to minimize compaction, the use of suitable rooting media, establishment of compatible ground cover, and the planting of both commercial and native tree species (Burger *et al.*, 2005; Zipper *et al.*, 2011). By improving soil physical and biological properties, FRA promotes soil stabilization, enhances biodiversity, and accelerates long-term ecosystem recovery. The approach has been successfully implemented for post-mining land use and ecological restoration in several mining regions (Franklin *et al.*, 2012; Gerlitz, 2019).

**Emerging Technologies in Mine Land Restoration**

Recent mine land restoration plans increasingly integrate ecological intensification and technological innovation to increase restoration effectiveness, monitoring precision, and long-term sustainability. Novel approaches integrate climate-responsive restoration

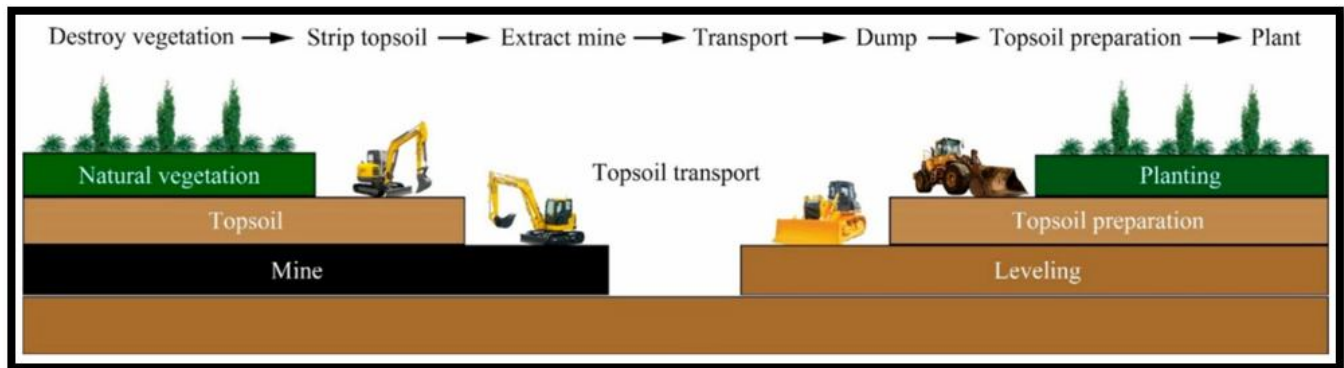
frameworks, biotechnology, engineered alterations, and digital monitoring.

**Remote Sensing, UAVs, and Digital Monitoring**

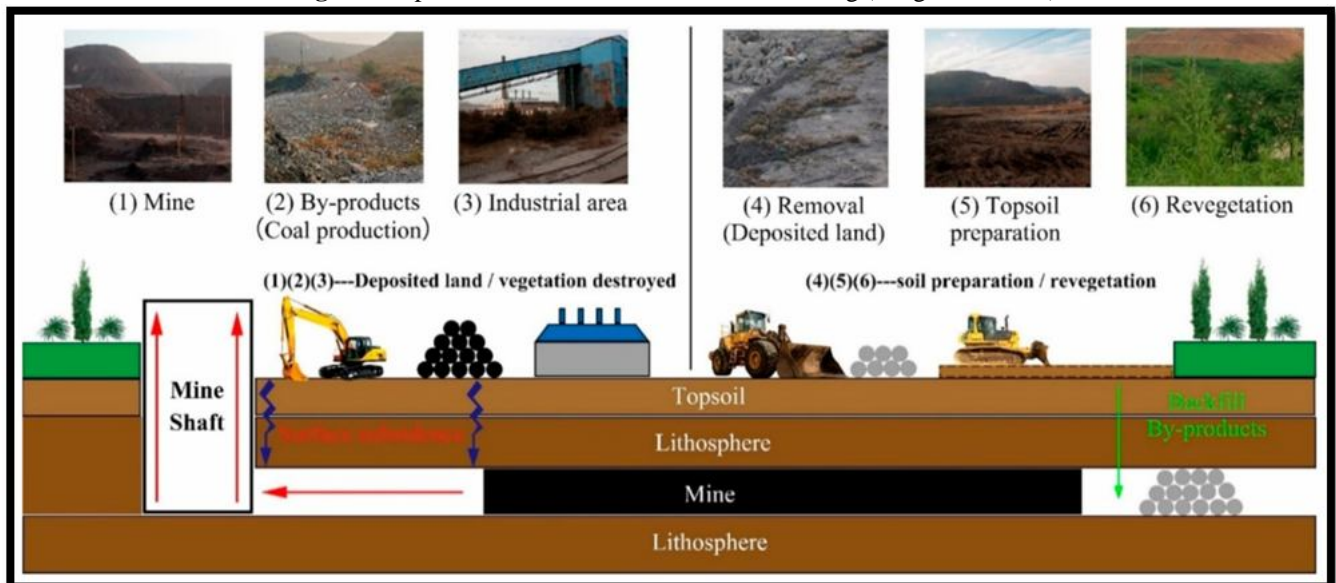
Mine reclamation evaluation is being revolutionized by advanced remote sensing technologies. Vegetation recovery, soil stability, and landform evolution in reclaimed mining regions are increasingly being assessed using high-resolution satellite images, UAV-based surveys, LiDAR mapping, and multispectral vegetation indices (e.g., NDVI) (Huang and Liu, 2013; Ren *et al.*, 2024). Long-term monitoring of post-mining land-use changes and restoration efficacy at regional and global levels is made possible by time-series geospatial information. Site-specific restoration planning and risk assessment are further supported by the incorporation of GIS-based spatial modelling (Swamy *et al.*, 2025).

**Microbial Community Engineering and Functional Inoculants**

Restoration techniques have evolved toward community engineering and functional microbial



**Fig. 1:** The process and reclamation of surface mining (Feng *et al.*, 2021).



**Fig. 2:** The process and reclamation of underground mining (Feng *et al.*, 2021).

inoculation due to recent developments in soil microbiology (Glick *et al.*, 1999). Metagenomic and high-throughput sequencing tools can now provide detailed characterization of microbial succession in reclaimed mine soils (Garris *et al.*, 2016). In coal and metal mine spoils, application of plant growth-promoting rhizobacteria (PGPR), nitrogen-fixing bacteria, and arbuscular mycorrhizal fungi has demonstrated increased plant survival, improved nutrient uptake, and sped up soil aggregation (Maciel-Rodríguez *et al.*, 2025; Mao *et al.*, 2024). A potential area of mine soil bio-restoration is the use of synthetic microbial consortia that are intended to improve nutrient cycling and stress tolerance (Liang *et al.*, 2022).

### Biochar, Nanomaterials, and Engineered Amendments

Nowadays, engineered soil amendments are gaining importance in the rehabilitation of mine land. The potential of biochar made from agricultural waste has been widely studied for its ability to strengthen soil structure, improve cation exchange capacity, immobilise heavy metals, and foster microbial biomass in degraded mine substrates (Murtaza *et al.*, 2023; Chen *et al.*, 2024). Furthermore, new nanomaterials and mineral-based stabilizers are being investigated to improve nutrient retention and decrease pollutant mobility in mine spoils (Mitra and Saha, 2025). These methods support carbon sequestration and long-term soil stabilization.

### Nature-Based Solutions and Climate-Responsive Restoration

Nature-based solutions (NbS) are increasingly promoted in mine land restoration in order to improve

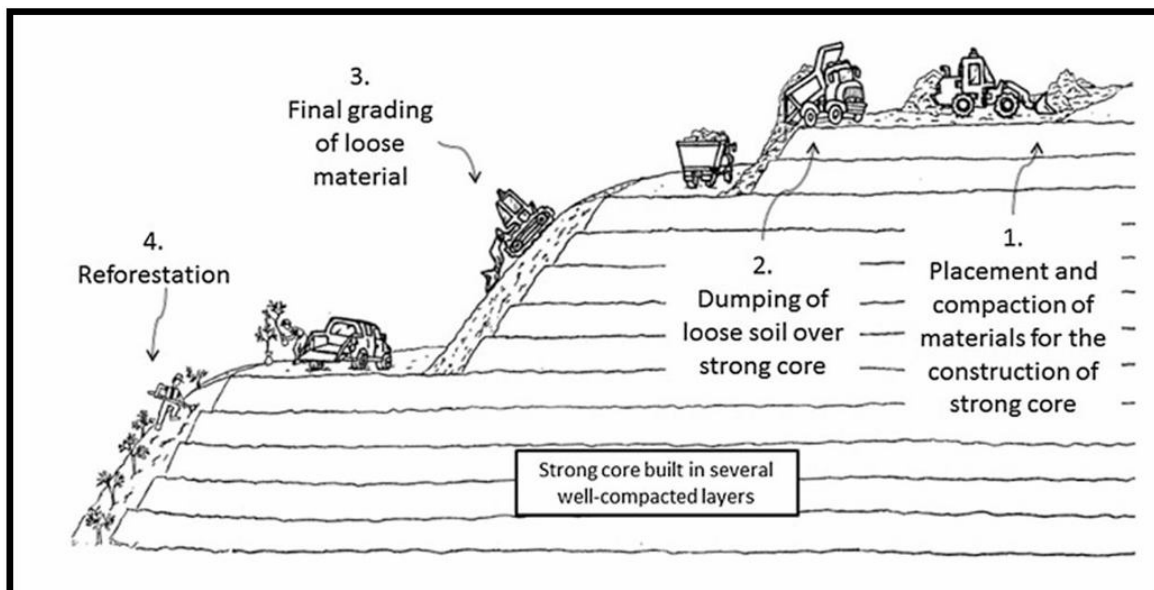
resilience to climate variability and boost biodiversity and ecosystem services. Climate-adaptive afforestation techniques, mixed-species plantation systems, and assisted natural regeneration are being integrated into post-mining land-use planning (Pathaket *et al.*, 2022; Arneth *et al.*, 2021). Restoration programs now increasingly take into account the carbon sequestration potential, ecosystem service valuation, and landscape-level connectivity as part of sustainable mine closure planning (Santos *et al.*, 2025).

### Evaluation of Reclamation and Restoration Success

Evaluation of ecosystem recovery beyond vegetation growth is necessary to determine the success of mining land reclamation. Reclaimed sites are compared to undisturbed reference ecosystems in terms of soil physicochemical characteristics, biological activity, and ecological functioning to measure the effectiveness of restoration. Since they represent soil functional recovery and ecosystem stability, indicators such as soil microbial biomass, enzyme activity, and nutrient cycling activities are frequently employed to assess restoration success (Sheoran *et al.*, 2010; Skousen *et al.*, 2017).

Soil microbial communities play a key role in ecosystem restoration through their involvement in soil aggregation, nutrient mineralization, and organic matter breakdown (Glick *et al.*, 1999). Microbial biomass, respiration, and metabolic activity measurements offer crucial insights into the success of reclamation techniques and the establishment of stable soil systems (Edgerton *et al.*, 1995; Skousen *et al.*, 2011). Microbial population recovery is regarded as a crucial sign of sustained improvements in soil quality.

Mycorrhizal associations are also important indicators



**Fig. 3:** Depiction of the reclamation process according to FRA (Jeldes *et al.*, 2013).

of restoration effectiveness because mycorrhizal connections boost plant nutrient uptake and stress tolerance in disturbed soils (Gould *et al.*, 1996; Skousen *et al.*, 2011). Plant-soil interactions and ecosystem resilience can be better understood by evaluating mycorrhizal activity using bioassays, measuring root colonisation, and estimating mycorrhizal inoculum potential (Allen and Friese, 1992; Caravaca *et al.*, 2002).

Soil enzyme activities, especially dehydrogenase and hydrolase, act as sensitive indicators of nutrient cycling and biological activity in the soil. Monitoring these biochemical parameters helps provide early evidence of changes in soil fertility and ecological recovery following reclamation (Glick *et al.*, 1999; Maiti and Ghose, 2005). In general, assessing the effectiveness and sustainability of mine land restoration initiatives requires a comprehensive evaluation of soil physical, chemical, and biological markers (Santos *et al.*, 2025).

### Sustainable and Eco-Friendly Mining Practices

Sustainable mining practices underscore the integration of environmental restoration measures into mine planning and operation to reduce long-term ecological effects. Pre-mining land-use planning, controlled spoil disposal, and topsoil conservation are important strategies to minimize environmental deterioration and promote post-mining restoration (Zipper *et al.*, 2011; Arneth *et al.*, 2021).

Eco-friendly mining approaches integrate rehabilitation techniques such as water management, landform stabilization, and restoration-oriented mine design throughout the mining lifecycle. These methods increase post-mining ecosystem recovery, lower rehabilitation costs, and improve restoration efficiency (Abdul-

Rahaman *et al.*, 2025; Solangi and Alyamani, 2025).

Advanced tools such as ecological modelling and remote sensing facilitate impact assessment and restoration progress tracking, enabling adaptive management of reclaimed landscapes (Ren *et al.*, 2024; Swamy *et al.*, 2025). Sustainable mine land management also requires effective policy frameworks and cooperation between governmental organizations, industry players, and local communities in order to guarantee long-term land productivity and ecologically conscious resource extraction (Arneth *et al.*, 2021).

### Challenges in Mine Land Reclamation

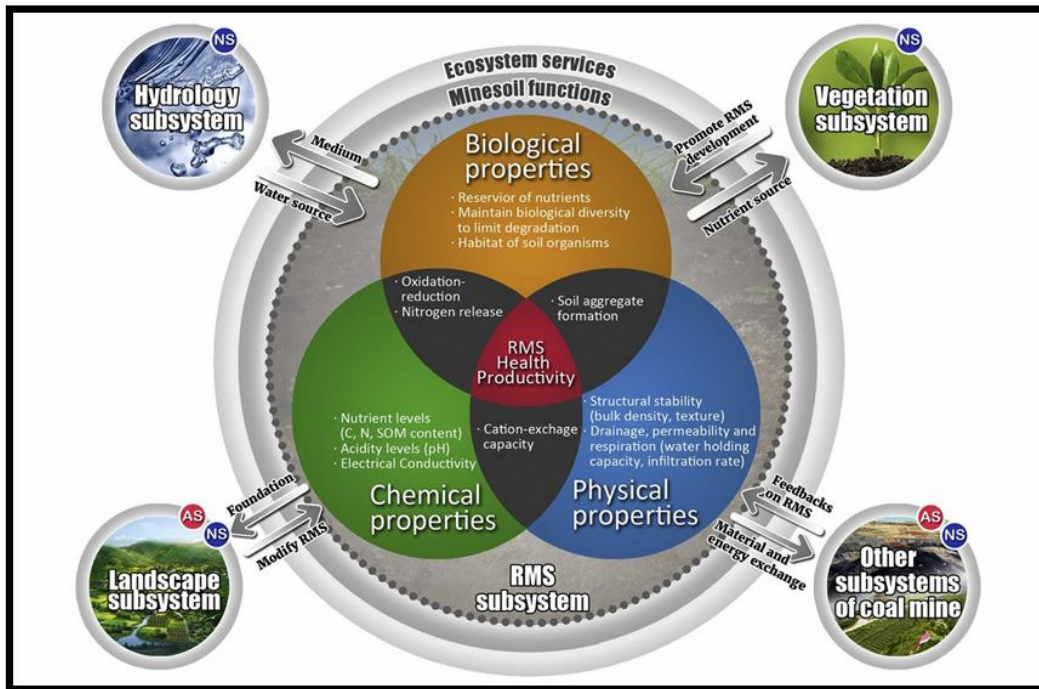
Despite advances in reclamation practices, mine land restoration continues to face substantial ecological and socioeconomic barriers. Poor structure, low organic carbon, excessive pH, and high metal concentrations are common characteristics of mine substrates, which collectively restrict plant establishment and hinder ecosystem recovery (Tordoff *et al.*, 2000; Feng *et al.*, 2019).

Another critical obstacle is the slow recovery of soil biological processes. Even though vegetation cover may appear in a few years, it frequently takes considerably longer to restore microbial diversity, nitrogen cycling, and soil functional stability (Edgerton *et al.*, 1995; Mao *et al.*, 2024). Reclaimed ecosystems may therefore continue to be functionally juvenile yet physically established.

Inconsistent evaluation further complicates restoration assessment. Reclamation success is often judged based on vegetation cover rather than overall ecosystem functionality, leading to differences in reported outcomes (Skousen *et al.*, 2017; Santos *et al.*, 2025). In many areas,

**Table 1:** List of species suitable for reclamation in different mined areas (Feng *et al.*, 2021).

S. No.	Mine Area	Suitable Plants
1.	Gypsum	<i>Prosopis cineraria</i> (Khejri), <i>Zizyphus mauratiana</i> (Ber)
2.	Bentonite	<i>Maytenus emerginata</i>
3.	Ochre	<i>Acacia nilotica</i> , <i>Butea monosperma</i> , <i>Euphorbia nerifolia</i> (thor)
4.	Marble	<i>Prosopis cineraria</i> , <i>Prosopis juliflora</i>
5.	Limestone	<i>Prosopis juliflora</i> , <i>Terminalia arjuna</i> , <i>Zizyphus mauritiana</i> , <i>Ailanthus excelsa</i> , <i>Azadirachta indica</i> , <i>Butea monosperma</i> , <i>Madhuca lentifolia</i>
6.	Rock Phosphate	<i>Acacia catechu</i> (Khair), <i>Dalbergia sissoo</i> , <i>Eucalyptus hybrid</i>
7.	Zinc tailings	<i>Ficus tomentosa</i> , <i>Prosopis juliflora</i> , <i>Azadirachta indica</i>
8.	Lignite	<i>Terminalia arjuna</i> , <i>Dalbergia sissoo</i> , <i>Bamboo</i>
9.	Bauxite	<i>Acacia auriculiformis</i> , <i>Pinus caribaea</i> , <i>Gravillea robusta</i> , <i>E. camaldulensis</i> , <i>Grevillea pteridifolia</i> , <i>Pongamia pinnata</i>
10.	Iron-Ore	<i>Delonix regia</i> , <i>Jacaranda</i> , <i>Bombax malabaricum</i> , <i>Samanea sama</i>
11.	Salty lands	<i>Eucalyptus</i> , <i>Phoenix</i> , <i>Tamarix</i>
12.	Area liable to inundation	<i>Acacia nilotica</i> , <i>Butea monosperma</i> , <i>Zixphus mauratiana</i>
13.	Water logged Saline areas	<i>Eucalyptus robusta</i> , <i>E. rudis</i>



**Fig. 4:** Interlinkages between the RMS (reclaimed mine soils) subsystem and other subsystems. AS and NS represent artificial systems and natural systems, respectively, and the marks on the edge of every subsystem (Feng *et al.*, 2019).

there is still a limitation of standardized indicators and long-term monitoring (Martins *et al.*, 2020).

Effective execution of restoration initiatives is also hampered by socioeconomic factors, such as high rehabilitation costs, a lack of professional experience, and poor institutional coordination (Martins *et al.*, 2020; Arneht *et al.*, 2021). Furthermore, there is additional uncertainty due to growing climatic variability, particularly in arid and semi-arid mining regions, where water scarcity and extreme weather events adversely affect vegetation survival (Fenta *et al.*, 2019; Schulze, 2023).

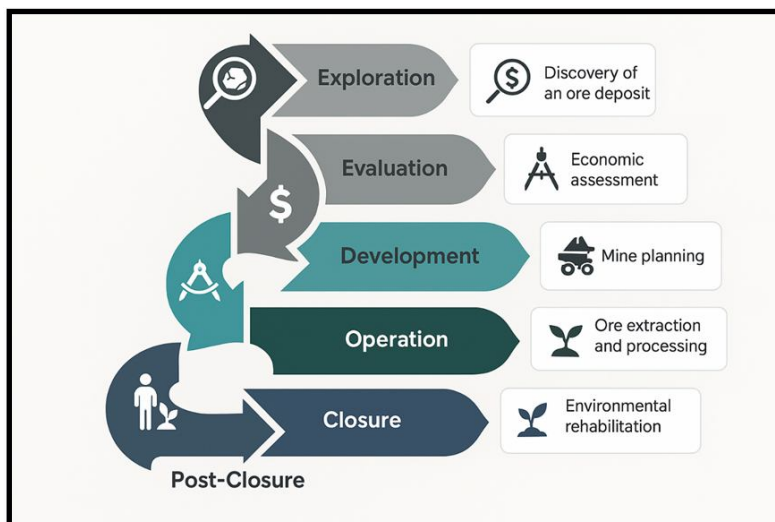
Addressing these challenges needs integrated, adaptive, and long-term management approaches, supported by scientific monitoring and policy commitment.

**Research Gaps in Mine Land Restoration**

There is still an array of substantial knowledge gaps in mine land reclamation, despite a great deal of research. The absence of long-term studies assessing the sustainability of reclaimed ecosystems is a significant drawback. While long-term dynamics of soil carbon sequestration, microbial succession, and ecosystem resilience are still poorly understood, the majority of studies concentrate on short-term vegetation establishment (Franklin *et al.*, 2012; Mao *et al.*, 2024).

Another significant gap is the inadequate mechanistic understanding of plant-microbe-soil interactions in reclaimed mine sites. Despite their widespread use, microbial inoculation and revegetation techniques need more research to determine their long-term impacts on ecosystem stability, soil structure development, and nutrient cycling (Martins *et al.*, 2020; Song *et al.*, 2024).

There are very few comparative analyses of various reclamation strategies in various types of environments. Finding appropriate management techniques is hampered by the



**Fig. 5:** Eco-friendly Mining.

lack of standardized frameworks for evaluating restoration efficacy across sites and mining systems (Maiti and Ghose, 2005; Skousen *et al.*, 2017).

Furthermore, the integration of climate change concerns into mine restoration planning remains limited. Research is required to evaluate the potential contributions of climate-resilient restoration techniques to carbon sequestration and ecosystem services (Fenta *et al.*, 2019; Schulze, 2023).

Therefore, to increase the efficacy and sustainability of mine land restoration projects, future research should use interdisciplinary approaches that incorporate ecological processes, technical innovation, and socioeconomic considerations.

### Conclusion

Mine land reclamation is essential for rebuilding ecological services, re-establishing plants in disturbed mining landscapes, and restoring degraded soils. In order to achieve long-term ecosystem stability, effective restoration necessitates integrated approaches that incorporate biological recovery, technological monitoring, soil amendment, and adaptive management techniques. In addition, mine land reclamation contributes significantly to achieving several United Nations Sustainable Development Goals (SDGs), especially SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land).

Sustainable mining methods support socioeconomic growth, environmental preservation, and resource efficiency. Recent studies have suggested indicator systems for analyzing ecological sustainability, land-use efficiency, and environmental quality in mining locations in order to evaluate the role of mine restoration in contributing to the SDGs. Thus, incorporating SDG concepts into reclamation planning enhances long-term sustainability in post-mining landscapes, biodiversity conservation, and ecosystem restoration.

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