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Bio-mediated soil improvement techniques for slope stability

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Abstract

Soil stability is a crucial factor in mitigating landslides and ensuring the long-term durability of infrastructure built on slopes. Traditional soil stabilization techniques rely heavily on chemical additives and mechanical reinforcements, which can be expensive, labor-intensive, and environmentally harmful. As an alternative, bio-mediated soil improvement methods harness biological processes to enhance soil cohesion, reduce erosion, and increase load-bearing capacity, offering a more sustainable and eco-friendly approach to geotechnical engineering. This paper explores key bio-mediated soil improvement techniques, including microbial-induced calcite precipitation (MICP), bio-polymer treatments, and plant-root reinforcement. MICP leverages the ability of specific bacteria to precipitate calcium carbonate, thereby enhancing soil strength and reducing permeability. Bio-polymer treatments use natural polymers derived from microbial or plant sources to improve soil aggregation and water retention properties. Plant-root reinforcement capitalizes on vegetation to provide mechanical stability by interlocking soil particles and preventing surface erosion. The effectiveness, advantages, and limitations of these bio-mediated methods are analyzed in detail, along with case studies demonstrating their application in real-world slope stabilization projects. Comparative assessments of their performance, cost-effectiveness, and environmental impact are provided to highlight their viability as sustainable alternatives to conventional stabilization approaches. Additionally, future research directions are proposed to improve the efficiency, durability, and scalability of bio-mediated soil improvement techniques, particularly in the context of large-scale infrastructure and climate change resilience. By integrating biological solutions with modern engineering practices, bio-mediated soil improvement offers promising potential for enhancing slope stability while minimizing environmental disruption. This paper aims to contribute to the ongoing development of sustainable geotechnical solutions and foster broader adoption of bio-mediated approaches in slope stabilization efforts worldwide.

Keywords: Bio-mediated soil improvement; Slope stabilization; Microbial-induced calcite precipitation (MICP); Bio-polymer treatments; Plant-root reinforcement

1. Introduction

Slope failures and landslides pose significant risks to infrastructure, human settlements, and natural ecosystems, particularly in regions prone to heavy rainfall, earthquakes, and deforestation. Unstable slopes can lead to catastrophic damage, disrupting transportation networks, damaging buildings, and causing loss of life. As a result, soil stabilization is a critical engineering challenge that requires effective and sustainable solutions. Traditional soil stabilization techniques, including cement grouting, chemical stabilization, and mechanical reinforcements such as retaining walls, have been widely used to improve soil strength and stability. However, these methods often come with environmental drawbacks, such as high carbon emissions, soil degradation, and groundwater contamination[1].

To address these concerns, bio-mediated soil improvement techniques have emerged as an environmentally friendly and cost-effective alternative. These methods leverage natural biological processes to enhance soil cohesion, reduce erosion, and increase bearing capacity without relying on synthetic chemicals or excessive mechanical interventions.

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Bio-mediated approaches, such as microbial-induced calcite precipitation (MICP), bio-polymer treatment, and plant-root reinforcement, have gained significant attention for their potential in stabilizing slopes in an ecologically sustainable manner. This paper reviews these key bio-mediated soil improvement techniques, exploring their mechanisms, applications, advantages, and limitations in slope stabilization projects.

2. Bio-Mediated Soil Improvement Techniques

2.1. Microbial-Induced Calcite Precipitation (MICP)

MICP is a bio-geochemical process that utilizes bacteria, such as *Sporosarcina pasteurii*, to precipitate calcium carbonate (CaCO_3) within the soil matrix. This natural cementation process enhances soil cohesion, reduces permeability, and increases shear strength, making it a promising technique for slope stabilization[2].

The mechanism of MICP is based on the hydrolysis of urea by ureolytic bacteria. The enzymatic reaction increases the alkalinity of the soil environment, leading to the precipitation of calcium carbonate, which binds soil particles together. This process mimics natural carbonate cementation, reinforcing the soil structure while maintaining permeability control. Studies have demonstrated that MICP can significantly enhance the load-bearing capacity of loose soils, reducing the likelihood of slope failures and landslides.

MICP has been successfully applied in various geotechnical engineering projects, including slope stabilization, erosion control, and foundation reinforcement. It has been tested in field-scale applications to improve the stability of road embankments, mitigate coastal erosion, and reinforce weak soil layers in landslide-prone areas. The technique offers a durable and self-healing soil stabilization solution, as microbial activity can be reactivated under favorable environmental conditions.

One of the key advantages of MICP is its environmental sustainability. Unlike cement-based stabilization methods, which contribute to significant CO_2 emissions, MICP operates under ambient conditions with minimal ecological impact. It also offers long-term durability, as the precipitated calcium carbonate resists dissolution in natural soil environments. However, challenges such as bacterial survival, uniform distribution of cementation, and cost-effective implementation need further research to enhance its scalability and efficiency.

2.2. Bio-Polymer Treatment

Bio-polymers are natural or synthetic organic compounds that improve soil stability by increasing cohesion and reducing erosion. Commonly used bio-polymers in geotechnical applications include xanthan gum, guar gum, and alginate, which form viscous gels that bind soil particles together. These biodegradable polymers enhance soil water retention, reduce permeability, and increase shear strength, making them suitable for slope stabilization in diverse environments.

The mechanism of bio-polymer treatment involves the formation of an organic matrix within the soil, which improves particle adhesion and creates a more stable structure. Unlike chemical stabilizers, bio-polymers do not introduce harmful residues into the environment, making them a sustainable alternative for erosion control and soil reinforcement. The effectiveness of bio-polymer treatments depends on factors such as polymer concentration, soil type, and environmental conditions.

Bio-polymer treatment has been widely used in geotechnical engineering applications, including road embankments, slope stabilization, and desert reclamation. It is particularly useful in arid regions, where soil erosion due to wind and water runoff is a major concern. By improving soil moisture retention, bio-polymers help prevent desiccation cracks and surface degradation. Additionally, they have been applied in agricultural landscapes to enhance soil fertility and reduce water loss.

A major advantage of bio-polymer treatments is their non-toxic and biodegradable nature, making them an environmentally friendly alternative to traditional chemical stabilizers. They are adaptable to various soil types and can be applied using simple spraying or mixing techniques. However, bio-polymer degradation over time and its sensitivity to environmental factors such as temperature and microbial activity require further optimization to enhance long-term stability.

2.3. Plant-Root Reinforcement

Plant-root reinforcement, also known as bio-engineering or phytostabilization, leverages the natural ability of plant roots to bind soil particles together, preventing erosion and enhancing slope stability. Deep-rooted vegetation such as vetiver grass (*Chrysopogon zizanioides*), willows (*Salix* species), and bamboo (*Bambusoideae*) have been extensively used for stabilizing slopes and riverbanks.

The mechanism of plant-root reinforcement is based on both mechanical and biological interactions between roots and soil. The penetration of roots into the soil enhances its shear strength by interlocking particles and forming a fibrous network that resists displacement. Additionally, plant roots improve soil moisture regulation, reducing the risk of desiccation-induced cracks and soil instability. Certain plant species also contribute to microbial activity that promotes natural soil aggregation and stabilization.

Plant-root reinforcement has been successfully implemented in slope protection projects, flood prevention initiatives, and ecological restoration efforts. Vegetative cover not only stabilizes slopes but also enhances biodiversity, mitigates the urban heat island effect, and improves aesthetic value. In coastal areas, mangroves and salt-tolerant grasses have been used to prevent shoreline erosion and protect infrastructure from storm surges.

One of the key advantages of plant-root reinforcement is its cost-effectiveness. Unlike mechanical stabilization methods that require extensive infrastructure and maintenance, vegetation-based approaches offer long-term stability with minimal input costs. Additionally, they contribute to carbon sequestration and improve air and water quality. However, the effectiveness of plant-root reinforcement depends on factors such as soil conditions, climate, and root development time, necessitating careful species selection and site-specific management strategies.

Bio-mediated soil improvement techniques present a sustainable and environmentally friendly alternative to conventional soil stabilization methods. MICP, bio-polymer treatment, and plant-root reinforcement each offer unique advantages in enhancing soil cohesion, reducing erosion, and improving slope stability. While these techniques have demonstrated promising results in laboratory and field applications, further research is needed to optimize their implementation, improve durability, and enhance scalability for large-scale infrastructure projects.

Future advancements in bio-mediated soil stabilization may include the integration of multiple techniques, such as combining MICP with bio-polymers or using engineered plant species for enhanced root reinforcement. Additionally, the development of smart monitoring systems using IoT and remote sensing could provide real-time data on soil stability, improving the effectiveness of bio-mediated solutions.

By harnessing natural biological processes, bio-mediated soil improvement offers a viable pathway toward more sustainable geotechnical engineering practices. Widespread adoption of these techniques could significantly reduce environmental impacts, lower construction costs, and contribute to more resilient infrastructure in landslide-prone areas worldwide[3].

3. Comparative Analysis of Bio-Mediated Techniques

Soil stabilization techniques play a critical role in preventing slope failures and ensuring infrastructure durability. Among bio-mediated approaches, microbial-induced calcite precipitation (MICP), bio-polymer treatments, and plant-root reinforcement have emerged as promising alternatives to conventional methods. Each technique operates through a unique mechanism, providing distinct advantages and facing specific challenges. The comparative analysis of these bio-mediated methods helps identify their suitability for various soil stabilization applications.

MICP utilizes bacterial activity to precipitate calcium carbonate (CaCO_3) within the soil matrix, forming a natural cementation that binds soil particles together. This process significantly enhances soil cohesion and reduces permeability, making it ideal for improving slope stability and erosion control. One of the key benefits of MICP is its long-term durability, as the precipitated CaCO_3 remains stable under varying environmental conditions. However, the method requires precise control of bacterial activity, chemical concentrations, and environmental factors, which can pose challenges in large-scale implementations.

Bio-polymer treatment, on the other hand, involves the introduction of biodegradable organic compounds such as xanthan gum and guar gum, which create an organic matrix within the soil. These polymers enhance soil cohesion, reduce water permeability, and improve resistance to erosion. The primary advantage of bio-polymer treatment lies in

its biodegradability and minimal environmental impact, making it a sustainable alternative to chemical stabilizers. However, the cost of bio-polymer production and its degradation over time may limit its large-scale adoption.

Plant-root reinforcement relies on natural root-soil interactions, where plant roots physically bind soil particles together, increasing shear strength and reducing susceptibility to erosion. This method is widely used in bio-engineering projects, particularly in regions prone to heavy rainfall and landslides. The advantages of plant-root reinforcement include its cost-effectiveness, ability to support biodiversity, and long-term ecological benefits. However, its effectiveness is dependent on factors such as plant species, soil composition, and climate conditions, making it less suitable for extreme environments.

By comparing these techniques, engineers and researchers can select the most appropriate method based on project requirements, soil conditions, and environmental considerations. The table below summarizes the comparative analysis of bio-mediated soil improvement techniques.

Table 1 Competitions of Bio-mediated soil improvement techniques

Technique	Mechanism	Key Benefits	Challenges
MICP	Bacterial CaCO ₃ precipitation	High strength, durable	Requires controlled conditions
Bio-Polymer Treatment	Organic matrix formation	Biodegradable, water retention	Cost of production
Plant-Root Reinforcement	Root-soil interaction	Natural erosion control	Limited effectiveness in extreme conditions

4. Case Studies and Experimental Results

To better understand the real-world applications of bio-mediated soil improvement techniques, case studies and experimental results provide valuable insights into their effectiveness and challenges. The following case studies highlight the implementation of MICP, bio-polymer treatment, and plant-root reinforcement in slope stabilization projects.

4.1. Case Study 1: MICP in Slope Stabilization

A field trial conducted in California demonstrated the effectiveness of MICP-treated slopes in reducing landslide risks. The study involved injecting ureolytic bacteria (*Sporosarcina pasteurii*) and calcium-rich compounds into a slope-prone region with weak soil properties. Over a period of several weeks, bacterial activity led to the precipitation of calcium carbonate, resulting in improved soil cohesion and shear strength.

The experimental results indicated that the MICP-treated slopes exhibited a 40% increase in shear strength compared to untreated soil. The treated area also showed a reduction in water permeability, which further contributed to slope stability. This case study highlights MICP's potential as a sustainable alternative to traditional chemical grouting for geotechnical applications.

4.2. Case Study 2: Bio-Polymer Application on Embankments

A research study conducted in India applied xanthan gum, a widely used bio-polymer, to a highway embankment in a monsoon-prone region. The primary objective was to evaluate the ability of bio-polymers to reduce soil erosion caused by heavy rainfall. The study involved spraying a bio-polymer solution over the embankment surface and monitoring its stability over multiple monsoon seasons.

The results demonstrated that the erosion rate was reduced by 30%, significantly enhancing the embankment's durability. Additionally, the treated soil retained moisture better than untreated soil, preventing desiccation cracks. The use of bio-polymers proved to be an effective and eco-friendly method for stabilizing highway embankments in regions with high rainfall intensity.

4.3. Case Study 3: Plant-Root Reinforcement in Riverbank Stabilization

A riverbank stabilization project in China utilized deep-rooted vegetation, including vetiver grass and willow trees, to prevent soil erosion and riverbank collapse. The project aimed to assess the role of plant-root reinforcement in maintaining slope integrity under fluctuating water levels and strong currents.

After several growing seasons, the treated riverbanks exhibited significant improvements in soil stability, reduced erosion, and increased biodiversity. The deep root systems of the selected plant species effectively anchored the soil, preventing sediment displacement. This case study emphasizes the ecological benefits of plant-root reinforcement and its potential in large-scale environmental restoration projects.

To further illustrate the effectiveness of bio-mediated soil improvement techniques, visual representations such as schematic diagrams and comparative bar charts provide valuable insights.

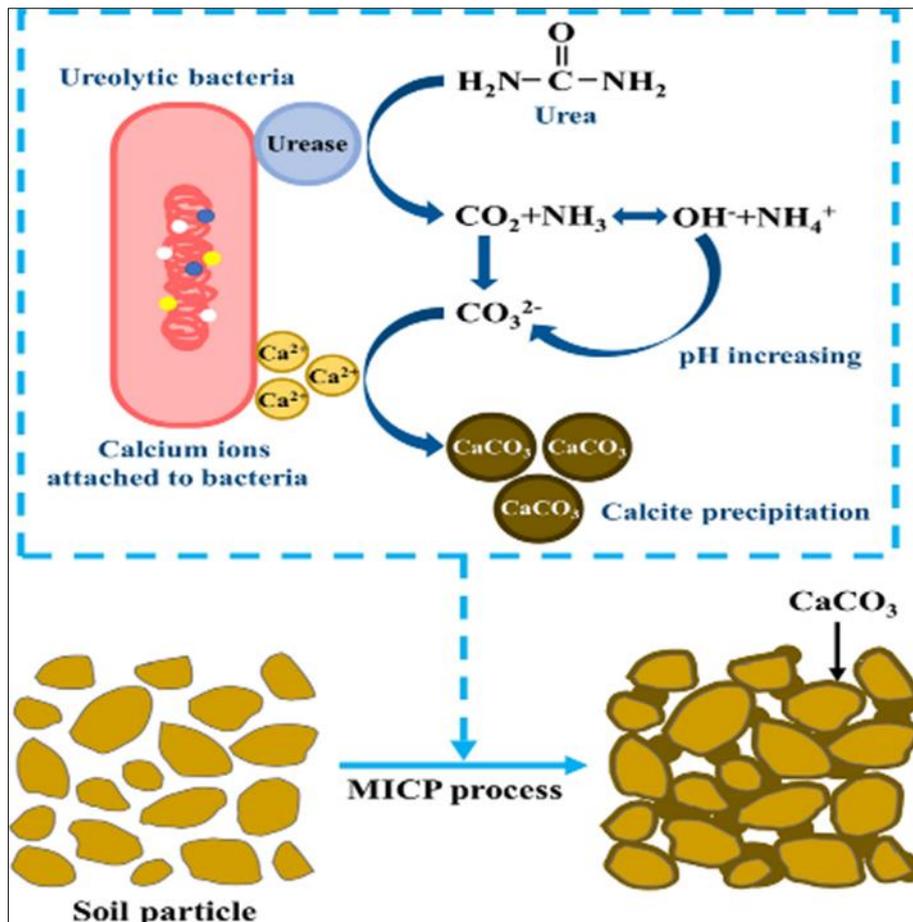


Figure 1 MICP Process for Soil Stabilization

A schematic diagram illustrating the role of ureolytic bacteria in CaCO_3 precipitation within soil, showcasing how bacterial activity leads to soil cementation and increased stability[4].

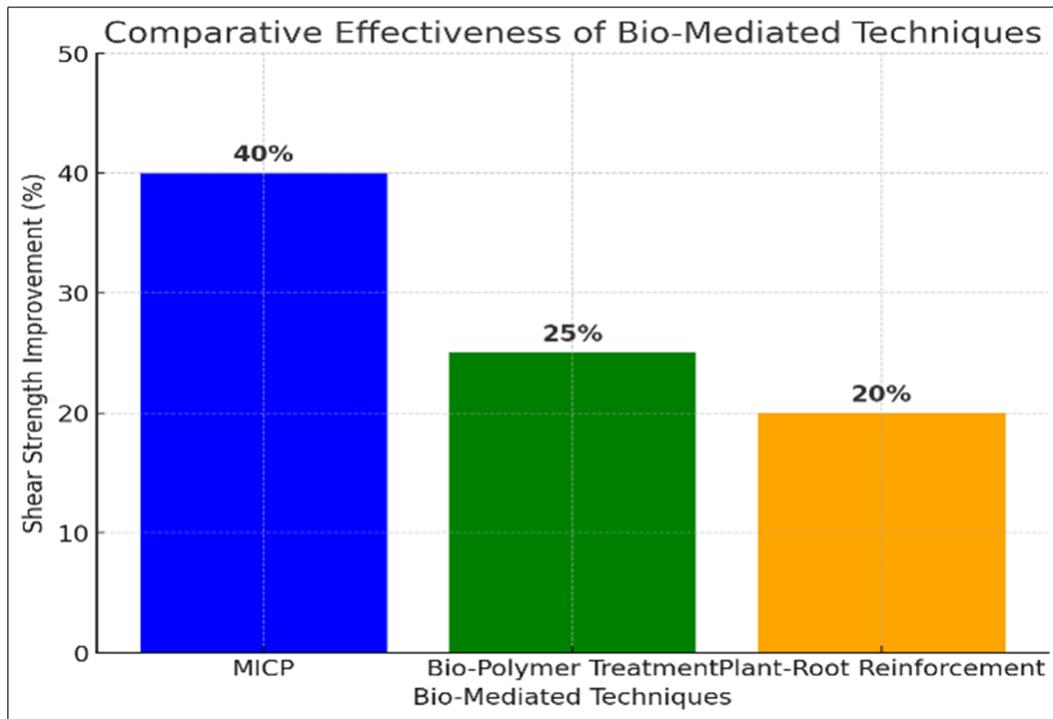


Figure 2 Comparative Effectiveness of Bio-Mediated Techniques

A bar chart comparing the shear strength improvement achieved through MICP, bio-polymer treatments, and plant-root reinforcement, based on experimental results.

The comparative effectiveness data suggest that:

- MICP demonstrates the highest improvement in shear strength due to its cementation effect.
- Bio-polymer treatments show moderate improvements, particularly in moisture retention and erosion control.
- Plant-root reinforcement provides long-term stabilization but is dependent on vegetation growth and soil conditions.

While bio-mediated soil improvement techniques offer sustainable alternatives, it is essential to compare them with traditional methods in terms of cost, environmental impact, durability, and scalability.

Table 2 Comparison of Traditional vs. Bio-Mediated Soil Improvement Techniques

Parameter	Traditional Methods	Bio-Mediated Methods
Cost	High	Moderate
Environmental Impact	High (carbon emissions, chemicals)	Low (eco-friendly, biodegradable)
Durability	High (cement, grouting)	Moderate to High
Scalability	High (widely implemented)	Moderate (requires further optimization)

Traditional soil stabilization methods such as cement grouting and mechanical reinforcements are highly durable and scalable but come at a significant environmental and economic cost. In contrast, bio-mediated techniques provide an eco-friendly alternative with moderate scalability, requiring further research to enhance their large-scale applications.

Bio-mediated soil improvement techniques have demonstrated their potential in providing sustainable and cost-effective solutions for slope stabilization. MICP, bio-polymer treatment, and plant-root reinforcement each offer distinct advantages that contribute to soil cohesion, erosion control, and environmental sustainability. While MICP provides

high-strength cementation, bio-polymer treatments enhance water retention, and plant-root reinforcement supports ecological restoration.

Future research directions should focus on enhancing the efficiency and scalability of these techniques. Integrating multiple bio-mediated approaches, such as combining MICP with bio-polymer treatment, could yield more robust stabilization solutions. Additionally, advancements in biotechnological engineering, IoT-based soil monitoring, and AI-driven predictive modeling can further optimize bio-mediated soil stabilization for real-world applications.

By embracing bio-mediated approaches, geotechnical engineers and policymakers can develop resilient, eco-friendly, and cost-effective solutions for infrastructure projects in landslide-prone regions, ultimately contributing to a more sustainable future in civil and environmental engineering[5].

5. Conclusion

Bio-mediated soil improvement techniques provide innovative and environmentally sustainable alternatives for stabilizing slopes and mitigating landslides. These methods leverage natural biological processes to enhance soil properties, improve cohesion, and reduce erosion, offering significant advantages over traditional chemical and mechanical stabilization techniques. Among the most promising bio-mediated methods are microbial-induced calcite precipitation (MICP), bio-polymer treatments, and plant-root reinforcement. Each of these approaches has distinct mechanisms, benefits, and challenges that influence their suitability for various applications in slope stabilization. MICP, which involves the use of bacteria such as *Sporosarcina pasteurii* to induce calcium carbonate (CaCO_3) precipitation within the soil matrix, has demonstrated significant improvements in soil shear strength and durability. The ability of ureolytic bacteria to hydrolyze urea and create conditions conducive to CaCO_3 precipitation enhances soil cohesion and reduces permeability, making MICP an effective solution for reinforcing slopes. However, challenges such as the need for controlled environmental conditions, long-term stability of the microbial activity, and potential cost barriers must be addressed to enable large-scale adoption. Bio-polymer treatments, which involve the application of biodegradable polymers like xanthan gum and guar gum, offer another promising approach to soil stabilization. These polymers create organic matrices within the soil, enhancing cohesion, increasing water retention, and reducing erosion. The advantages of bio-polymers include their adaptability to different soil types, sustainability, and minimal environmental impact. Nevertheless, concerns regarding the cost of bio-polymer production, degradation rates under varying climatic conditions, and potential variability in performance need to be further investigated. Plant-root reinforcement, a well-established bio-engineering approach, utilizes vegetation to improve soil stability through root-soil interactions. The deep and fibrous root systems of plants such as vetiver grass, willows, and bamboo contribute to soil anchoring, reducing erosion and increasing shear strength. This method is cost-effective, enhances biodiversity, and improves aesthetic value. However, its effectiveness is limited in extreme weather conditions, steep slopes, and regions with poor vegetation growth, necessitating a hybrid approach that combines plant-root reinforcement with other bio-mediated techniques.

Despite the potential of these bio-mediated approaches, challenges remain in scaling up their implementation for large infrastructure projects. The long-term durability of biologically induced soil improvements is a key area of concern, as microbial activity, bio-polymer stability, and plant-root interactions may degrade over time. Research into optimizing microbial strains for enhanced calcite precipitation, developing more resilient and cost-effective bio-polymers, and selecting plant species with high soil reinforcement potential will be critical in improving the longevity and effectiveness of these techniques. Furthermore, the integration of bio-mediated soil improvement methods with conventional engineering approaches can create hybrid stabilization strategies that maximize effectiveness while minimizing environmental impact. Advances in geotechnical engineering, biotechnology, and materials science can contribute to the refinement of bio-mediated techniques, improving their applicability across diverse geological conditions. Multi-disciplinary collaborations involving engineers, environmental scientists, and policymakers will be essential to addressing technical, economic, and regulatory challenges associated with bio-mediated soil stabilization. The role of policy and regulation in promoting bio-mediated soil stabilization should also be considered. Governments and environmental agencies can encourage the adoption of these sustainable practices through incentives, research funding, and guidelines that support eco-friendly soil stabilization projects. Establishing industry standards and best practices for the application of bio-mediated techniques will be necessary to facilitate widespread acceptance and implementation in construction and infrastructure projects. Moreover, field trials and case studies play a crucial role in demonstrating the real-world effectiveness of bio-mediated soil improvement methods. Large-scale experimental projects in different climatic and geological settings can provide valuable insights into the practical performance, scalability, and cost-effectiveness of these techniques. Lessons learned from successful case studies can inform future research and engineering practices, accelerating the transition from laboratory-scale research to full-scale application. As climate change continues to increase the frequency and severity of landslides and soil erosion, the need for

sustainable slope stabilization methods will become even more critical. Bio-mediated techniques align with global sustainability goals by reducing carbon footprints, minimizing chemical pollution, and utilizing renewable biological resources for soil improvement. Future advancements in biotechnology, nanotechnology, and artificial intelligence could further enhance the precision, efficiency, and adaptability of bio-mediated soil stabilization methods. In conclusion, bio-mediated soil improvement techniques present a promising and sustainable alternative to conventional soil stabilization methods. While significant progress has been made in understanding and applying methods such as MICP, bio-polymer treatments, and plant-root reinforcement, further research is needed to overcome challenges related to scalability, cost, and long-term performance. By fostering collaboration across scientific disciplines and promoting policy support, bio-mediated soil stabilization can become a mainstream solution for enhancing slope stability, protecting infrastructure, and mitigating landslide risks in an environmentally responsible manner.

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