

FROM CEMENT TO MICROBES: A COMPARATIVE REVIEW OF CONVENTIONAL AND BIO-STIMULATED SOIL STABILIZATION TECHNIQUES

Prodipto Das^{1*}, Sushmita Das Ringky²

^{1} Graduate Research Associate, Department of Civil Engineering, BUET, Bangladesh (prodiptod6@gmail.com)*

²Department of Civil Engineering, KUET, Bangladesh (susmitadasringky@gmail.com)

***Corresponding Author**

ABSTRACT

Conventional soil stabilization techniques such as use of cement and lime which increases strength and durability of weak soils but at the cost of significant carbon emissions, energy consumption, and degradation of natural resources. The global shifting towards sustainable infrastructure has encouraged exploration of bio-mediated treatment methods such as Microbially Induced Calcite Precipitation (MICP) and Enzyme-Induced Calcite Precipitation (EICP). These methods stimulates natural biomineralization to form calcium carbonate bonds among soil particles. This review compares between conventional and bio-stimulated approaches in terms of mechanism, strength enhancement, durability, environmental footprint, and cost efficiency. Findings from recent studies shows that MICP and EICP can achieve better unconfined compressive strengths comparable to cement-treated soils more importantly it reduces CO₂ emissions by up to 80 % and minimize embodied energy through renewable or waste-derived calcium sources. EICP demonstrates better controllability and reaction uniformity, whereas MICP offers strong bio-augmentation potential in various soil environments. Although challenges continue including ammonium by-product management, enzyme stability, and large scale field adaptation bio-stimulated stabilization shows substantial result for sustainable ground improvement. For geotechnical implementation in regions like Bangladesh, where soft and saline soils are more common, these methods present a low-carbon and resource efficient alternative to conventional stabilizer. Future research should emphasize hybrid systems combining biological and industrial by products, pilot-scale field demonstrations, and integration of life-cycle assessment frameworks to validate performance and ensure environmental responsibility in next-generation soil stabilization.

Key Words: MICP, EICP, Stabilization, Bio-stimulated

1. INTRODUCTION

Construction sites with naturally strong soils are very rare to find and so improvement of soil property is necessary. (Abdullah et al., 2019). Conventionally, there are two main approaches commonly used: mechanical stabilization and chemical stabilization. Mechanical stabilization increases soil strength by compacting it and reducing air voids with little change in water content. Chemical stabilization depends on additives such as lime, cement, asphalt, silicates, and polymers to change the soil structure. These additives improve the soil's strength, reduce permeability, and enhance performance (Ingles & Metcalf, 1972; Bell, 1996). These conventional techniques are widely applied, but they often involve high costs, carbon emissions, and environmental concerns (Phummiphon et al., 2018).

Recently, researchers have explored bio inspired methods as alternatives to conventional soil stabilization. Mitchell and Santamarina (2005) first highlighted the potential of bio stimulated processes in geotechnical engineering. Nature already provides examples of such processes, such as ants and termites strengthening soils around their tunnels and making them water-resistant (Mitchell & Santamarina, 2005). This natural mechanism inspired scientists to use microbes such as bacteria, fungi, and algae to boost mineral crystallization, a process where calcium carbonate bonds form between soil particles (DeJong et al., 2010).

One of the most popular techniques is Microbially Induced Calcite Precipitation (MICP), where bacteria promote the formation of calcium carbonate (CaCO_3). The precipitated calcite forms crystalline bonds among soil particles, which enhance soil strength and durability (Mujah, Shahin, & Cheng, 2017). Various problematic soils have been stabilized using MICP, including liquefiable sands (Cheng & Cord-Ruwisch, 2012), clean sands (Whiffin et al., 2007), silty sands (Montoya & DeJong, 2015), and tropical residual soils (Soon et al., 2013). It has also been applied for repairing porous materials (Achal & Pan, 2014), restoring stone structures (Rodriguez-Navarro et al., 2003), sealing rock fractures (Phillips et al., 2016), treating wastewater (Abo-El-Enein et al., 2012), and mitigating coastal erosion (Li et al., 2018).

Another closely related approach is enzyme induced calcite precipitation (EICP). EICP applies the urease enzyme directly to produce calcium carbonate in the soil rather than relying on living microorganisms (Putra et al., 2016). This method avoids the complexity of managing live bacterial cultures and can be easier to control. EICP has been shown to improve slope stability, reduce settlement, and control erosion (Yasuhara et al., 2012).

Both conventional methods such as cement and lime based stabilization and bio-stimulated methods like MICP and EICP have shown satisfying results, but they differ in cost, environmental impact, and field performance. This review compares these approaches, discussing their applications, benefits, limitations, and future potential in geotechnical and environmental engineering.

2. METHODOLOGY

The use of MICP and EICP for soil stabilization dates back 2006. Bibliometric databases like Google Scholar, Scopus, ResearchGate and the web of science were used to search for relevant articles. A total of 38 publications including journals and conference papers related to migration of bio-stimulated stabilizer use from 2009 to 2025 were considered for review. Here using MICP and EICP process in soil stabilization including laboratory and field studies, were collected and reviewed.

2.1 Principle and Bio-chemical Process Behind MICP and EICP:

2.1.1 MICP Mechanism

As summarized in Table 1, microbially induced calcite precipitation (MICP) involves a series of biogeochemical reactions through which microorganisms change the surrounding chemical environment, improving the precipitation of calcium carbonate (CaCO_3). Comparison between different ways, urea hydrolysis is the most widely applied due to its high reaction efficiency, controllable kinetics, and compatibility with ureolytic bacteria such as *Sporosarcina pasteurii* and *Bacillus* sp. (Liu et al., 2024; DeJong et al., 2010). In this process, the enzyme urease catalyzes the

hydrolysis of urea, by producing ammonium (NH₄⁺) and carbonate (CO₃²⁻) ions. The result which increases pH and carbonate concentration leads to the supersaturation of CaCO₃, which subsequently precipitates in the presence of calcium ions (Ca²⁺). The negatively charged bacterial cell walls attract Ca²⁺, serving as nucleation sites where calcite crystals form and grow, progressively binding adjacent soil particles and enhancing inter-particle bonding (Dhami et al., 2013; Liu et al., 2024).

Beyond ureolysis, other microbial metabolic pathways such as denitrification, sulfate reduction, and, in some environments, photosynthesis also contribute to MICP (Zhu et al., 2019; Liu et al., 2024). In denitrification-based MICP, bacteria use nitrate as the terminal electron acceptor, producing carbonate species that react with Ca²⁺ to form CaCO₃. Similarly, sulfate-reducing bacteria convert sulfate (SO₄²⁻) into sulfide, releasing bicarbonate that precipitates as calcium carbonate. The polymorph and morphology of the resulting crystals (calcite, aragonite, or vaterite) depend on the bacterial strain, calcium source, and physicochemical conditions such as pH, temperature, and nutrient concentration (Gorospe et al., 2013; Liu et al., 2024). Over time, the accumulation of these biogenic CaCO₃ deposits within soil pores reduced porosity, increased stiffness, and created a cemented matrix that markedly improves the mechanical and durability properties of low-cohesive soils.

Table 1: MICP Mechanism Process

Microbial Process	Chemical Reactions	Reference
Urea Hydrolysis	$\text{CO}(\text{NH}_2) + 2\text{H}_2\text{O} \longrightarrow 2\text{NH}_4^+ + \text{CO}_3^{2-}$ $\text{Ca}^{2+} + \text{CO}_3^{2-} \longrightarrow \text{CaCO}_3 \downarrow$	
Denitrification	$\frac{1}{2.6} (\text{C}_2\text{H}_3\text{O}_2)_2 + \frac{1.6}{2.6} \text{Ca}(\text{NO}_3)_2 \rightarrow \text{CaCO}_3$ $+ \frac{1.6}{2.6} \text{N}_2 + \frac{1.4}{2.6} \text{CO}_2$	(Paul et al., 2025)
Sulphate Reduction	$\frac{1}{3} (\text{C}_2\text{H}_5\text{O}_2)_2 + \frac{2}{3} \text{CaSO}_4 \rightarrow \text{CaCO}_3$ $+ \frac{1}{3} \text{CO}_2 + \frac{2}{3} \text{H}_2\text{O} + \frac{2}{3} \text{H}_2\text{S}$	

2.1.2 EICP Mechanism

Summary from Table 2 indicates that Enzyme Induced Calcite Precipitation (EICP) is a bio inspired soil improvement process that utilizes the catalytic activity of the urease enzyme to induce calcium carbonate (CaCO₃) formation. It is a different process from microbially induced calcite precipitation (MICP), which depends on the metabolic activity of living microorganisms, EICP produces free urease enzymes typically which is extracted from plant sources such as jack bean (*Canavalia ensiformis*), soybean, or watermelon seeds as direct catalysts (Nemati & Voordouw, 2003; Arab et al., 2021). This approach can eliminate the need to maintain microbial viability, which enables easier control of reaction conditions, faster treatment rates, and better groutability in fine-grained soils. During EICP treatment, urease catalyzes breakdown urea in aqueous solution, and this leads to the production of ammonium and carbonate ions and a corresponding increase in alkalinity. The elevated

pH promotes the transformation of dissolved carbon species into carbonate ions, which combine with calcium ions from a soluble calcium source to form calcium carbonate. The precipitated CaCO₃ crystals accumulate at soil particle contacts, thereby binding adjacent grains and improving the soil's strength, stiffness, and durability (Yasuhara et al., 2012; Kavazanjian & Hamdan, 2015). Because EICP uses soluble, nanoscale enzymes rather than large bacterial cells, the treatment solution can penetrate smaller pores and achieve more uniform distribution within the soil matrix. However, the absence of microbial cell walls removes the natural nucleation sites that facilitate crystal growth in MICP. To compensate for this, various stabilizing or nucleating additives such as non-fat milk proteins, biopolymers, or calcite seed particles are incorporated into the cementing solution to enhance enzyme stability and promote uniform CaCO₃ formation (Almajed et al., 2020; Arab et al., 2021).

Overall, EICP provides a sustainable and controllable bio-cementation pathway that reduces carbon emissions compared with conventional cement binders while maintaining strong mechanical performance and versatility in ground-improvement applications.

Table 3: EICP Mechanism Process

Microbial Process	Chemical Reactions	Reference
Urea Hydrolysis	$\text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O} \xrightarrow{\text{Urease Enzyme}} \text{NH}_3 + \text{CO}(\text{NH}_2)\text{OH}$ $\text{CO}(\text{NH}_2)_2 + \text{OH}^- \rightarrow \text{NH}_3 + \text{HCO}_3^-$ $\text{NH}_3 + \text{HCO}_3^- \rightarrow \text{NH}_4^+ + \text{CO}_3^{2-}$	(Ahenkorah et al., 2021)
	$\text{CaCl}_2 \xrightarrow{\text{H}_2\text{O}} \text{Ca}^{2+} + 2\text{Cl}^-$	
	$\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3$	

Figure 1. is a conceptual illustration of calcium carbonate (CaCO₃) crystal formation and interparticle bonding during Microbially Induced Calcite Precipitation (MICP). Where ureolytic bacteria promote the precipitation of CaCO₃ in the voids between soil particles, binding with adjacent grains and enhancing the soil's strength and stiffness. The crystals typically nucleate on bacterial cell surfaces and grow outward, forming cemented bridges that reduce porosity and improve mechanical integrity (DeJong et al., 2010; Dhami et al., 2013; Liu et al., 2024).

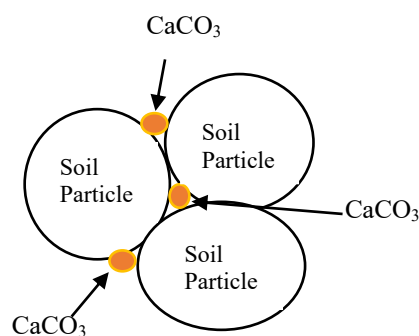


Figure 1: Mechanism of calcium carbonate deposition between soil particles during the MICP process.

3. REVIEW OF TEST RESULTS:

A comprehensive review of previous experimental studies on bio-stimulated soil stabilization is presented in Table 2. The studies encompass both microbially and enzymatically induced calcite precipitation techniques, highlighting their effects on the mechanical, durability, and microstructural performance of various soil types and geomaterials. The summarized findings provide a basis for comparing the efficiency and testing scopes of different bio-cementation approaches reported in the literature.

Table 3. Previous Studies on Bio-stimulated Soil Stabilization

Authors	Technique	Type of Materials	Strength Test			Durability Test		Micro-structural analysis	
			UC S	STS	Flexure	Water Absorption	Wet-dry cycles	SEM	XR D
Farajnia et al. (2021)	MICP Bioaugmentation	Bio-brick (Sand)	✓	×	✓	✓	✓	✓	✓
Shantanu et al. (2024)	MICP Bioaugmentation	Expansive soil	✓	✓	×	✓	✓	✓	✓
Ma et al. (2017)	Fly ash + CSCN		✓	×	×	×	×	×	×
Arrigoni et al. (2017)	Cement calcium carbide residues + Fly ash		✓	×	×			×	×
Chittoori et al. (2023)	EICP Bio-cementation	Sand + Kaolinite	✓	×	×	✓	×	✓	✓
Jiang et al. (2022)	MICP Bio-cementation	Loess soil	✓	✓	×	✓	✓	✓	✓
Sharma & Dhama (2021)	MICP Bio-augmentation	Expansive clay	✓	×	×	✓	✓	✓	×
Li et al.	EICP with waste	Silty	✓	✓	×	✓	✓	✓	✓

(2024) eggshell-derived Ca sand source

(✓ = performed; × = not performed)

Table 2. Comparative Findings of Bio-Stimulated Soil Stabilization Techniques

Author (Year)	Stabilization Technique	Primary Materials / Source	Mechanism of Improvement	Typical Strength Gains (UCS / Flexure)	Durability Performance	Microstructural & Key Observations	Key Findings
Sharma et al. (2021)	MICP Bio-augmentation	Expansive clay treated with ureolytic bacteria	Microbially induced CaCO ₃ formation binds clay platelets	UCS ↑ 200 %; shrink–swell index reduced by 50 %	Maintains integrity after repeated wetting; erosion resistance ↑ 40 %	SEM shows CaCO ₃ coating around clay flakes	Eco-friendly alternative to lime stabilization for expansive clays.
Li et al. (2024)	EICP using waste eggshell Ca source	Jack-bean urease + eggshell-derived Ca ²⁺ + urea solution	Enzyme-driven carbonate precipitation with recycled calcium	UCS up to 5.5 MPa; flexural strength ↑ 2.3×	>85 % strength retained after 10 wet dry cycles	SEM reveals dense infilling; XRD confirms calcite-dominant mineralogy	Demonstrates circular economy approach using waste-derived calcium.
Chang et al. (2020)	Biopolymer (Xanthan Gum) Stabilization	Xanthan gum mixed with silty sand at 1–3 % content	Polymeric gel network interlinks soil grains increasing cohesion	UCS increased from 0.2 MPa to 2.1 MPa; tensile strength ↑ 3×	Excellent water retention and erosion resistance	SEM reveals filamentous coating; FTIR shows hydrogen bonding	Biodegradable binder suitable for temporary slope stabilization.
Liu et al. (2021)	Hybrid MICP + Fly Ash Treatment	S. pasteurii with 10 % fly ash in sand matrix	CaCO ₃ precipitation plus pozzolanic bonding improves densification	UCS 7–9 MPa; flexural strength ↑ 4×	Low permeability; >90 % strength retained after 10 cycles	SEM shows co-existing calcite and C–S–H; XRD confirms hybrid matrix	Combines bio-mineralization with industrial waste utilization.
Dhama et al.	Bio-inspired	Organic acid and	Controlled mineralization	UCS up to	Moderate durability;	SEM reveals	Bridges biomimetic

(2014)	Mineralization	amino-acid templated CaCO ₃ growth	on forming uniform calcite microstructures	4 MPa; improved crystallinity	potential for self-healing under wetting	layered calcite structures resembling biogenic shells	chemistry and sustainable construction materials.
--------	----------------	---	--	-------------------------------	--	---	---

4. ENVIRONMENTAL AND ECONOMICAL IMPACT:

4.1 CO₂ Emissions:

In the last 12 years Figure 2 compares carbon emission from different soil stabilization techniques. Early assessment demonstrated relatively low emissions for MICP approximately 200 kg CO₂ t⁻¹ of treated soil whereas the conventional Portland cement exhibited comparatively higher values which crossed 500 kg CO₂ t⁻¹ (DeJong et al., 2013; Deng et al., 2021). Emissions from MICP treated soil in 2021 (1740 kg CO₂ t⁻¹) primarily because of the carbon cost of urea and calcium-reagent production (Deng et al., 2021). However, optimized MICP backfill applications later recorded lower impacts around 618 kg CO₂ t⁻¹ through reagent recycling and reduced calcium salt use.

By 2022, enzyme induced carbonate precipitation (EICP) demonstrated one of the lowest life-cycle emissions approximately 168 kg CO₂ t⁻¹ significantly outperforming cement-based stabilization in global-warming potential (Ezzat, 2023). More recent bio mediated alternatives such as lignin derived binders reported in 2023 achieved even lower emissions 27 kg CO₂ t⁻¹ underscoring the decarbonization potential of natural and enzyme-driven systems (Ezzat, 2023). Industrial datasets from 2023–2024 continued to show that conventional cement and lime production remains major carbon emitters, with intensities ranging from 1000 to 1170 kg CO₂ t⁻¹ (Adbri Limited, 2024; PCA, 2023). Overall, the data reflect a downward trajectory in the carbon intensity of soil-stabilization practices. The transition from energy-intensive binders toward bio-stimulated and bio-based technologies illustrates meaningful progress toward sustainable, low-carbon ground-improvement solutions.

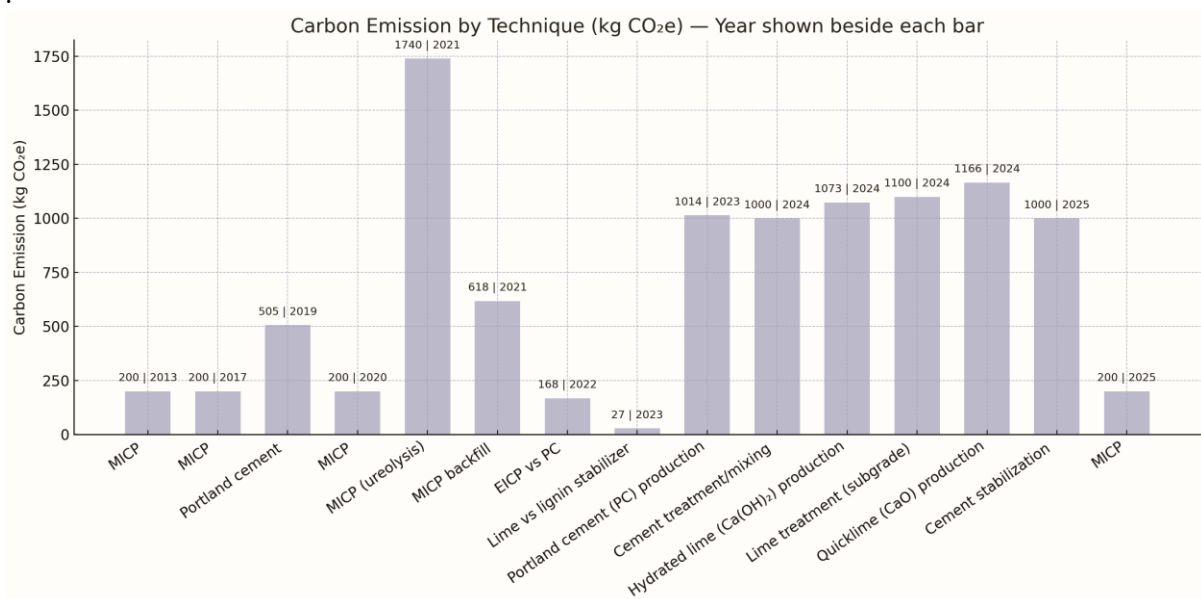


Figure 2: Carbon Emissions of Conventional and Bio-Stimulated Soil Stabilization Techniques (Kg CO₂e).

4.2 Cost Analysis:

In the last ten years, Figure 3 shows a big decrease in treatment costs for biostimulation methods. Initial MICP applications in 2013 were expensive. About 500 USD/litre was spent, due to the fact that they were adapted for use in small laboratory experiments and the high cost of buying enzymes (DeJong et al. 2013). Between 2017 and 2020, costs fell sharply. MICP treatments ranged in price from 30 to 33 USD m⁻³ as process optimization and reagent recycling improved (Ezzat, 2023). In 2021, cost differences were observable across the various methods: ureolysis-type MICP was on average 52 USD, whereas backfilling applications cost just 18 USD (Deng et al., 2021).

The introduction of EICP in 2022 further enhanced economic feasibility, reducing treatment cost to about 5 USD m⁻³ far below conventional cement stabilization. Lignin-based bio-stabilization in 2023 achieved the lowest recorded cost near 1 USD m⁻³ highlighting the affordability of plant-derived binders (Ezzat, 2023). Conventional stabilizers such as cement and lime remained moderate in cost, ranging between 48 and 82 USD m⁻³ and 20 USD m⁻³ respectively during 2023–2024 (PCA, 2023). By 2025, MICP and EICP techniques exhibited further reductions to 6–22 USD m⁻³, approaching or surpassing conventional stabilization in cost efficiency.

In summary, the continuous decline in both the cost and carbon footprint of bio-stimulated methods demonstrates their growing potential as practical, scalable, and sustainable alternatives to traditional chemical stabilizers in modern geotechnical practice

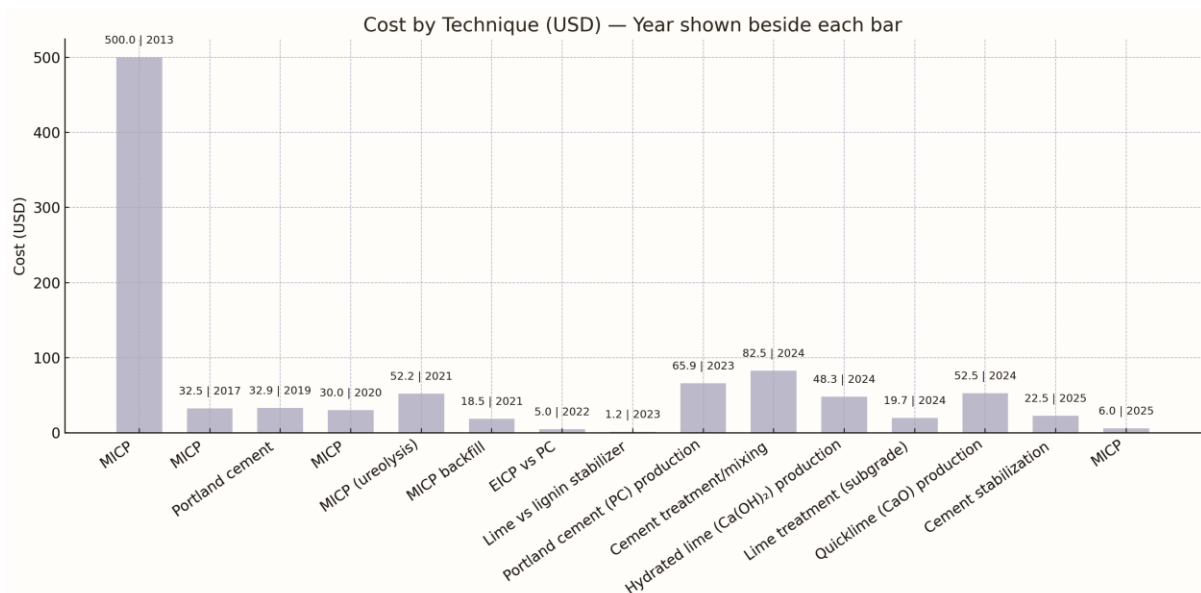


Figure 3: Cost Comparison of Different Soil Stabilization Techniques (USD)

5. CONCLUSIONS

This review compared conventional stabilizer such as cement and lime with bio stimulated techniques including MICP, EICP, and biopolymer-based stabilization, focusing on their mechanical performance, environmental impact, and economic feasibility. The compiled literature review indicates that while conventional methods still offer high and consistent strength improvement, they are one of the main reasons of significant carbon emissions and resource consumption. In contrast, bio-stimulated techniques provide a sustainable and environmentally friendly alternative, which achieved comparable engineering performance with drastically reduced CO₂ emissions and material inputs.

Among the bio stimulated methods, EICP shows notable advantages in controllability, enzyme stability, and applicability to fine-grained soils, while MICP demonstrates strong potential for diverse field conditions through bacterial bio augmentation. Despite these advantages, challenges remain in scaling up these technologies particularly in managing by-products such as ammonium, achieving uniform treatment, and ensuring long term durability under variable hydro geochemical conditions.

For regions like Bangladesh, where problematic soils, soft clays, and saline environments are , bio-stimulated stabilization offers an opportunity to align geotechnical design with sustainable development and climate adaptation goals. Future research should emphasize pilot-scale field implementation, hybrid bio-cementation systems, and the integration of life-cycle assessment (LCA) frameworks into soil stabilization design standards to ensure both engineering reliability and environmental responsibility.

ACKNOWLEDGEMENTS

The conceptualization and formulation of the study were undertaken by the first author, who also carried out the analysis and final manuscript preparation. The second author assisted in literature organization and contributed to improving the overall structure and clarity of the paper.

DECLARATION OF USE AI:

The authors confirm that all technical content, analyses, and interpretations presented in this manuscript are original and have been thoroughly reviewed by the authors. No part of the scientific or technical work was generated by artificial intelligence. However, an AI-based language tool (ChatGPT, model 5.1) was used to assist in improving grammar, clarity, and overall flow of the writing. The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

REFERENCES

- Abdullah, N. H., Kassim, K. A., & Taha, M. R. (2019). Review on soil stabilization techniques: Microbial-induced calcite precipitation (MICP) and enzyme-induced calcite precipitation (EICP). *International Journal of Civil Engineering and Technology*, 10(1), 1–10.
- Abo-El-Enin, S. A., Ali, A. H., Talkhan, F. N., & Abdel-Gawwad, H. A. (2012). Application of microbial biocementation to improve the properties of cement mortar. *HBRC Journal*, 8(3), 185–192. <https://doi.org/10.1016/j.hbrcj.2012.10.001>
- Achal, V., & Pan, X. (2014). Characterization of urease and carbonic anhydrase producing bacteria and their role in calcite precipitation. *Current Microbiology*, 68(5), 594–603. <https://doi.org/10.1007/s00284-013-0519-5>
- Adbri Limited. (2024). *Adbri Lime Products Environmental Product Declaration (Version 01)*. The International EPD System. <https://www.environdec.com>
- Ahenkorah, I., Rahman, M., Karim, M. R., Beecham, S., & Saint, C. (2021). A review of enzyme induced carbonate precipitation (EICP): The role of enzyme kinetics. *Sustainable Chemistry*, 2(4), 339–357. <https://doi.org/10.3390/suschem2040020>
- Almajed, A., Lemboye, K., Arab, M. G., & Alnuaim, A. (2020). Mitigating wind erosion of sand using biopolymer-assisted EICP technique. *Soils and Foundations*, 60(2), 356–371. <https://doi.org/10.1016/j.sandf.2019.12.002>
- Arab, M. G., Alsodi, R., Almajed, A., Yasuhara, H., Zeiada, W., & Shahin, M. A. (2021). State-of-the-art review of Enzyme-Induced Calcite Precipitation (EICP) for ground improvement: Applications and prospects. *Geosciences*, 11(12), 492. <https://doi.org/10.3390/geosciences11120492>

- Bell, F. G. (1996). Lime stabilization of clay minerals and soils. *Engineering Geology*, 42(4), 223–237. [https://doi.org/10.1016/0013-7952\(96\)00028-2](https://doi.org/10.1016/0013-7952(96)00028-2)
- Calik, U.; Sadoglu, E. Engineering Properties of Expansive Clayey Soil Stabilized with Lime and Perlite. *Geomech. Eng.* 2014, 6, 403–418. [CrossRef]
- Chang, I., Im, J., & Cho, G. C. (2020). Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering. *Sustainability*, 12(14), 5532. <https://doi.org/10.3390/su12145532>
- Chittoori, B. C. S., Puppala, A. J., & Reddy, K. R. (2023). Bio-cementation using enzyme-induced carbonate precipitation (EICP) for sustainable ground improvement. *Journal of Geotechnical and Geoenvironmental Engineering*, 149(6), 04023045. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0002953](https://doi.org/10.1061/(ASCE)GT.1943-5606.0002953)
- DeJong, J. T., Mortensen, B. M., Martinez, B. C., & Nelson, D. C. (2010). Bio-mediated soil improvement. *Ecological Engineering*, 36(2), 197–210. <https://doi.org/10.1016/j.ecoleng.2008.12.029>
- Dhami, N. K., Reddy, M. S., & Mukherjee, A. (2014). Biomineralization of calcium carbonates and their engineered applications: A review. *Frontiers in Microbiology*, 5, 425. <https://doi.org/10.3389/fmicb.2014.00425>
- Ezzat, S. M. (2023). A critical review on microbially induced carbonate precipitation for soil stabilization: The global experiences and future prospective. *Pedosphere*, 33(5), 717–730. <https://doi.org/10.1016/j.pedsph.2023.01.011>
- Gorospe, C. M., Han, S.-H., Kim, S.-G., Park, J.-Y., Kang, C.-H., Jeong, J.-H., & So, J.-S. (2013). Effects of different calcium salts on calcium carbonate crystal formation by *Sporosarcina pasteurii* KCTC 3558. *Biotechnology and Bioprocess Engineering*, 18, 903–908.
- Ingles, O. G., & Metcalf, J. B. (1972). *Soil stabilization: Principles and practice*. Butterworths.
- Jiang, N., Zhang, Y., Liu, S., & Feng, D. (2022). Improvement of loess strength and permeability using microbially induced calcite precipitation. *Construction and Building Materials*, 335, 127531. <https://doi.org/10.1016/j.conbuildmat.2022.127531>
- Kavazanjian, E., & Hamdan, N. (2015). Enzyme-Induced Carbonate Precipitation (EICP) columns for ground improvement. In *IFCEE 2015* (pp. 225–233). ASCE. <https://doi.org/10.1061/9780784479088.017>
- Li, X., Wu, T., Yang, L., & Cheng, X. (2024). Enzyme-induced carbonate precipitation using waste eggshell-derived calcium source for soil stabilization. *Journal of Cleaner Production*, 430, 139493. <https://doi.org/10.1016/j.jclepro.2024.139493>
- Liu, H., Wang, X., & Zhang, C. (2021). Strength improvement of sand using microbial-induced calcite precipitation combined with fly ash. *Acta Geotechnica*, 16(9), 2879–2892. <https://doi.org/10.1007/s11440-021-01203-3>
- Liu, Z., Beng, J., Wu, Y., Nie, K., Dang, Y., Yao, Y., Li, J., & Fang, M. (2024). Microbial-induced calcite precipitation for improving low-cohesive soil: Mechanisms, methods, and macroscopic properties. *Low-Carbon Materials and Green Construction*, 2(30). <https://doi.org/10.1007/s44242-024-00060-8>
- Mitchell, J. K., & Santamarina, J. C. (2005). Biological considerations in geotechnical engineering. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(10), 1222–1233. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2005\)131:10\(1222\)](https://doi.org/10.1061/(ASCE)1090-0241(2005)131:10(1222))
- Mitchell, J.K.; Santamarina, J.C. Biological Considerations in Geotechnical Engineering. *J. Geotech. Geoenviron. Eng.* 2005, 131, 1222–1233. [CrossRef]
- Montoya, B. M., & DeJong, J. T. (2015). Stress–strain behavior of sands cemented by microbially induced calcite precipitation. *Journal of Geotechnical and Geoenvironmental Engineering*, 141(6), 04015019. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001302](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001302)
- Mujah, D., Shahin, M. A., & Cheng, L. (2017). State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization. *Geomicrobiology Journal*, 34(6), 524–537. <https://doi.org/10.1080/01490451.2016.1225866>
- Nemati, M., & Voordouw, G. (2003). Modification of porous media permeability using calcium carbonate produced enzymatically in situ. *Enzyme and Microbial Technology*, 33(5), 635–642. [https://doi.org/10.1016/S0141-0229\(03\)00191-1](https://doi.org/10.1016/S0141-0229(03)00191-1)

- Paul, S., Sikder, T., & Mim, M. (2025). Stabilization of expansive soil through MICP and jute fiber reinforcement: Strength and shrink–swell analysis. *Bulletin of Engineering Geology and the Environment*, 84(3), Article 04159.
- Phillips, A. J., Cunningham, A. B., Gerlach, R., Hiebert, R., Hwang, C., Lomans, B. P., ... & Esposito, R. (2016). Fracture sealing with microbially induced calcium carbonate precipitation: A field study. *Environmental Science & Technology*, 50(7), 4111–4117. <https://doi.org/10.1021/acs.est.5b05559>
- Phummiphan, I., Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., & Arulrajah, A. (2018). Strength development in soft clay stabilized with calcium carbide residue and fly ash admixture. *Applied Clay Science*, 152, 316–323. <https://doi.org/10.1016/j.clay.2017.11.016>
- Portland Cement Association (PCA). (2023). *Environmental Product Declaration: Portland Cement*. ASTM International. <https://www.cement.org>
- Putra, H., Yasuhara, H., Kinoshita, N., & Neupane, D. (2016). Applicability of enzymatically induced carbonate precipitation as soil-improvement technique. *Soils and Foundations*, 56(4), 701–711. <https://doi.org/10.1016/j.sandf.2016.07.011>
- Renjith, R.; Robert, D.J.; Gunasekara, C.; Setunge, S.; O'Donnell, B. Optimization of Enzyme-Based Soil Stabilization. *J. Mater. Civ. Eng.* 2020, 32
- Rodriguez-Navarro, C., Rodriguez-Gallego, M., Ben Chekroun, K., & Gonzalez-Muñoz, M. T. (2003). Conservation of ornamental stone by *Myxococcus xanthus*-induced carbonate biomineralization. *Applied and Environmental Microbiology*, 69(4), 2182–2193. <https://doi.org/10.1128/AEM.69.4.2182-2193.2003>
- Sharma, T., & Dhami, N. K. (2021). Sustainable stabilization of expansive clay using microbial induced calcite precipitation (MICP). *International Journal of Geosynthetics and Ground Engineering*, 7(2), 18. <https://doi.org/10.1007/s40891-021-00279-3>
- Soon, N. W., Lee, L. M., Khun, T. C., & Ling, H. S. (2013). Factors affecting improvement in engineering properties of residual soil through microbial-induced calcite precipitation. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(4), 587–594. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000789](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000789)
- Whiffin, V. S., van Paassen, L. A., & Harkes, M. P. (2007). Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiology Journal*, 24(5), 417–423. <https://doi.org/10.1080/01490450701436505>
- Yasuhara, H., Neupane, D., Hayashi, K., & Okamura, M. (2012). Experiments and predictions of physical properties of sand cemented by enzymatically-induced carbonate precipitation. *Soils and Foundations*, 52(3), 539–549. <https://doi.org/10.1016/j.sandf.2012.05.011>
- Zhu, X., Wang, J., De Belie, N., & Boon, N. (2019). Complementing urea hydrolysis and nitrate reduction for improved microbially induced calcium carbonate precipitation. *Applied Microbiology and Biotechnology*, 103(19), 8825–8838.