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Sustainable Mine Land Rehabilitation Using Bio-Cementation and Geopolymers: A review of on applications, challenges, & future perspectives

***Kipkorir Yano Yator*[1] *and Zakaria Yakin*[2]**

[1]*Michigan Technological University, U.S.A*

[2]*Kwame Nkrumah University of Science and Technology, Ghana*

Abstract: While mining plays a pivotal role in global economic development, it often results in severely degraded landscapes that present long-term ecological and socio-economic challenges. Conventional mine land rehabilitation approaches which are often dependent on Portland cement and other carbon-intensive materials, increasingly present various challenges such as environmental footprint, cost, and limited long-term effectiveness. In response, sustainable technologies such as bio-cementation and geopolymers have emerged as promising alternatives that align with low-carbon development goals and circular economy principles. This review critically examines the potential of bio-cementation and geopolymers in sustainable mine land rehabilitation, highlighting their principles, applications, and limitations. Bio-cementation, primarily based on microbially induced calcium carbonate precipitation (MICP), enhances soil stability, reduces permeability, suppresses dust, and immobilizes toxic metals through carbonate precipitation. Various case studies demonstrate its effectiveness in stabilizing mine tailings and controlling erosion, although challenges still remain in their scalability, nutrient costs, and durability under variable environmental conditions. Geopolymers, synthesized through the alkali activation of aluminosilicate precursors such as fly ash, slag, and mine tailings, offer superior mechanical strength, chemical durability, and the ability to encapsulate heavy metals. Their environmental benefits, including up to 80% lower CO_2 emissions compared to cement, are balanced against constraints such as precursor variability, activator cost, and limited long-term field data. A comparative analysis of the two approaches reveals complementary strengths: bio-cementation excels in eco-compatibility and in-situ stabilization, while geopolymers provide robust structural integrity and long-term contaminant immobilization. Key barriers include performance variability, logistical constraints in remote mining areas, and limited industry awareness. The integration of bio-cementation and geopolymer strategies may provide multifunctional rehabilitation systems that address both geotechnical and environmental needs.

Keywords: Mine land rehabilitation, bio-cementation, geopolymers, sustainability, MICP, circular economy, heavy metal immobilization.

INTRODUCTION

Mining remains one of the most resource-intensive and environmentally disruptive human activities, leaving behind vast stretches of degraded land after resource extraction. Globally, abandoned mine sites are characterized by unstable soil structures, heavy metal contamination, dust pollution, and biodiversity loss (Kiventerä, *et al.*, 2021). These environmental legacies not only impair ecosystem functions but also pose long-term risks to water quality, agriculture, and human health. Traditional mine land rehabilitation methods, such as the use of Portland cement for soil stabilization and chemical amendments for contaminant immobilization, often face limitations due to their high carbon footprint, cost, and limited ecological compatibility (Yilmaz, *et al.*, 2020). Consequently, there is a pressing need for sustainable, low-carbon, and durable approaches to restoring post-mining landscapes.

Over the past decade, sustainable materials such as **bio-cementation** and **geopolymers** have emerged as promising alternatives for mine land rehabilitation. Bio-cementation, primarily achieved through microbially induced calcium carbonate precipitation (MICP), harnesses microbial processes to bind soil particles, reduce permeability, and immobilize contaminants (Dhami *et al.*, 2021). This biologically driven technique has shown potential in addressing soil erosion, dust suppression, and heavy metal stabilization in mining-impacted regions. Similarly, geopolymers produced through the alkali activation of aluminosilicate-rich industrial byproducts such as fly ash, slag, and mine tailings moffer a sustainable substitute for ordinary Portland cement (OPC) due to their lower CO_2 emissions and ability to encapsulate hazardous elements (Provis, & Bernal, 2019; Zhang, *et al.*, 2022). The integration of these two innovative material systems aligns with circular economy principles, where waste and biological processes are leveraged to achieve environmental restoration.

The environmental and socioeconomic importance of developing sustainable mine rehabilitation strategies cannot be overstated. With an estimated **7–10 billion tonnes of mine waste generated annually worldwide** (Lottermoser, 2021), finding effective ways to stabilize, reuse, or transform

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***Corresponding Author:** Zakaria Yakin

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such waste is crucial for mitigating land degradation. Moreover, global commitments such as the United Nations Sustainable Development Goals (SDGs), particularly Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Action), and Goal 15 (Life on Land), emphasize the urgent need for sustainable resource management and environmental protection (United Nations, 2015; United Nations, 2023) emphasize the importance of innovative and environmentally responsible rehabilitation solutions. Bio-cementation and geopolymers have the potential to support these targets by reducing reliance on carbon-intensive materials, improving land reuse potential, and ensuring ecological resilience in rehabilitated mine sites.

Despite their promise, both technologies face significant challenges in large-scale adoption. Bio-cementation, while eco-friendly, is limited by the variability of microbial performance under different environmental conditions, the cost of nutrient supply, and uncertainties surrounding long-term durability (Al Qabany, & Soga, 2021). Geopolymers, although technically advanced, often require careful control of raw material chemistry, curing conditions, and alkaline activator handling, which pose logistical barriers in remote mining regions (Li, *et al.,* 2022). Furthermore, policy and regulatory frameworks have yet to fully integrate or incentivize the use of such innovative materials in mine land rehabilitation projects. These gaps underscore the need for a critical review of the state-of-the-art applications, challenges, and future perspectives of bio-cementation and geopolymer technologies in the mining sector.

This paper provides a critical review of the role of **bio-cementation and geopolymers** in advancing sustainable mine land rehabilitation. Drawing on recent developments, the discussion highlights the fundamental principles and practical applications of these two innovative technologies in stabilizing mine soils, immobilizing contaminants, and restoring degraded post-mining landscapes. Particular attention is given to their environmental, economic, and technical performance in comparison with conventional rehabilitation methods, offering insights into their potential advantages and limitations. The review also identifies the current challenges and barriers that hinder their large-scale adoption, ranging from technical uncertainties to regulatory and cost constraints. Finally, the paper outlines emerging research trends, innovations, and future perspectives that may shape the integration of bio-cementation and geopolymers into sustainable mining practices, with the ultimate aim of providing guidance to researchers, practitioners, and policymakers committed to achieving resilient post-mining ecosystems.

Mine Land Degradation and the Need for Sustainable Rehabilitation

Mining is one of the most resource-intensive industries and is often associated with severe environmental disturbances that persist long after resource extraction ceases. Post-mining landscapes are typically characterized by soil erosion, compaction, and loss of fertility, which hinder vegetation regrowth and ecosystem restoration (Kiventerä, *et al.,* 2021). In many abandoned sites, tailings and waste rock piles contain toxic heavy metals such as arsenic, lead, and cadmium, which leach into surface and groundwater systems, thereby contaminating drinking water sources and agricultural soils (Lottermoser, 2021). Dust pollution from uncovered tailings further exacerbates air quality problems, while altered hydrological regimes due to excavation and dewatering activities can permanently disrupt groundwater recharge and flow patterns (Mhlongo, & Amponsah-Dacosta, 2016). These cumulative impacts highlight the urgency of adopting robust, sustainable strategies for land stabilization and ecosystem recovery in mining-affected regions.

The socioeconomic consequences of abandoned mine lands are equally significant. Communities dependent on mining often face declining livelihoods once extraction ends, leading to unemployment, poverty, and loss of social cohesion (Mensah *et al.,* 2018). Degraded landscapes also limit opportunities for alternative land uses such as agriculture, forestry, or tourism, thereby constraining regional economic diversification. In some cases, the health costs associated with exposure to heavy metals and polluted water bodies impose additional burdens on already vulnerable populations (Ogola, *et al.,* 2002). Consequently, addressing mine land degradation is not only an ecological imperative but also a socioeconomic necessity for ensuring long-term community resilience. Sustainable mine land rehabilitation has therefore emerged as a critical component of environmental stewardship and circular economy frameworks. Unlike conventional methods that often rely heavily on carbon-intensive materials such as Portland cement, sustainable approaches emphasize low-carbon technologies, waste reuse, and ecosystem

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compatibility (Yilmaz *et al.,* 2020). Techniques such as bio-cementation and the use of geopolymers derived from industrial by-products exemplify this paradigm shift by simultaneously addressing soil stabilization, contaminant immobilization, and waste valorization. Integrating such approaches into mine rehabilitation aligns with global commitments under the United Nations Sustainable Development Goals (SDGs), particularly Goal 12 (responsible consumption and production), Goal 13 (climate action), and Goal 15 (life on land). Ultimately, sustainable rehabilitation strategies seek not only to restore ecological functions but also to create value from mining legacies, transforming degraded lands into resilient, productive landscapes.

Table 1: Problem–Solution Framework for Sustainable Mine Land Rehabilitation (Provis & Bernal, 2019)

Degradation Issues	Environmental & Socioeconomic Impacts	Sustainable Rehabilitation Solutions
Soil erosion & loss of fertility	Hinders vegetation regrowth; desertification risk	Bio-cementation for soil binding; organic amendments to restore fertility
Groundwater & surface water contamination (heavy metals, acid mine drainage)	Unsafe drinking water, reduced agricultural productivity, ecosystem toxicity	Geopolymers to immobilize contaminants; phytoremediation for metal uptake
Dust pollution from tailings	Respiratory health risks; reduced air quality	Bio-cementation for dust suppression; surface sealing using eco-friendly binders
Altered hydrology (excavation, dewatering)	Reduced groundwater recharge; flooding in abandoned pits	Engineered wetland restoration; controlled backfilling with geopolymer-stabilized tailings
Loss of biodiversity & vegetation cover	Habitat destruction; ecosystem imbalance	Re-vegetation with native species; soil stabilization using bio-cementation
Socioeconomic decline (post-mining unemployment, poor land reuse options)	Poverty, health costs, limited land for agriculture/tourism	Circular economy: reuse mine waste in geopolymers; community-based rehabilitation projects
High carbon footprint of conventional methods (e.g., Portland cement use)	Climate change contribution; costly materials	Low-carbon geopolymers; microbial-induced carbonate precipitation (MICP)

Bio-Cementation in Mine Land Rehabilitation

Bio-cementation refers to biologically driven processes that enhance soil stability and reduce permeability through the precipitation of calcium carbonate minerals. The most widely studied approach is microbially induced calcium carbonate precipitation (MICP), in which microorganisms, typically ureolytic bacteria such as *Sporosarcina pasteurii*, hydrolyze urea to produce carbonate ions that subsequently combine with calcium ions to form calcite crystals (Dhami *et al.,* 2021). These calcite precipitates bind soil particles, fill voids, and improve the geotechnical properties of degraded substrates, thereby offering a sustainable pathway for strengthening mine-impacted landscapes. The primary pathway of bio-cementation relies on microbial urease activity, which facilitates urea hydrolysis and produces ammonium and carbonate ions. In the presence of calcium sources, these carbonate ions precipitate as $CaCO_3$ crystals. Crystal nucleation and growth within soil pores promote inter-particle bonding, thereby enhancing strength and reducing permeability (Al Qabany, & Soga, 2021). While alternative microbial pathways such as denitrification and sulfate reduction have been explored, urea hydrolysis remains the most efficient and widely implemented process for large-scale applications.

Applications

Bio-cementation has shown considerable promise in mine land rehabilitation due to its ability to stabilize loose tailings, suppress dust emissions, and control erosion on waste rock piles and slopes. Furthermore, it plays a vital role in immobilizing toxic heavy metals such as lead, cadmium, and arsenic, either through co-precipitation with carbonates or by reducing their leachability (DeJong *et al.,* 2013). These applications highlight its multifunctional benefits for ecological restoration in mining regions. Practical demonstrations reinforce the potential of bio-cementation. For instance, Jiang *et al.,* (2020) applied MICP on mine tailings in China and observed significant reductions in dust emissions along with improvements in compressive strength of the tailings surface. Similarly, laboratory experiments by Achal *et al.,* (2015) confirmed that

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MICP could immobilize heavy metals in gold mine tailings, reducing leachable concentrations by more than 80%. These studies illustrate both the environmental and engineering effectiveness of bio-cementation technologies. The advantages of bio-cementation include its low carbon footprint relative to Portland cement, ecological compatibility, and multifunctionality in stabilization and contaminant immobilization. However, several limitations hinder its widespread adoption. Concerns about durability under fluctuating environmental conditions, the costs associated with nutrient supply for microbial growth, and challenges in scaling up to large mine sites remain critical barriers. Additionally, potential ecological risks, such as ammonia release during urea hydrolysis, further complicate large-scale implementation (Li, *et al.*, 2022).

Geopolymers in Mine Land Rehabilitation

Geopolymers are alkali-activated aluminosilicate binders produced by reacting silica- and alumina-rich industrial byproducts with alkaline activators such as sodium hydroxide or sodium silicate. The resulting geopolymerization process generates amorphous to semi-crystalline three-dimensional aluminosilicate networks, which exhibit excellent mechanical strength and chemical durability (Provis, & Bernal, 2019). This makes geopolymers a promising substitute for Portland cement in mine rehabilitation applications. A wide range of raw materials can serve as precursors for geopolymer synthesis, including fly ash, blast furnace slag, mine tailings, red mud, and natural clays (Zhang *et al.*, 2022). Importantly, the direct utilization of mine tailings as feedstock exemplifies circular economy principles, as it transforms hazardous waste into valuable stabilizing agents.

Applications

Geopolymers have been successfully applied in mine land rehabilitation to stabilize waste materials, strengthen soils, and immobilize toxic elements. Their binding capacity reduces dust emissions from fine particles, while their mechanical properties enhance the compressive and shear strength of degraded substrates. Moreover, the geopolymer matrix has demonstrated the ability to encapsulate hazardous metals such as arsenic, lead, and chromium, thereby reducing their leachability and potential environmental risks (Yang, *et al.*, 2021).

Laboratory and field-scale studies support the practical potential of geopolymers. For example, research in Australia demonstrated that gold mine tailings could be transformed into geopolymer composites capable of immobilizing arsenic while significantly improving unconfined compressive strength (Jha & Sivapullaiah, 2017). Large-scale pilot projects in China have also successfully utilized fly ash–slag geopolymers to stabilize mine tailings dams, leading to improved structural integrity and reduced seepage risks (Zhang, *et al.*, 2022). These cases highlight the versatility and effectiveness of geopolymer-based

Solutions.

Geopolymers provide considerable environmental advantages, including up to 80% lower CO_2 emissions compared with Portland cement, while also delivering superior mechanical performance and excellent chemical resistance. Despite these benefits, several challenges persist. The heterogeneous composition of mine tailings often leads to variability in precursor properties, which complicates standardization. Dependence on alkaline activators, which are costly and require careful handling, further limits feasibility. Additionally, long-term field data on durability under different climatic conditions remain limited, and logistical challenges in producing geopolymers on-site in remote mining areas must be addressed before widespread adoption is possible (Provis & Bernal, 2019).

Comparative Analysis: Bio-Cementation vs. Geopolymer

A comparative assessment of bio-cementation and geopolymers highlights their respective strengths and limitations in sustainable mine land rehabilitation. From a performance perspective, geopolymers typically exhibit superior mechanical strength and long-term durability compared to bio-cemented systems. Their high compressive strength and chemical resistance make them particularly suitable for stabilizing mine tailings dams and contaminated soils under harsh environmental conditions (Provis, & Bernal, 2019; Zhang, *et al.*, 2022). Bio-cementation, while offering moderate strength improvements, is more effective for reducing soil permeability, stabilizing loose substrates, and mitigating dust pollution, making it advantageous for surface stabilization and erosion control (Dhami, *et al.*, 2021). However, concerns remain about the long-term durability of bio-cementation under variable climatic and geochemical conditions (Li, *et al.*, 2022).

Economic considerations are central to the large-scale adoption of both technologies. Geopolymer

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production can be cost-competitive with Portland cement, particularly when industrial by-products such as fly ash, slag, or mine tailings are locally available. However, costs associated with alkaline activators and curing requirements may present barriers in remote mining regions (Jha & Sivapullaiah, 2017). In contrast, bio-cementation requires relatively simple equipment and low initial energy input, but nutrient supply for microbial growth, culture preparation, and process monitoring can increase operational costs. Scalability is another challenge, as bio-cementation treatments often need repeated applications to cover large mine areas, whereas geopolymers can be cast or sprayed in bulk applications (DeJong, *et al.*, 2013).

The environmental footprint of the two approaches also differs significantly. Geopolymers have up to 80% lower CO_2 emissions compared to ordinary Portland cement and contribute to circular economy practices by utilizing industrial waste as precursors (Provis & Bernal, 2019). Bio-cementation, on the other hand, has an even lower carbon footprint due to its biological basis, though ammonia release during urea hydrolysis poses a potential ecological risk (Al Qabany & Soga, 2021). Both approaches contribute to ecosystem compatibility by reducing reliance on carbon-intensive materials and mitigating contaminant mobility in mine soils.

Suitability under site-specific conditions further distinguishes the two technologies. Bio-cementation is particularly advantageous in arid and semi-arid climates where dust suppression and surface stabilization are priorities. It is also effective in soils with high permeability that require sealing against water infiltration. Geopolymers, however, are more suited to sites with high concentrations of toxic metals or where structural reinforcement of tailings dams is necessary, as their dense aluminosilicate matrices immobilize contaminants and enhance substrate strength (Yang, *et al.*, 2021). Thus, while both technologies present sustainable alternatives to conventional mine rehabilitation materials, their optimal application depends on site-specific environmental conditions, material availability, and long-term rehabilitation goals.

Table 2: Comparison of Bio-Cementation and Geopolymers in Mine Land Rehabilitation ((Dhami, *et al.*, 2021)

Aspect	Bio-Cementation (MICP)	Geopolymers
Principle	Microbial precipitation of calcium carbonate (mainly via urea hydrolysis).	Alkali activation of aluminosilicate precursors to form a geopolymer binder.
Key Inputs	Ureolytic bacteria (*Sporosarcina pasteurii*), urea, calcium source.	Fly ash, slag, mine tailings, red mud, clay; alkaline activators ($NaOH$, Na_2SiO_3).
Mechanism	Microbes hydrolyze urea → carbonate ions → $CaCO_3$ crystals cement soil particles.	Dissolution of aluminosilicates in alkaline medium → polycondensation → hardened geopolymer matrix.
Main Applications	- Tailings stabilization - Dust suppression - Slope/erosion control - Heavy metal immobilization	- Mine waste stabilization - Soil strengthening - Encapsulation of toxic elements (As, Pb, Cr) - Tailings dam reinforcement
Environmental Benefits	- Low carbon footprint vs. Portland cement - Ecological compatibility - Uses natural microbial processes	- Up to 80% lower CO_2 emissions vs. cement - Utilizes industrial/mining waste - High chemical durability
Strengths	- Multifunctional (strength + contaminant immobilization) - Can be applied in-situ - Bio-based and self-healing potential	- High compressive strength - Excellent durability - Effective heavy metal immobilization - Circular economy approach
Limitations	- Ammonia release during urea hydrolysis - Nutrient supply costs - Durability under varying climates uncertain - Limited scalability	- Variability in raw material quality - High pH activators pose handling risks - Limited long-term field data - On-site production logistics
TRL (Technology Readiness Level)	Pilot-scale applications; some field trials ongoing.	Laboratory- and pilot-scale studies; few large-scale demonstrations.

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Challenges in Application

Despite the growing interest in bio-cementation and geopolymers as sustainable solutions for mine land rehabilitation, several challenges hinder their widespread adoption. One of the key technical barriers is the difficulty of scaling up laboratory results to field-scale applications. While both technologies have demonstrated promising outcomes under controlled conditions, achieving consistent performance in complex mine environments remains problematic. For bio-cementation, microbial activity can vary significantly depending on soil composition, temperature, and moisture levels, leading to inconsistent outcomes in terms of strength development and contaminant immobilization (Al Qabany, & Soga, 2021). Similarly, geopolymers face challenges related to quality control, as variations in precursor chemistry especially when using heterogeneous mine tailings can cause unpredictable mechanical and chemical performance (Provis, & Bernal, 2019).

Environmental concerns also require careful consideration. Bio-cementation, while inherently eco-friendly, may release ammonia as a byproduct of urea hydrolysis, raising the risk of localized soil and water pollution (Li, *et al.,* 2022). Additionally, the long-term ecological interactions of introduced microbial cultures with native soil biota remain poorly understood, creating uncertainty about unintended impacts on ecosystem dynamics. Geopolymers, though low-carbon, involve the use of highly alkaline activators such as sodium hydroxide and sodium silicate, which pose handling and disposal risks if not carefully managed (Zhang, *et al.,* 2022). These environmental uncertainties underscore the need for further life-cycle assessments and ecological monitoring of rehabilitation projects employing these materials.

Economic and logistical issues also limit application in many mining regions. Bio-cementation requires a reliable supply of microbial cultures and nutrients, which can become costly in large-scale treatments. The need for repeated applications to cover extensive mine areas further increases operational expenses. Geopolymers, on the other hand, depend heavily on the local availability of suitable precursors such as fly ash, slag, or tailings, as well as infrastructure for mixing and curing. In remote mining areas, transporting raw materials and activators adds logistical complexity and cost (Jha, & Sivapullaiah, 2017). These economic barriers often make conventional materials such as Portland cement appear more attractive despite their environmental drawbacks.

Policy and regulatory frameworks present another major obstacle. In most jurisdictions, bio-based and geopolymer technologies are not yet fully integrated into mine rehabilitation standards or incentivized through policy instruments. The lack of clear regulatory guidelines, certification standards, and performance benchmarks discourages industry stakeholders from adopting these innovations (Mhlongo & Amponsah-Dacosta, 2016). This policy vacuum perpetuates reliance on conventional, carbon-intensive rehabilitation practices.

Finally, limited industry awareness and acceptance remain significant challenges. Many mining companies and contractors are unfamiliar with the technical principles, benefits, and limitations of bio-cementation and geopolymers. Without extensive demonstration projects, training, and knowledge dissemination, industry actors may perceive these technologies as risky or unproven. Building awareness, coupled with robust field evidence and supportive policy frameworks, will be critical for overcoming skepticism and facilitating mainstream adoption of sustainable rehabilitation practices.

Future Perspectives and Research Directions

The future of sustainable mine land rehabilitation lies in advancing both bio-cementation and geopolymer technologies through scientific innovation, integration, and policy support. In bio-cementation, significant progress is expected from the use of genetically engineered microbes with enhanced urease activity, tolerance to extreme environments, and the ability to precipitate alternative minerals beyond calcium carbonate. Such microbial strains could improve durability, reduce ammonia byproducts, and broaden applicability in diverse mine environments (Li *et al.,* 2022). Moreover, hybrid systems that combine bio-cementation with chemical or physical stabilization techniques are being explored to address scalability challenges while maintaining environmental benefits. For geopolymers, research is focusing on nano-additives (e.g., nano-silica, carbon nanotubes) that enhance mechanical strength, reduce porosity, and improve long-term durability. Additionally, the integration of 3D-printing technologies with geopolymer binders opens opportunities for in-situ construction of

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engineered barriers, slope stabilization structures, and capping systems directly at mine sites (Provis & Bernal, 2019). Such technological convergence can accelerate the application of geopolymers in large-scale rehabilitation. A promising research direction is the integration of bio-cementation and geopolymer approaches, leveraging the microbial-induced precipitation for initial soil stabilization and the geopolymer matrix for long-term strength and contaminant immobilization. This synergistic strategy could provide multifunctional rehabilitation solutions that address both geotechnical stability and environmental remediation.

To ensure environmental soundness, comprehensive life cycle assessment (LCA) studies are essential. These will quantify energy inputs, greenhouse gas emissions, and ecological impacts compared to conventional cement-based approaches. Beyond technological innovation, supportive policy frameworks and incentives will be critical for scaling adoption. Public-private partnerships can facilitate demonstration projects, reduce financial risks, and encourage industry uptake. Finally, aligning these rehabilitation approaches with global sustainability agendas such as the UN Sustainable Development Goals (SDGs), circular economy principles, and climate change mitigation commitments will strengthen their relevance. By transforming mine wastes into valuable resources and reducing carbon footprints, bio-cementation and geopolymers have the potential to contribute meaningfully to sustainable development at both local and global levels.

CONCLUSION

This review highlights the emerging role of bio-cementation and geopolymers as innovative and sustainable alternatives to conventional mine land rehabilitation practices. Bio-cementation offers a biologically driven method for stabilizing soils, reducing erosion, and immobilizing heavy metals, while geopolymers provide a chemically robust pathway for stabilizing mine wastes and enhancing structural durability. Both technologies demonstrate significant potential to lower carbon emissions, utilize waste materials, and improve ecological outcomes in post-mining landscapes. However, challenges persist in scalability, durability, economic feasibility, and regulatory integration. Addressing these issues requires not only scientific innovation but also cross-sector collaboration, supportive policy mechanisms, and industry awareness. Looking forward, the convergence of bio-cementation and geopolymer research, coupled with sustainability assessments and alignment with global development agendas, could unlock transformative pathways for the mining industry. Bio-cementation and geopolymers represent promising solutions for sustainable mine land rehabilitation. Their successful implementation will depend on integrated strategies and multidisciplinary research that bring together microbiology, materials science, engineering, policy, and industry practice. By bridging these domains, the mining sector can transition toward more resilient, low-carbon, and environmentally restorative rehabilitation practices.

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