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A Critical Review of MICP and EICP for Sustainable Soil Stabilization: Mechanisms, Engineering Performance, Environmental Trade-Offs, and Implementation Challenges

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Abstract - Traditional cement- and lime-based soil stabilization's environmental constraints have driven the search for sustainable alternatives in geotechnical engineering. Bio-mediated methods like Microbial-Induced Calcite Precipitation (MICP) and Enzyme-Induced Calcite Precipitation (EICP) are gaining attention for their ability to improve soil properties through biologically induced calcium carbonate. This review covers recent advances (2020–2026) on mechanisms, performance, sustainability, and challenges of MICP and EICP for soil stabilization, based on about 120 peer-reviewed studies from major databases. EICP typically shows better penetration in fine soils due to no bacterial size limits, while MICP offers stronger bonding in granular soils from bacterial nucleation. Significant progress has been made in strength, permeability, erosion, and swelling, but issues like non-uniform treatment, ammonia release, brittleness, cost, and durability remain barriers. Tropical lateritic soils are understudied despite their importance in developing countries. Emerging techniques like non-ureolytic methods, fiber systems, nanomaterials, and waste reagents show promise for sustainability and field use. Future work should focus on field validation, durability testing, eco-friendly precipitation, and standard design to move bio-stabilization from research to real-world infrastructure.

Keywords: Microbial-Induced Calcite Precipitation, Enzyme-Induced Calcite Precipitation, Biomineralization, Sustainable Soil Stabilization, Bio-Cementation.

I. INTRODUCTION

The demand for sustainable infrastructure renews interest in ground improvement technologies that offer engineering performance with minimal environmental impact (Haque and Uddin, 2024). Traditional stabilization with Portland cement and lime remains common for weak soils due to proven effectiveness; however, concerns over cement's high embodied energy, greenhouse gases, and environmental footprint have increased the search for alternative, low-carbon solutions in geotechnical engineering (Mohammed et al., 2023). Bio-mediated soil stabilization is sustainable, using biological mineral precipitation to enhance soil properties. Almajed et al. (2021) regard it as eco-friendly because it uses biochemical reactions instead of energy-intensive cement. Fu et al. (2023a) showed calcium carbonate precipitation can strengthen soil, lower permeability, and improve mechanics, indicating bio-cementation as a bio-geochemical and geotechnical process. Microbial-induced calcite precipitation (MICP) and enzyme-induced calcite precipitation (EICP) are recent biomineralization techniques gaining attention (Zhang et al., 2023). MICP uses ureolytic bacteria like Sporosarcina pasteurii to catalyze urea hydrolysis and promote calcite growth, with bacterial surfaces as nucleation sites (Payan et al., 2024). EICP, a cell-free process using enzymes, avoids bacteria, improving treatment penetration and ease of implementation, but raises enzyme stability concerns (Saif et al., 2022). Performance varies due to different nucleation, transport, and precipitation mechanisms, with EICP being advantageous in finer soils (Almajed et al., 2021). Ureolysis releases ammonium ions that could cause environmental issues like ammonia emissions and eutrophication; hence, sustainability depends on factors like reagent sourcing, ammonia management, and energy use (Wang et al., 2024).

Recent studies show MICP and EICP improve soil properties. Almajed *et al.* (2020) found EICP-treated sands gained strength; Liu *et al*. (2021) report bio-cementation boosts erosion resistance. Eryürük *et al*. (2025) observed MICP increases stiffness and shear resistance. Gowthaman *et al*. (2023) demonstrated low-cost EICP works in sandy soils, showing field potential. Boruah et al. (2025) identified key factors: soil density, treatment cycles, bacterial activity, and calcium carbonate distribution. Despite progress, issues like non-uniform treatment, rapid calcite causing clogging, and uneven cementation reduce reliability (Cui *et al*., 2021). Fu *et al.* (2023b) noted calcite distribution as a barrier; Tang et al. (2020) said excess calcite lowers permeability, limiting depth. Ishara *et al*. (2024) added heterogeneity can weaken strength, showing MICP and EICP are transport-controlled, not traditional additive soil treatments. Rahman *et al*. (2020) suggested bio-mediated stabilization could lower cement use via waste-derived reagents and controls. Wang *et al*. (2024) warned ureolysis releases ammonium ions, which may cause ammonia emissions, nutrient loading, eutrophication, and groundwater contamination.

Abdullah et al. (2026) noted bio-enzymatic stabilization in problematic soils may be vulnerable to wetting and leaching, raising concerns about performance during seasonal moisture changes. Zhang et al. (2024) called for improved treatment protocols to ensure durability in environmental conditions. Jiang et al. (2025) found that EICP-treated calcareous sands might exhibit brittle post-peak behavior, while Mehmood et al. (2025) reported that fiber-reinforced bio-cementation enhances ductility and swelling resistance in expansive soils. A knowledge gap exists for tropical lateritic soils. Al-Riahi et al. (2024) emphasized mineralogical and microstructural changes in problematic soils, and Yusuf et al. (2025) stressed combining bio-stabilization with sustainable geotechnical practices in developing regions. Ali and Almurshedi (2024) reviewed bio-cementation mechanisms and uses, while Sarma and Mishra (2024) discussed microbial calcium carbonate precipitation as a geoenvironmental technology. Jamaldar et al. (2024) showed fiber improves ductility in bio-based earthen composites; Deylaghian et al. (2025) suggested non-ureolytic EICP to reduce environmental ammonia risks.

This review critically assesses recent developments from 2020 to 2026 regarding the applicability and challenges associated with Microbially Induced Calcium Carbonate Precipitation (MICP) and Enzyme-Induced Calcium Carbonate Precipitation (EICP) for sustainable soil stabilization. Specifically, the objectives of this review are to: (i) compare the stabilization mechanisms of MICP and EICP; (ii) evaluate their applicability across various soil types; (iii) assess the reported mechanical, hydraulic, and durability enhancements; (iv) analyze sustainability implications and environmental trade-offs; (v) identify the primary scientific and engineering limitations impacting field-scale implementation; and (vi) propose future research directions necessary to transition MICP and EICP from laboratory-scale technologies to reliable geotechnical engineering practices. By integrating insights on mechanisms, performance, sustainability, and design readiness, this review offers a comprehensive framework for understanding the current maturity of MICP and EICP as sustainable, bio-mediated soil stabilization techniques.

II. METHODOLOGY

This review adopted a PRISMA-inspired systematic literature synthesis approach to ensure transparency, reproducibility, and methodological rigor in the selection and interpretation of relevant studies. The procedure was designed to identify peer-reviewed research and review articles addressing microbial-induced calcite precipitation (MICP) and enzyme-induced calcite precipitation (EICP) for sustainable soil stabilization. As summarized in Table 1, the literature search covered studies published between 2020 and 2026, with emphasis on recent developments in bio-mediated soil improvement, ground improvement, calcite precipitation mechanisms, sustainability assessment, and geotechnical performance.

Relevant publications were retrieved from major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. These databases were selected because they index high-quality geotechnical, geoenvironmental, construction materials, and sustainability-related journals. The search process used subject-specific keywords such as “Microbial-Induced Calcite Precipitation,” “Enzyme-Induced Calcite Precipitation,” “MICP,” “EICP,” “bio-cementation,” “biomineralization,” “calcite precipitation,” “ureolysis,” “ground improvement,” and “sustainable soil stabilization.” Boolean combinations, including “MICP AND soil stabilization,” “EICP AND ground improvement,” “bio-cementation AND sustainability,” “ureolysis AND calcite precipitation,” and “bio-mediated stabilization AND geotechnical engineering,” were applied to improve the precision and thematic relevance of the retrieved records.

The literature screening involved four stages: identification, screening, eligibility, and final inclusion, shown in Figure 1. Studies were retrieved through database searches and references, then duplicates and irrelevant papers were removed. The eligibility stage assessed full texts for details on methodology, evidence, modelling, or reviews related to MICP/EICP soil stabilization. Articles contributing to understanding mechanisms, performance, applications, sustainability, limitations, or future developments of MICP and EICP were included. Inclusion criteria prioritized peer-reviewed journal articles in Q1 or Q2, written in English, from 2020-2026, and focused on geotechnical or geoenvironmental applications. The review covered experimental, numerical, field studies, life-cycle assessments, and reviews. Exclusions included duplicates, incomplete conference abstracts, non-peer-reviewed articles, predatory journals, and studies unrelated to soil stabilization or bio-mediated calcite precipitation.

Based on the screening, 52 articles were chosen for review, providing evidence on MICP/EICP mechanisms, efficiency, soil use, performance, durability, sustainability, limitations, and future challenges. They were grouped into six themes: stabilization, soil use, engineering performance, durability, sustainability, and challenges, allowing structured comparison of their features, methods, findings, and limitations. The review compares studies to identify consistencies, contradictions, gaps, and issues, focusing on performance differences, calcite content vs. strength, environmental concerns like ammonium, durability, and tropical soil research gaps. Figure 1 shows the screening process—from database searching, reference tracking, duplicate removal, screening, eligibility assessment, to excluding unsuitable records, leading to 52 articles for review. It provides a clear visual summary of literature selection and categorization.

Table 1. Literature selection framework adopted for the review

Review component	Description
Review period	2020–2026
Databases searched	Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Google Scholar
Main search terms	MICP, EICP, microbial-induced calcite precipitation, enzyme-induced calcite precipitation, bio-cementation, biomineralization, calcite precipitation, ureolysis, sustainable soil stabilization
Search strategy	Keyword-based search using Boolean combinations
Study focus	MICP and EICP for geotechnical and geoenvironmental soil stabilization
Screening framework	PRISMA-inspired identification, screening, eligibility, and inclusion process
Final studies retained	52 selected review and research articles
Inclusion criteria	Peer-reviewed journal articles; preferably Q1/Q2 indexed sources; experimental, numerical, field-scale, sustainability, and review studies; English-language publications
Exclusion criteria	Duplicate records, incomplete conference abstracts, non-peer-reviewed documents, predatory journals, and studies unrelated to soil stabilization or bio-mediated calcite precipitation

Synthesis approach	Thematic synthesis and critical comparative interpretation

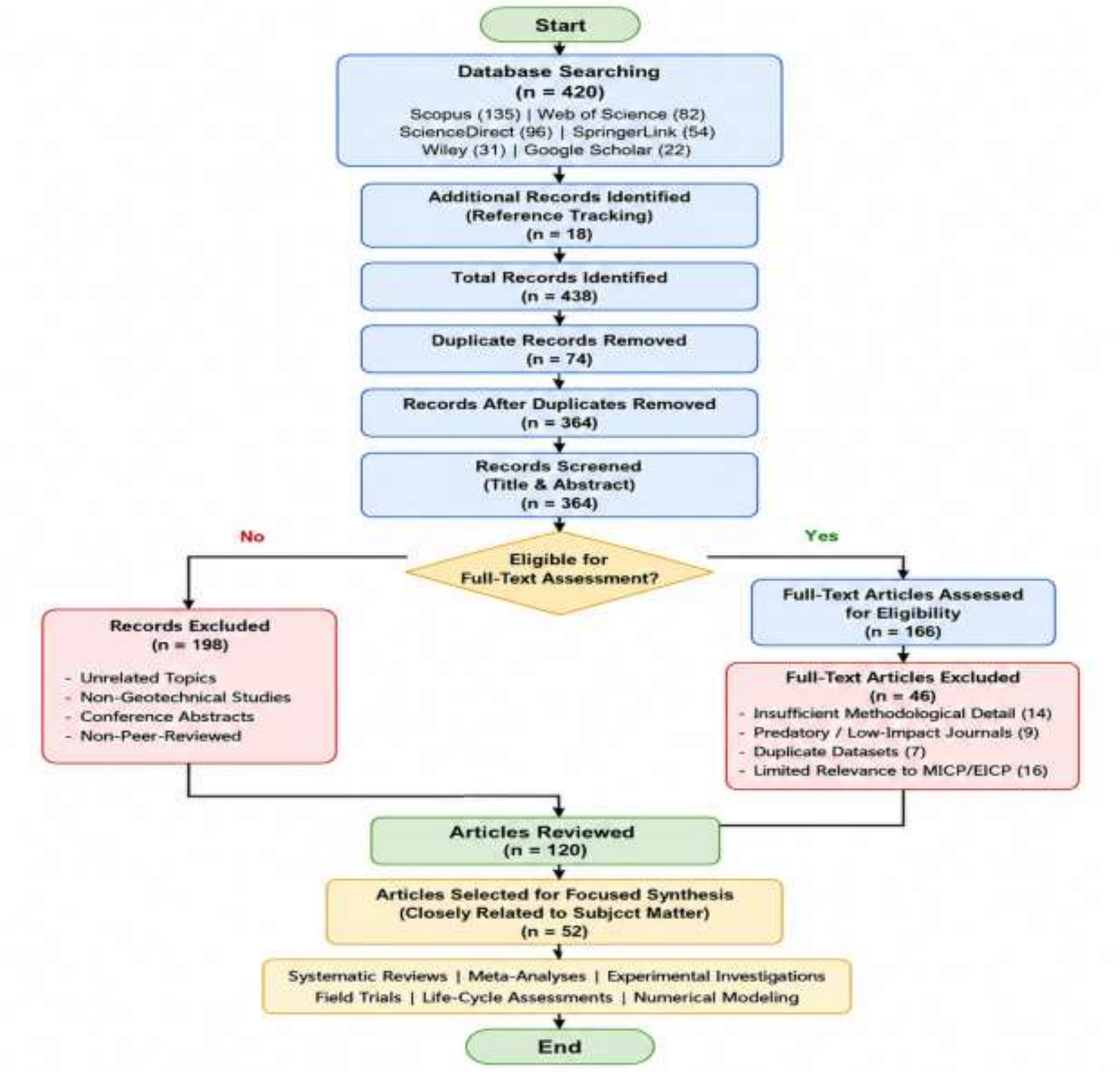

Figure 1. PRISMA-based literature screening and selection flowchart

III. RESULTS AND DISCUSSION

3.1 Evidence Base and Thematic Structure of the Review

The screening identified 120 articles on MICP, EICP, biomineralization, bio-cementation, and soil stabilization, with 52 from 2020-2026 analyzed for mechanisms, applications, performance, sustainability, durability, and challenges. These included reviews, experiments, field trials, assessments, models, and critiques. The large pool provided background, while the 52 articles formed the core for evaluating MICP and EICP as sustainable methods. The field has progressed from proof-of-concept to practical applications, including performance, environmental, hybrid stabilization, and early field-scale projects. Evidence is uneven: granular soils and erosion are well-studied, but lateritic soils, organic soils, high-plasticity clays, pavements, cyclic loading, and durability are less explored. Studies focus on six themes: reaction mechanisms, soil applicability, performance, durability, sustainability, and field challenges. MICP and EICP are seen as interconnected systems, not just chemical stabilization. Table 2 outlines three research directions: understanding mechanisms like ureolysis and calcite precipitation; engineering to improve soil strength; and sustainability with low-cost reagents and waste use. Evidence remains insufficient for practical implementation, especially for lateritic soils, cyclic loading, durability, quality control, and pavement performance.

Table 2. Thematic synthesis of selected MICP/EICP studies for soil stabilization

Thematic focus	Representative studies	Main synthesis outcome	Critical gap identified
Mechanisms and reaction pathways	Miftah *et al.* (2020); Fu *et al.* (2023a); Zhang *et al.* (2023); Sarma and Mishra (2024); Baidya *et al.* (2023)	Ureolysis-driven calcite precipitation remains the dominant mechanism in most MICP/EICP systems. Engineering performance depends not only on $CaCO_3$ quantity, but also on nucleation sites, crystal morphology, particle-contact bonding, and pore-scale distribution.	$CaCO_3$ content is often reported without sufficient microstructural evidence on bonding location, crystal continuity, and pore-scale cementation efficiency.
EICP development and optimization	Putra *et al.* (2020); Ahenkorah *et al.* (2021); Arab *et al.* (2021); Saif *et al.* (2022); Cui *et al.* (2021); Deylaghian *et al.* (2025)	EICP avoids bacterial cultivation and can improve treatment penetration in finer soils. Meta-analytical and experimental evidence show that enzyme activity, reagent concentration, pH, and calcium source strongly control performance. Low-pH and non-ureolytic EICP pathways are emerging to improve uniformity and reduce ammonia impacts.	Enzyme instability, pH sensitivity, urease cost, catalytic durability, and long-term field performance remain unresolved.
MICP performance in granular soils	Choi *et al.* (2020); Liu *et al.* (2021); Meng *et al.* (2021); Tang *et al.* (2020); Eryürük *et al.* (2025); Boruah *et al.* (2025)	MICP improves strength, stiffness, erosion resistance, and liquefaction resistance in sands through bacterial nucleation and interparticle calcite bonding. Treatment efficiency is strongly influenced by particle size, soil density, bacterial activity, and chemical concentration.	Premature clogging, non-uniform cementation, cost, and limited field-scale QA/QC remain major barriers.
Fine-grained and problematic soils	Arpajirakul *et al.* (2021); Gowthaman *et al.* (2022); Almajed *et al.* (2024); Raj *et al.* (2026); Bodner *et al.* (2026); Abdullah *et al.* (2026)	MICP/EICP can improve selected low-plasticity, gypseous, expansive, and problematic soils, but treatment performance is controlled by pore structure, permeability, pH, mineralogy, and leaching susceptibility.	High-plasticity clays, organic soils, collapsible gypseous soils, and expansive soils require assisted delivery systems, hybrid stabilization, and long-term durability validation.

Mechanical and hydraulic performance	Almajed *et al.* (2020); Jiang *et al.* (2025); Li *et al.* (2024); Shaivan *et al.* (2025); Mehmood *et al.* (2025); Liu *et al.* (2021)	Bio-cementation can improve UCS, shear strength, stiffness, erosion resistance, and hydraulic behaviour. Carbonate-rich soils may enhance nucleation, while fiber reinforcement can improve ductility and reduce brittleness.	UCS dominates the literature; CBR, resilient modulus, cyclic response, post-peak behaviour, and pavement-relevant performance indices remain underreported.
Sustainability and life-cycle performance	Rahman *et al.* (2020); Alotaibi *et al.* (2022); Fouladi *et al.* (2023); Lajmiri *et al.* (2025); Wang *et al.* (2024); Almajed *et al.* (2021)	MICP/EICP can reduce carbon burden relative to cement/lime where waste-derived reagents, low-cost calcium sources, and optimized treatment protocols are adopted. However, ureolysis-related ammonia generation remains a major environmental concern.	Sustainability claims remain incomplete without ammonia capture, reagent sourcing analysis, energy accounting, effluent treatment, and full life-cycle assessment.
Numerical modelling and predictive design	Hommel *et al.* (2020); Jiang *et al.* (2025); Fu *et al.* (2023a); Zhang *et al.* (2024)	Numerical modelling can help predict $CaCO_3$ distribution, damage evolution, treatment depth, and post-peak behaviour. These models are essential for moving from empirical trial-based treatment toward rational design.	Few models are calibrated with field-scale data, and limited work couples biochemical reaction, transport, hydraulic change, and mechanical response in one predictive framework.
Field-scale implementation and design	Ossai *et al.* (2020); Meng *et al.* (2021); Gowthaman *et al.* (2023); Ezzat (2023); Ishara *et al.* (2024); Almajed *et al.* (2021)	Field-scale applications are feasible for erosion control, dust suppression, and sandy soil stabilization where reagent delivery and precipitation rate are carefully controlled.	Lack of design standards, QA/QC procedures, durability monitoring, construction specifications, and scale-up models limits routine adoption.
Geoenvironmental and remediation applications	Xu and Wang (2023); Sarma and Mishra (2024); Baidya *et al.* (2023); Yu *et al.* (2026)	MICP has potential beyond strength improvement, including heavy-metal immobilization, fracture sealing, erosion control, and geoenvironmental remediation.	Most remediation studies remain laboratory-based, and their interaction with long-term leaching, groundwater chemistry, and field hydraulic gradients remains uncertain.
Hybrid and emerging systems	Jamaldar *et al.* (2024); Mehmood *et al.* (2025); Ratna Atika Huwaida *et al.* (2026); Agnesia *et al.* (2026); Yusuf *et al.* (2025); Ma *et al.* (2025)	Hybrid systems involving fibers, chitosan, skimmed milk, sucrose, waste materials, biopolymers, and complementary bio-based stabilizers can improve ductility, crack resistance, strength, and cost-efficiency.	Hybrid mechanisms, long-term durability, compatibility with MICP/EICP reactions, and field-scale performance remain poorly quantified.

3.2 Fundamental Mechanisms of MICP and EICP

The stabilization mechanisms of MICP and EICP involve ureolysis-driven calcium carbonate precipitation. In geotechnical engineering, bio-cementation effectiveness depends not just on calcium carbonate formation but on whether calcite forms at key points like particle contacts, pore throats, and bonding zones. Continuous calcite at contact points enhances strength and stiffness, while disconnected pore-fill crystals can lower permeability without offering similar mechanical benefits. During ureolysis, urease catalyzes urea hydrolysis to produce ammonium and carbonate ions, as shown in Equation 1.

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^{+} + CO_3^{2-} \quad (1)$$

The carbonate ions generated in Equation (1) react with calcium ions supplied through calcium chloride, calcium nitrate, calcium acetate, or waste-derived calcium sources to form calcium carbonate, as expressed in Equation 2:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s) \quad (2)$$

Equation (2) outlines the mineralization stage in soil mechanics, where calcium carbonate's ($CaCO_3$) distribution and form are crucial. Particle-contact precipitation boosts load transfer and stiffness, but too much pore filling can reduce hydraulic conductivity and block reagent penetration.

The overall ureolysis-induced calcite precipitation process is summarized in Equation 3:

$$CO(NH_2)_2 + 2H_2O + Ca^{2+} \rightarrow 2NH_4^{+} + CaCO_3(s) \quad (3)$$

Equation (3) shows MICP and EICP's dual nature. Calcium carbonate enhances geotechnical properties by boosting bonding, stiffness, erosion resistance, and stability. However, ammonium ions can cause ammonia loss, eutrophication, or groundwater contamination if not managed properly. This explains why recent studies view MICP and EICP as geoenvironmental systems, not just geotechnical methods.

The efficiency of calcium carbonate precipitation may be evaluated as in Equation 4:

$$\eta CaCO_3 = (M_p / M_t) \times 100 \quad (4)$$

$\eta CaCO_3$ indicates calcium carbonate precipitation efficiency as a percentage, with Mp as the measured precipitate mass and Mt as the theoretical mass based on calcium or carbonate ions. While Equation (4) measures reaction efficiency, it doesn't directly predict soil strength. Studies show that $CaCO_3$ placement, crystal shape, and bonding are more crucial for engineering performance than the total precipitated amount.

For mechanical interpretation, normalized UCS improvement may be expressed as in Equation 5:

$$UCS\ improvement\ (\%) = [(UCS_t - UCS_u) / UCS_u] \times 100 \quad (5)$$

where UCS_t is the unconfined compressive strength of treated soil and UCS_u is that of untreated soil. Equation (5) enables comparison across studies but should be interpreted carefully because results vary with soil gradation, density, curing time, reagent concentration, treatment cycles, bacterial/enzyme activity, and specimen shape.

Permeability reduction may be expressed as Equation 6:

$$Permeability\ reduction\ (\%) = [(k_u - k_t) / k_u] \times 100 \quad (6)$$

Where;

k_u = hydraulic conductivity of untreated soil; and

k_t = hydraulic conductivity of treated soil.

Equation (6) is especially important because permeability reduction is both a benefit and a risk. It improves erosion resistance and seepage control but may also reduce subsequent reagent penetration, thereby producing non-uniform cementation.

The principal mechanistic distinction between MICP and EICP lies in the source of urease and the nucleation environment. In MICP, ureolytic bacteria serve both as enzyme producers and nucleation surfaces. Their cell walls attract calcium ions and promote calcite precipitation around microbial colonies, which can produce strong interparticle bonding in sands and other permeable granular soils. However, bacterial cell mobility is limited in fine-grained soils because bacterial cells are larger than many clay and silt pore throats.

EICP avoids the bacterial cell-size limitation by using free urease enzymes. This improves its potential penetration in finer pore networks and eliminates the need for bacterial cultivation. However, EICP introduces other constraints because free enzymes may be sensitive to pH, temperature, ionic strength, denaturation, and adsorption onto clay minerals. Therefore, EICP is not inherently superior to MICP; its effectiveness depends on enzyme stability, soil chemistry, hydraulic conductivity, delivery method, and the target engineering function.

A recurring contradiction in the literature is that higher $CaCO_3$ content does not always lead to higher strength. This can be explained by the difference between calcite quantity and functionality. Calcite at particle contacts aids load transfer, while isolated pore-fill calcite mainly reduces permeability. Future studies should report $CaCO_3$ content alongside SEM, XRD, micro-CT, or image-based evidence of calcite distribution and bonding.

3.3 Applicability of MICP and EICP Across Soil Types

The applicability of MICP and EICP varies with soil characteristics like gradation, pore structure, hydraulic conductivity, plasticity, mineralogy, pH, organic matter, and treatment method. This dependence is crucial because a method effective in clean sand may fail in clayey, organic, expansive, carbonate-rich, or lateritic soils. Granular soils are most studied due to their connected pore spaces that allow movement of bacterial suspensions, enzyme solutions, urea, and calcium reagents. While sands and silty sands often show improved strength, stiffness, erosion resistance, and hydraulic stability after MICP or EICP, performance varies. Fine and dense sands may clog near injection points, reducing penetration and causing uneven cementation.

Fine-grained soils are harder to stabilize due to low hydraulic conductivity limiting bacterial and enzyme transport. In MICP, bacterial mobility is restricted by pore size, while in EICP, enzyme molecules penetrate finer pores more easily but face issues like adsorption, pH buffering, and flow paths, reducing treatment uniformity. These soils may need staged injection, electrokinetics, fracturing, carrier enzymes, or hybrids. Expansive soils pose added challenges, requiring solutions for mechanical weakness and moisture-related volume change. Bio-cementation alone may improve cohesion but not fully control swelling/shrinkage. Hybrid methods with fibers and calcite precipitation offer better stabilization, enhancing tensile resistance, crack control, bonding, and stiffness.

Lateritic soils are under-researched yet crucial in tropical pavement and foundation construction. Their unique composition and wet-dry cycles impact urease activity, calcium, calcite formation, and durability. Extrapolating from silica sand studies is scientifically weak and could lead to misleading designs.

Table 3 indicates MICP and EICP are not universal stabilizers; their use should be soil-specific, mechanism-driven, and validated in lab and field. For granular soils, focus on controlling precipitation; for fine-grained soils, on reagent delivery; for lateritic soils, on mineral compatibility and durability in tropical cycles.

Table 3. Comparative applicability of MICP and EICP across soil types

Soil type	MICP applicability	EICP applicability	Main limitation	Engineering implication
Coarse sand	High	High	Local injection clogging	Suitable for strength improvement and erosion control
Medium sand	High	High	Treatment-cycle sensitivity	Strong potential for ground improvement
Fine sand	Moderate	High	Premature precipitation and non-uniformity	Requires staged injection and concentration control

Silty sand	Moderate	High	Partial clogging and reagent loss	EICP may provide better penetration
Low-plasticity clay	Low–moderate	Moderate	Restricted transport and enzyme adsorption	Assisted delivery may be required
High-plasticity clay	Low	Low–moderate	Very low permeability	Hybrid or electrokinetic delivery may be necessary
Expansive soil	Low	Moderate	Swelling and shrinkage	Fiber-EICP systems are promising
Carbonate-rich soil	Moderate–high	Moderate–high	Brittle post-peak response	Strong nucleation potential but ductility concern
Organic soil	Low	Low	Organic inhibition of urease activity	Requires further validation
Lateritic soil	Under-researched	Under-researched	Fe/Al oxides, variable pH, aggregated structure	Major tropical research gap

3.4 Mechanical, Hydraulic, and Durability Performance

The main benefit of MICP and EICP is forming calcium carbonate bonds that increase cohesion, stiffness, erosion resistance, and load capacity. Yet, performance varies based on soil type, density, calcite distribution, treatment, curing, reagent chemistry, and microstructure. UCS is the most common measure of performance, especially in sands and carbonate-rich soils, with many studies reporting significant improvements. However, high percentage gains can be misleading, as untreated soils often have low initial UCS; thus, absolute strength, stiffness, post-peak behaviour, and durability are also important.

The relationship between $CaCO_3$ content and strength is complex. Moderate calcite at contacts can improve strength, but excess carbonate as disconnected pore-fill may weaken it. Studies show high strength at moderate $CaCO_3$ levels and limited strength with more carbonate. Future assessments should combine mechanical tests with microstructure evidence. Hydraulic conductivity generally decreases after MICP or EICP due to calcite filling pores, which benefits seepage control, erosion, and liquefaction resistance. However, too much permeability reduction can hinder reagent penetration and cause uneven cementation. Therefore, permeability reduction should be optimized.

CBR and resilient modulus are underreported compared to UCS, despite their importance in pavement engineering. This is a weakness because pavement design relies more on penetration resistance, soaked CBR, resilient modulus, and cyclic deformation than on UCS alone. The lack of CBR data for lateritic soils is especially significant in tropical road engineering. Durability is still not well understood. Short-term curing results do not always predict long-term performance under conditions like wetting-drying cycles, freeze-thaw, rainfall erosion, traffic, chemical attack, and biological activity. Bio-cemented soils may also become brittle after peak strength because calcite bridges increase stiffness but reduce ductility, raising concerns for slopes, pavements, foundations, and seismic areas where residual strength and deformation capacity are essential.

Figure 2 shows the process from reagent transport to calcite precipitation, bonding, permeability change, strength increase, and durability. It also indicates that excessive pore filling can boost hydraulic resistance but reduce reagent penetration and uniformity.

Table 4. Engineering performance indicators for MICP/EICP-treated soils

Engineering property	Typical response	Governing mechanism	Main design concern
UCS	Frequently increases in granular soils	Calcite bridging and particle bonding	Brittle peak behaviour
CBR	Improvement reported in selected studies	Cementation and penetration resistance	Limited lateritic soil data
Shear strength	Cohesion usually increases; friction angle varies	Contact bonding and densification	Post-peak brittleness
Hydraulic conductivity	Generally, decreases	Pore filling and reduced void connectivity	Reduced reagent penetration
Erosion resistance	Usually improves	Surface crusting and interparticle bonding	Rainfall durability uncertain
Swelling potential	May reduce in expansive soils	Calcite bonding and hybrid reinforcement	Limited field evidence
Liquefaction resistance	Potential improvement	Stiffness increases and pore modification	Limited cyclic field data
Durability	Mixed evidence	Calcite stability under exposure	Long-term service life uncertain

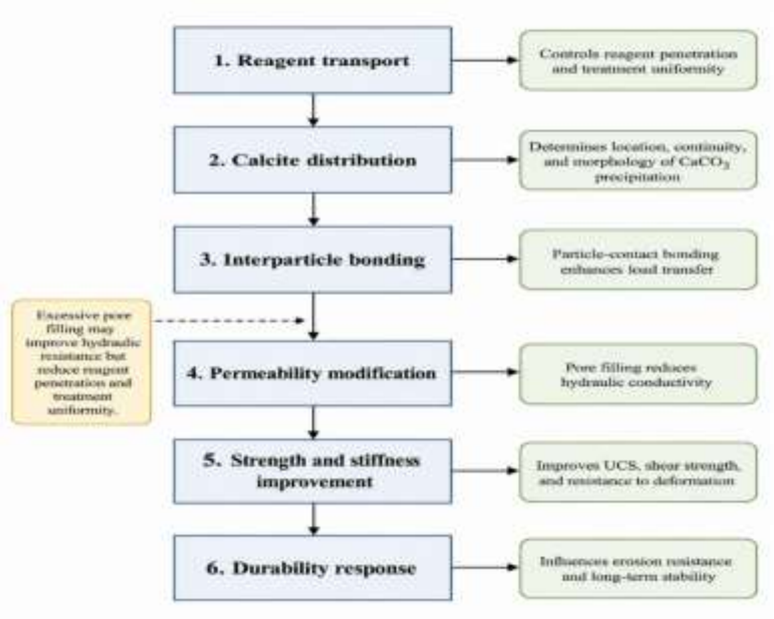

Figure 2. Conceptual relationship between calcite distribution and engineering performance

3.5 Sustainability and Environmental Implications

The principal sustainability argument for MICP and EICP is their potential to reduce dependence on Portland cement and lime. Compared with conventional cementitious stabilization, bio-mediated stabilization can reduce carbon emissions, embodied energy, and abiotic resource depletion, particularly where waste-derived calcium sources, crude enzyme extracts, or low-cost reagents are used. However, the sustainability advantage is conditional rather than automatic.

The central environmental limitation is ammonia generation. Equation (1) shows that ammonium ions are unavoidable products of ureolytic carbonate precipitation. If released uncontrolled, ammonium may cause ammonia volatilization, nutrient loading, eutrophication, and groundwater contamination. Therefore, any claim that MICP or EICP is environmentally sustainable must include ammonia management.

A conceptual sustainability balance may be expressed in Equation 7:

$$NSB = \mathrm{CO}_{2\mathrm{red}} + RS - N\mathrm{H}_{4\mathrm{i}} - TE - RC \quad (7)$$

Where;
NSB = Net sustainability benefit;
CO_2red = CO_2 reduction;
RS =resource savings;
NH4i = ammonia impact;
TE =treatment energy; and
RC = reagent cost.

Table 5 shows that conventional stabilization and bio-mediated stabilization differ in environmental impacts. Cement and lime are carbon-intensive but reliable. MICP and EICP have lower carbon potential but need stricter environmental controls, especially for ammonium, reagent sourcing, and monitoring. Emerging approaches such as low-pH EICP, non-ureolytic precipitation, crude enzyme extraction, waste-derived calcium sources, and circular-economy reagent systems are important because they address two major barriers: environmental safety and cost. Nevertheless, these approaches require more field evidence before they can be considered reliable engineering alternatives.

Table 5. Sustainability comparison between conventional and bio-mediated stabilization

Criterion	Cement/lime stabilization	MICP	EICP
Carbon footprint	High	Low–moderate	Low–moderate
Energy demand	High	Moderate	Moderate
Ammonia generation	None	High if ureolytic	High if ureolytic
Treatment uniformity	High	Moderate	Moderate–high
Fine-soil suitability	Moderate	Low	Moderate
Field maturity	High	Moderate	Emerging
Cost sensitivity	Binder cost	Nutrient and bacterial cultivation cost	Enzyme cost
Main environmental risk	CO_2 emissions	Ammonia and nutrient loading	Ammonia and enzyme production
Sustainability opportunity	Low-carbon binders	Waste calcium and ammonia capture	Crude enzymes and non-ureolytic pathways

3.6 Challenges, Research Gaps, and Future Direction

The studies show treatment non-uniformity is a key challenge. Bio-cementation depends on fluid transport, reaction rate, calcium, enzymes or bacteria, and pore geometry. Fast calcite blocks flow; slow calcite allows reagents to escape. Reaction-rate control is vital for performance. Ammonia generation is a major geoenvironmental barrier, especially in large-scale ureolytic treatment, which needs lots of urea, producing ammonium by-products that must be managed. This prompts interest in low-pH EICP, non-ureolytic methods, ammonia capture, and alternative carbonate routes. Durability is weak, with many showing short-term gains but lacking long-term data under conditions like wet-drying, freeze-thaw, erosion, traffic, chemicals, or microbes. This limits confidence. More research on lateritic soils is urgent due to their complex mineralogy, oxide content, pH buffering, and structure, differing from silica sands. As common in tropical infrastructure, limited data from these soils reduces the overall relevance.

Table 6. Major challenges and recommended research directions

Challenge	Engineering implication	Recommended research direction
Non-uniform precipitation	Uneven strength and unreliable field performance	Low-pH systems, staged injection, improved delivery control
Ammonia generation	Geoenvironmental contamination risk	Non-ureolytic pathways and ammonia capture
High enzyme cost	Limited large-scale adoption	Agricultural enzyme sources and crude extracts
Brittle behaviour	Sudden failure under loading	Fiber-reinforced bio-cementation
Limited lateritic soil evidence	Weak tropical application basis	Laboratory and field validation on tropical soils
Lack of standards	Difficult design adoption	QA/QC protocols and design guidelines
Limited durability data	Uncertain service life	Wet-dry, freeze-thaw, and cyclic loading studies
Field-scale uncertainty	Laboratory results may not scale	Pilot-scale monitored field trials

- Elucidate reaction pathways, nucleation, and crystal growth.
- Enhance control over calcite distribution, morphology, and bonding.

- Develop low-cost, eco-friendly calcium and nitrogen sources.
- Promote circular economy and reduce environmental footprint.

- Combine MICP/EICP with fibers, biopolymers, and additives.
- Improve ductility, toughness, and long-term durability.

- Conduct pilot and full-scale trials in diverse soil conditions.
- Evaluate long-term performance and environmental impacts.

- Leverage machine learning and data analytics for prediction and optimization.
- Enable rapid, reliable, and cost-effective treatment design.

- Develop guidelines, design standards, and construction protocols.
- Establish QA/QC procedures for consistent and safe implementation.

- Integrate MICP/EICP into mainstream geotechnical practice.
- Deliver resilient, low-carbon, and sustainable infrastructure.

Figure 3. Future research roadmap for MICP/EICP-based sustainable soil stabilization

Figure 3 shows six research pathways: mechanism optimization, waste-derived reagents, hybrid reinforcement, field-scale validation, AI-assisted design, and standardization. It emphasizes that routine engineering adoption requires integrating reaction chemistry, soil mechanics, environmental control, numerical modeling, durability testing, and design guidance.

IV. CONCLUSION

This review assessed the applicability and challenges associated with Microbially Induced Calcite Precipitation (MICP) and Enzyme-Induced Calcite Precipitation (EICP) for sustainable soil stabilization. It compared their mechanisms, soil suitability, engineering performance, sustainability implications, limitations, and future research needs. The findings indicate that both techniques enhance soil behavior via calcium carbonate precipitation within pores and at particle-contact zones. MICP is generally more effective in granular soils due to bacterial cells promoting calcite nucleation and interparticle bonding, whereas EICP may perform better in finer soils by minimizing microbial cell-size restrictions. Both methods can improve strength, stiffness, erosion resistance, and hydraulic behavior, although their performance is influenced by soil type, permeability, mineralogy, reagent transport, calcite distribution, and curing conditions. Nonetheless, limitations such as non-uniform precipitation, ammonia generation, brittleness, uncertain durability, cost, and the absence of standardized design protocols restrict field application. Consequently, future research should focus on low-ammonia pathways, field validation, hybrid reinforcement, utilization of waste-derived reagents, long-term durability testing, and assessment of tropical lateritic soils.

The future research directions shall focused on:

- development of low-ammonia or non-ureolytic precipitation pathways;
- field-scale validation under realistic geotechnical and environmental conditions;
- improved reagent delivery and treatment uniformity;
- hybrid stabilization using fibers, biopolymers, nanomaterials, or waste-derived materials; and
- further investigation of tropical lateritic soils and other underrepresented problematic soils.

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