Advances in Sustainable Geotechnical Engineering: A Review of Bio-mediated Soil Stabilisation, Cellular Confinement Systems, and Waste-Based Soil Improvements

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Abstract. The growing demand for sustainable infrastructure has accelerated the evolution of environmentally responsible practices in geotechnical engineering. Traditional soil improvement techniques, particularly those dependent on cement and lime, are associated with high carbon emissions, significant energy consumption, and long-term ecological consequences. In response, a new generation of green technologies has emerged, aiming to enhance soil performance while minimising environmental costs. This review explores three innovative approaches to sustainable ground improvement: bio-mediated soil stabilisation with a focus on Microbially Induced Calcite Precipitation (MICP), Cellular Confinement Systems (CCS), and waste-based soil improvement techniques. Bio-mediated methods offer biologically driven alternatives to chemical binders by promoting calcite precipitation, which strengthens soil and reduces erosion with a relatively low carbon footprint. CCS systems increase mechanical stability by redistributing loads through a geocellular matrix, often composed of recyclable or biodegradable materials. Waste-based improvements leverage industrial, agricultural, and construction-derived by-products such as fly ash, rice husk ash, and recycled concrete aggregates to enhance soil properties while advancing circular economy goals and reducing dependence on virgin resources. A comparative assessment highlights that each technique exhibits distinct advantages and limitations in terms of performance, environmental impact, scalability, and field applicability. Key challenges include regulatory uncertainty, material variability, and questions about long-term durability. Future directions point toward hybrid approaches that integrate multiple methods, AI-enabled monitoring systems to optimise treatment outcomes, and supportive policies that encourage widespread implementation. Taken together, these advancements mark a significant transition toward more resilient, efficient, and sustainable geotechnical engineering practices.

Keywords: Sustainable Geotechnical Engineering; Bio-mediated Soil Stabilisation; Cellular Confinement Systems; Waste-based Soil Improvement; Carbon Footprint Reduction.

INTRODUCTION

The growing imperative for sustainable development has profoundly reshaped the landscape of civil and geotechnical engineering over the past few decades. As societies worldwide grapple with the dual challenges of rapid urbanisation and environmental degradation, engineers are being called upon to not only deliver structurally sound and cost-effective solutions but to do so in a manner that minimises ecological harm and promotes long-term environmental stewardship [1]. This shift in priorities has catalysed the emergence of sustainable geotechnical engineering, a discipline focused on designing and implementing ground improvement techniques that reduce environmental impact while ensuring technical reliability and safety. Historically, soil stabilisation has relied heavily on conventional techniques such as cement and lime treatment, which, although effective, are highly resource-intensive and environmentally detrimental [2]. Cement production, for instance, is a significant contributor to global greenhouse gas emissions, accounting for an estimated 7 to 8 per cent of worldwide CO_2 emissions. In addition to carbon emissions, these traditional methods often involve extensive energy use, depletion of virgin materials, and risks of contaminating soil and groundwater through chemical leaching. Such drawbacks are increasingly unacceptable in an era where sustainability metrics are becoming central to infrastructure planning and development [3].

In response to these concerns, a new generation of innovative soil improvement strategies has gained traction, rooted in principles of environmental compatibility, material circularity, and reduced carbon intensity. These methods seek to harness biological, physical, and industrial synergies to stabilise soil in more sustainable ways [4]. Among the most promising approaches are Bio-mediated Soil Stabilisation, particularly through Microbially Induced Calcite Precipitation (MICP), Cellular Confinement Systems (CCS), which utilise geosynthetic structures to reinforce soil mechanically, and Waste-Based Soil Improvement Techniques, which repurpose industrial and agricultural by-products to reduce reliance on conventional binders and promote resource efficiency [5].

This review synthesises recent advances in these three sustainable techniques, providing an in-depth exploration of their mechanisms, performance characteristics, environmental advantages, and practical applications. Each method is first discussed independently, with attention to its scientific underpinnings and engineering outcomes, before moving to a comparative analysis that evaluates their relative strengths, limitations, and readiness for field-scale deployment. Finally, the paper addresses emerging trends, research gaps, and implementation challenges ranging from regulatory acceptance and material variability to long-term durability and public perception.

By critically assessing the current state and future potential of these technologies, this review aims to contribute to the growing body of knowledge at the intersection of geotechnical innovation and sustainability. It is intended as a resource for engineers, researchers, and policymakers committed to transitioning toward low-impact infrastructure solutions that are resilient, adaptive, and aligned with global sustainability objectives [6].

RESULTS AND DISCUSSION

Bio-Mediated Soil Stabilisation

Bio-mediated soil stabilisation is an emerging technique that involves the intentional application of biological processes, particularly those driven by microbial activity, to improve the engineering properties of soil. This approach represents a significant departure from conventional chemical-based stabilisation methods and lies at the intersection of several disciplines, including geotechnical engineering, microbiology, environmental science, and biochemistry. The concept, often referred to as bio-geotechnics, is grounded in the understanding that naturally occurring microbial processes can be directed and amplified to enhance soil strength, reduce hydraulic conductivity, and improve resistance to erosion, all while offering a more environmentally sustainable alternative to traditional chemical stabilisers [7].

Among the array of bio-mediated techniques currently under investigation, Microbially Induced Calcite Precipitation (MICP) has emerged as the most widely studied and practically promising. This method utilises specific microbial metabolic pathways that facilitate the precipitation of calcium carbonate ($CaCO_3$) within the soil matrix. The precipitated calcite acts as a binding agent, effectively cementing soil particles together and reducing porosity, which in turn enhances the mechanical strength and stability of the soil. MICP is particularly attractive because it offers a replicable and scalable mechanism for soil improvement, with successful demonstrations in both laboratory settings and pilot field applications [8].

Beyond MICP, researchers are also investigating alternative biological pathways and variations of the technique. Enzyme-Induced Calcite Precipitation (EICP), for example, substitutes living microbes with plant- or microbe-derived enzymes to initiate the same urea hydrolysis reaction, potentially offering better process control and fewer biohazards. Other promising microbial processes, such as denitrification and sulfate reduction, are being evaluated for their ability to produce similar cementation effects without some of the environmental drawbacks associated with ureolysis, such as ammonium by-product formation [9].

Microbial Processes Involved. At the heart of bio-mediated soil stabilisation, particularly Microbially Induced Calcite Precipitation (MICP), lie a series of microbial metabolic processes that facilitate the in-situ formation of calcium carbonate ($CaCO_3$) within the soil structure. These biologically driven pathways play a central role in enhancing the mechanical integrity of soils by reducing porosity, sealing voids, and strengthening inter-particle bonding. Beyond mechanical improvement, these processes also help reduce soil permeability, increase resistance to erosion, and promote overall geotechnical stability in an environmentally conscious manner [10].

Among these mechanisms, ureolysis is the most extensively studied and widely applied in MICP-based stabilisation. In this pathway, urease-producing bacteria such as *Sporosarcina pasteurii* catalyse the hydrolysis of urea into ammonium and carbonate ions. When calcium ions are present, this biochemical reaction leads to the precipitation of calcium carbonate, which binds soil grains together and improves unconfined compressive strength (UCS), stiffness, and erosion resistance [11]. The ureolytic pathway is highly favoured due to its rapid reaction kinetics, reproducibility, and ease of microbial cultivation. However, one of its drawbacks is the production of ammonium as a by-product, which may pose environmental hazards, especially if not properly contained or treated [12].

In response to the limitations of ureolysis, alternative microbial processes such as denitrification and sulfate reduction are gaining attention. In denitrification-driven MICP, nitrate ions serve as the terminal electron acceptor, enabling the microbial community to induce calcite precipitation without producing ammonium. Although this process proceeds at a slower rate compared to ureolysis, it is more environmentally benign and particularly suitable for use in nitrate-rich environments or soils with lower pH values. Similarly, sulfate-reducing bacteria (SRB) can contribute to carbonate precipitation by generating hydrogen sulfide. While this pathway holds potential, it introduces complex geochemical interactions and may result in undesirable by-products such as odour and toxicity, which require careful management [13].

A related but distinct innovation in this domain is Enzyme-Induced Calcite Precipitation (EICP), which eliminates the need for live microbial cultures. Instead, purified urease enzymes – often derived from plant sources like jack beans – are directly introduced into the soil matrix to catalyse the hydrolysis of urea. EICP offers a more controlled biochemical process, reduces the risk of bio-clogging, and lowers biohazard concerns, making it attractive for projects that require higher precision or simpler logistics. However, challenges related to enzyme cost, degradation over time, and uncertain long-term performance still need to be addressed through continued research. In essence, these microbial and enzymatic pathways form the scientific foundation of bio-mediated soil improvement techniques. Each pathway differs in terms of microbial or enzymatic agents involved, required substrates, by-products generated, and environmental suitability. Their continued evolution is driven by advances in microbial engineering, biochemistry, and environmental geotechnology [14].

To visually represent the diversity of these processes, Figure 1 provides a schematic overview of the mechanisms behind MICP, EICP, and denitrification-induced calcite precipitation, offering a comparative understanding of how these biological routes contribute to sustainable and effective soil stabilisation [15].

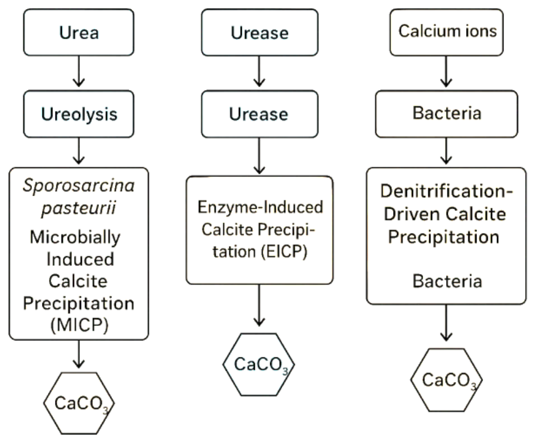

Figure 1 – Microbial Mechanisms of Soil Stabilisation

Schematic representation of the primary microbial processes involved in bio-mediated soil stabilisation. The ureolysis pathway facilitated by Sporosarcina pasteurii drives Microbially Induced Calcite Precipitation (MICP), while Enzyme-Induced Calcite Precipitation (EICP) utilises plant-based urease enzymes. Denitrification-driven calcite precipitation offers an alternative, environmentally benign mechanism for $CaCO_3$ formation without ammonium by-products.

Materials and Microorganisms. The effectiveness of Microbially Induced Calcite Precipitation (MICP) largely hinges on the specific microbial agents and chemical substrates employed during the treatment process. Among the microorganisms studied, *Sporosarcina pasteurii* has emerged as the most widely utilised bacterium due to its exceptional urease activity and its ability to thrive in alkaline, calcium-rich environments. This bacterium not only catalyses the hydrolysis of urea at a high rate but also exhibits robust survival characteristics under diverse geotechnical conditions, making it highly suitable for field-scale applications. In addition to *Sporosarcina pasteurii*, other urease-producing species such as *Bacillus megaterium* and *Bacillus subtilis* have been explored for MICP. While these organisms demonstrate moderate ureolytic capabilities, their overall performance in terms of calcite yield, tolerance to environmental stressors, and field applicability varies. The choice of microbial strain must therefore be carefully matched to site-specific conditions, such as pH, temperature, and the desired rate of precipitation [16].

The chemical substrates used to facilitate microbial calcite precipitation are equally important. Urea serves as the primary nitrogen source and is hydrolysed into carbonate and ammonium ions during the ureolytic process. Calcium chloride is typically supplied as the calcium source necessary for the formation of calcium carbonate. The ratio and concentration of these substrates must be optimised to promote effective microbial metabolism while avoiding excessive ammonia generation or unbalanced pH levels that could hinder bacterial activity [17]. Additionally, environmental conditions such as temperature, soil moisture content, and pH play a crucial role in the overall efficiency of the MICP process. Most ureolytic bacteria exhibit optimal activity within a neutral to slightly alkaline pH range and moderate temperature conditions (typically between 25°C and 35°C). Deviations from these ranges can slow the reaction kinetics or compromise bacterial viability. Furthermore, soil characteristics such as porosity, permeability, and grain size distribution significantly influence the uniformity of calcite precipitation. Soils with higher permeability facilitate the better transport of treatment solutions but may also result in uneven distribution or washout of microbes and reagents [18].

To ensure the successful implementation of MICP, a comprehensive understanding of the interactions between microbial agents, nutrient media, and the soil environment is essential. Fine-tuning these variables allows for controlled and repeatable improvements in soil strength and stability, thereby maximising the geotechnical and environmental benefits of this innovative technique [19].

Applications in Soil Stabilisation. Bio-mediated soil stabilisation, particularly through Microbially Induced Calcite Precipitation (MICP), has demonstrated significant potential in a range of geotechnical applications. Its versatility lies in its ability to enhance both the mechanical and hydraulic properties of soils, making it suitable for a wide range of engineering contexts. Laboratory investigations and pilot field trials have consistently shown substantial gains in Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR), both of which are critical indicators of soil performance under load. Depending on the soil type, microbial strain, and treatment protocol, strength improvements typically range from 200 to 1500 kPa, highlighting the adaptability of MICP to various geotechnical scenarios. One of the most promising applications of MICP is in the stabilisation of pavement subgrades and foundation soils, where improved strength and reduced compressibility are essential for structural integrity. In such settings, microbial treatment can reduce differential settlement, increase bearing capacity, and extend the service life of overlying infrastructure. Additionally, MICP has been successfully applied in the construction and reinforcement of retaining walls, embankments, and other load-bearing earth structures, offering an alternative to traditional cementitious or mechanical reinforcement methods [20].

Erosion control represents another valuable application domain, particularly in areas vulnerable to surface runoff, wind erosion, or coastal degradation. The microbial precipitation of calcium carbonate forms a thin calcite crust on the soil surface, which effectively binds loose particles together and reduces susceptibility to detachment. This crust serves as a natural protective layer, minimising soil loss and maintaining slope stability even under adverse environmental conditions. As such, MICP has been explored for use in protecting coastal dunes, riverbanks, and road embankments from erosive forces. Additionally, in hydraulic engineering, MICP has shown promise in sealing seepage paths in dams, levees, and other earthen water-retaining structures. By filling voids and reducing permeability, the microbial treatment acts as a bio-compatible grout that can replace or complement chemical sealants. This application not only enhances structural safety but also mitigates the environmental risks associated with conventional grouting materials [21].

Sustainability Aspects. From a sustainability standpoint, MICP and related bio-mediated processes offer several advantages over conventional soil stabilisers. The most significant benefit is the reduction in carbon emissions, especially when replacing cement-based binders. While urea production is energy-intensive, the overall carbon footprint of MICP remains substantially lower than Portland cement stabilisation, especially when paired with renewable energy and waste-derived reagents [22].

Material efficiency is another benefit. Microbial treatments require small volumes of reagent solutions and often eliminate the need for excavation or heavy equipment. However, the cost and energy inputs for cultivating microbes, preparing treatment solutions, and maintaining environmental conditions (e.g., temperature, moisture) must be carefully managed to ensure net sustainability gains. Despite its promise, several challenges remain, particularly in scaling the process for large geotechnical applications. Ensuring homogeneous treatment over extensive areas, achieving consistent calcite precipitation, and maintaining long-term stability under environmental loading are ongoing research priorities [23].

Limitations and Future Prospects. Despite the promising results achieved in laboratory settings, the practical deployment of Microbially Induced Calcite Precipitation (MICP) at the field scale remains constrained by several technical and environmental challenges. One of the primary limitations lies in the effective delivery of microbial cultures and nutrient solutions into subsurface soils. Achieving a uniform distribution of calcium carbonate precipitation across varying soil profiles is particularly challenging due to the heterogeneity of natural soils, which includes differences in permeability, porosity, and moisture content. This can result in uneven treatment zones, commonly referred to as bio-clogging, which may lead to inconsistent strength gains or localised failure zones [24].

Another concern involves the long-term durability of MICP-treated soils under real-world loading and environmental conditions. While short-term gains in unconfined compressive strength and erosion resistance have been well-documented, questions remain regarding performance under cyclic loading, seasonal freeze–thaw cycles, fluctuating pH levels, and exposure to aggressive chemical environments. These uncertainties limit the confidence of engineers and regulators in adopting MICP as a replacement for conventional stabilisers in critical infrastructure projects. Additionally, the by-products of some microbial processes – such as ammonium generated during ureolysis – can pose environmental risks if not properly managed, necessitating careful site assessment and waste treatment planning [25]. Moreover, from an implementation perspective, the scalability of MICP continues to be a significant hurdle. Cultivating microbial cultures in sufficient quantities, maintaining optimal environmental conditions (such as pH and temperature), and managing logistics for large-volume injection present economic and logistical barriers, particularly in remote or resource-limited areas [26].

Cellular Confinement Systems (CCS)

Concept and Mechanism. Cellular Confinement Systems (CCS), often referred to as geocells, represent a mechanically innovative and environmentally adaptive approach to soil stabilisation. These systems consist of three-dimensional, honeycomb-like networks formed from interconnected strips of polymeric material, typically expanded on-site and filled with soil, aggregates, or other locally available materials. Once deployed and compacted, the geocell matrix forms a semi-rigid, composite structure that enhances the engineering performance of weak or loose soils [27].

The core strength of geocells lies in their ability to confine the infill material laterally. This lateral confinement reduces shear deformation, limits vertical displacement, and distributes applied loads more effectively across a broader area. As a result, the geocell-reinforced soils exhibit improved bearing capacity, reduced differential settlement, and enhanced resistance to erosion and rutting. Traditionally, High-Density Polyethene (HDPE) has been the material of choice for manufacturing geocells due to its favourable strength-to-weight ratio, chemical resistance, and long service life. However, recent material innovations have introduced bio-based polymers and recycled plastic composites as alternatives. These new materials aim to reduce fossil fuel dependency, increase biodegradability, and align geocell applications more closely with sustainable development goals — all without sacrificing structural reliability [28].

Applications. The adaptability of CCS has led to its widespread adoption across diverse geotechnical applications. In road construction, geocells are used to stabilise base and subbase layers, especially in areas where subgrade soils are weak or moisture-sensitive. By reducing the need for thick aggregate layers, CCS not only improves pavement performance but also reduces material and transportation costs. In embankments and slopes, geocells are employed to control erosion and enhance structural integrity, particularly in steep or unstable terrains. The cellular matrix physically anchors the soil while allowing for integration with vegetative covers, creating green, aesthetically pleasing, and environmentally resilient landscapes [29].

Another growing area of application is in the reinforcement of soft soils for low-carbon infrastructure. CCS enables the use of marginal or recycled materials, including locally sourced sands, crushed concrete, and other secondary aggregates that might otherwise be unsuitable for structural use. This flexibility is particularly beneficial in resource-limited or remote regions where conventional materials are scarce or cost-prohibitive. Furthermore, due to their rapid deployment and minimal equipment requirements, geocells are well-suited for emergency applications such as disaster recovery, military installations, and temporary access roads. Their ease of installation and modularity make them a practical choice for infrastructure development in environmentally sensitive zones [30].

Sustainability and Environmental Benefits. From a sustainability perspective, cellular confinement systems offer multiple environmental and economic benefits when compared to traditional soil reinforcement methods. One of the most notable advantages is their contribution to material efficiency. By improving the load-bearing capacity of infill materials, geocells reduce the need for high-quality granular materials, thereby lessening the environmental impact associated with quarrying, transportation, and processing. This is especially important in regions where aggregate mining contributes significantly to habitat destruction or carbon emissions. Moreover, in terms of logistics and implementation, the lightweight and compact nature of geocell panels reduces fuel consumption during transport and lowers installation energy demands. This logistical simplicity becomes even more advantageous in remote or ecologically sensitive environments where mobilising heavy machinery is both costly and environmentally risky [31].

Durability is another key feature that supports the sustainable profile of geocells. HDPE-based geocells are resistant to UV radiation, chemical degradation, and microbial attack, offering a service life of over 75 years in most conditions. Moreover, the end-of-life recyclability of many geocell products contributes to circular economy principles, ensuring that the materials used can be repurposed instead of ending up in landfills. As technology continues to evolve, the introduction of biodegradable and renewable polymer-based geocells presents a pathway toward fully eco-compatible reinforcement systems that balance short-term performance needs with long-term ecological stewardship [32].

Waste-Based Soil Improvement

The application of circular economy principles to geotechnical engineering has sparked growing interest in utilising waste-derived materials for soil improvement. This strategy not only addresses environmental concerns associated with conventional binders, such as cement and lime, but also provides a valuable outlet for the reuse of industrial, agricultural, and construction waste. By diverting these materials from landfills and incorporating them into geotechnical designs, engineers can promote resource efficiency and reduce the carbon footprint of ground improvement activities [33].

A wide range of waste materials has demonstrated potential in enhancing soil performance. Industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and red mud exhibit cementitious or pozzolanic activity when mixed with appropriate chemical activators. Agricultural residues like rice husk ash (RHA) and sugarcane bagasse ash (SCBA) contain reactive silica and alumina that participate in stabilisation reactions. Additionally, construction and demolition (C&D) waste, such as crushed concrete, brick dust, and recycled aggregates, can be repurposed as fillers or soil substitutes in structural applications. This approach goes beyond mere substitution. It represents a deeper integration of sustainability, material performance, and environmental compliance into soil stabilisation strategies, aligning engineering goals with ecological stewardship [34].

Mechanical and Chemical Stabilisation. Waste-based soil stabilisation methods enhance strength and durability through mechanical reinforcement and chemical reactions. One of the most established techniques is fly ash–lime stabilisation, which relies on pozzolanic reactions between fly ash and calcium hydroxide. This interaction forms cementitious compounds, such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which enhance strength, durability, and reduce permeability. Additionally, agricultural ashes such as RHA and SCBA can provide similar benefits under alkaline conditions. Pre-treatment processes, such as calcination and sieving, are often required to improve reactivity and particle size distribution. Blending these materials with traditional binders helps reduce cement consumption while maintaining or enhancing performance outcomes. For example, replacing 20 to 50 % of cement or lime with fly ash can significantly lower CO_2 emissions. Similarly, GGBS has been effectively used as a partial lime substitute to enhance resistance to sulfate attack and improve long-term stability. These hybrid strategies enable engineers to customise stabilisation treatments based on soil conditions, project goals, and environmental considerations [35].

Case Studies and Experimental Results. Both laboratory experiments and field trials confirm the technical feasibility of improving soil with waste-based materials. Reported improvements in Unconfined Compressive Strength (UCS) for treated soft clays and silty soils typically range from 300 to 800 kPa. These treatments also tend to reduce soil permeability, enhancing resistance to seepage and erosion. Additionally, environmental assessments play a crucial role in evaluating the viability of these approaches. Leachability tests are conducted to monitor the release of heavy metals or toxic compounds from industrial by-products. Many waste-based binders, particularly when encapsulated within cementitious matrices, have shown minimal leaching and meet regulatory safety standards. Also, life cycle assessments indicate that stabilisation with fly ash or similar waste materials can reduce embodied carbon emissions by 40 to 60 % compared to traditional cement-based methods, depending on processing and transport distances. Field demonstrations, though less common than lab-scale studies, have validated these findings. For example, the stabilisation of expansive clays using RHA or C&D blends has improved bearing capacity, reduced shrink-swell behaviour, and enhanced performance under cyclic loads. However, these outcomes depend heavily on site-specific factors such as waste composition, moisture levels, and climatic conditions, underscoring the need for localised calibration [36].

Life Cycle Assessment and Feasibility. From a life cycle standpoint, waste-based soil stabilisation provides significant environmental and economic advantages. The proximity and availability of suitable waste streams, transportation logistics, and on-site processing capabilities largely influence its feasibility. In many regions, fly ash and other industrial by-products are available at little or no cost, making them economically competitive with commercial binders. Additionally, since these pozzolanic wastes typically require minimal processing, their embodied energy and associated emissions are relatively low. Nonetheless, certain pre-treatment steps, such as grinding and drying, can contribute to the energy footprint, depending on local infrastructure and energy sources. Despite the benefits, several challenges remain. Regulatory uncertainty around the classification and reuse of industrial waste in civil infrastructure can inhibit adoption. Technically, the long-term performance of stabilised soils under varying environmental conditions still requires further validation. Moreover, psychological and institutional barriers, including risk aversion among engineers and client unfamiliarity, can hinder implementation [37].

Comparative Evaluation

Performance Metrics. Bio-mediated stabilisation, cellular confinement systems (CCS), and waste-based improvements each offer distinct advantages in terms of geotechnical performance and sustainability. CCS and MICP are particularly effective in enhancing Unconfined Compressive Strength (UCS), especially in cohesionless or granular soils. Waste-based stabilisation performs well in cohesive soils, especially when used in conjunction with lime or cementitious activators. In terms of durability, CCS leads due to its physical confinement properties, which resist erosion, deformation, and surface degradation. MICP-treated soils also exhibit high erosion resistance through calcite binding, whereas the durability of waste-based treatments depends on material consistency, curing, and environmental exposure [32].

Environmental Impact. Bio-mediated methods such as MICP and Enzyme-Induced Calcite Precipitation (EICP) generally have the lowest carbon footprints, particularly when renewable substrates or by-product calcium sources are used. CCS contributes to sustainability by minimising material use and incorporating recyclable or biodegradable polymers. Waste-based stabilisation aligns with circular economy goals by diverting waste from landfills and reducing dependence on cement. However, environmental monitoring is essential to ensure that leachate or contaminant risks are effectively mitigated [38].

Cost and Practical Implementation. The cost and scalability of the three methods vary significantly. Waste-based stabilisation is often the most affordable option, especially in regions with abundant local waste materials. CCS requires moderate investment in materials and installation but offers cost advantages in remote or environmentally sensitive locations due to its logistical simplicity. Bio-mediated techniques, while promising in the lab, are currently more expensive and complex to scale due to the need for microbial cultivation, precise environmental control, and specialised delivery systems [39].

Furthermore, in terms of field readiness, CCS and waste-based methods are already supported by construction standards and engineering practice. MICP and other bio-based approaches, although scientifically validated, remain in earlier stages of commercial adoption due to performance variability and regulatory hurdles. To support decision-making, Table 1 provides a comparative summary of the key performance, environmental, and cost characteristics of each sustainable soil improvement technique [40].

Table 1 – Comparative Performance and Sustainability Assessment of Bio-mediated, Cellular Confinement, and Waste-Based Soil Improvement Techniques

Criteria	Bio-mediated Stabilisation (e.g., MICP/EICP)	Cellular Confinement Systems (CCS)	Waste-Based Soil Improvement
Primary Mechanism [41]	Microbial/enzymatic calcite precipitation	3D geocellular mechanical confinement	Pozzolanic or filler-based stabilisation using waste
Strength Gain (UCS) [42]	Moderate to High (200–1500 kPa)	High (especially in granular soils)	Moderate (300–800 kPa typical)
Erosion Resistance [43]	High (via calcite crust formation)	Very High (due to surface confinement)	Moderate to High (depends on material)
Carbon Footprint [44]	Very Low (especially EICP with waste urea)	Low (especially with recycled/biopolymers)	Low to Moderate (depending on waste transport and processing)
Material Source [45]	Renewable microbial/enzymatic agents	Synthetic, recycled, or biodegradable polymers	Industrial/agricultural/construction waste
Installation Complexity [46]	High (requires microbial culture and control)	Low (prefabricated, field-expandable)	Moderate (depends on processing needs)
Field Scalability [47]	Low to Moderate (ongoing research)	High (widely used in practice)	High (especially in LMICs)

Criteria	Bio-mediated Stabilisation (e.g., MICP/EICP)	Cellular Confinement Systems (CCS)	Waste-Based Soil Improvement
Cost [44]	High (currently, due to biotechnological inputs)	Moderate	Low (waste is often inexpensive)
Environmental Risks [37]	Ammonium by-products (if unmanaged)	Minimal	Leachate (requires testing)
Durability / Long-Term Stability [42]	Moderate (still under long-term evaluation)	High (lifespan > 75 years with HDPE)	Moderate (depends on waste composition)

The table highlights the distinct advantages, limitations, and practical considerations associated with each method, guiding the selection and implementation of sustainable geotechnical engineering projects.

Future Directions and Research Needs

The evolution of sustainable geotechnical engineering is increasingly oriented toward hybrid approaches that leverage the complementary strengths of multiple techniques. One promising direction is the integration of MICP with geocells, where microbial calcite precipitation enhances interparticle bonding while geocells provide macro-level confinement. Similarly, combining waste-based materials with bio-cementation may improve both mechanical performance and environmental resilience, enabling multi-functional stabilisation strategies suited to complex soil conditions [48].

To support the proposed hybridisation of sustainable soil improvement techniques, Figure 2 presents an integrated conceptual framework. This schematic illustrates how microbial treatments, recycled waste inputs, and AI-based monitoring systems can interact to form adaptive, high-performance stabilisation pathways [49].

A conceptual flowchart illustrating the synergistic integration of microbial cultures, waste-derived materials, and monitoring data into hybrid soil stabilisation pathways. The diagram emphasises the role of AI-based monitoring in optimising treatment strategies such as Microbially Induced Calcite Precipitation (MICP), Enzyme-Induced Calcite Precipitation (EICP), and chemically activated systems like geocells. Performance feedback loops drive sustainability outcomes, including reduced emissions, enhanced resource circularity, and improved unconfined compressive strength (UCS).

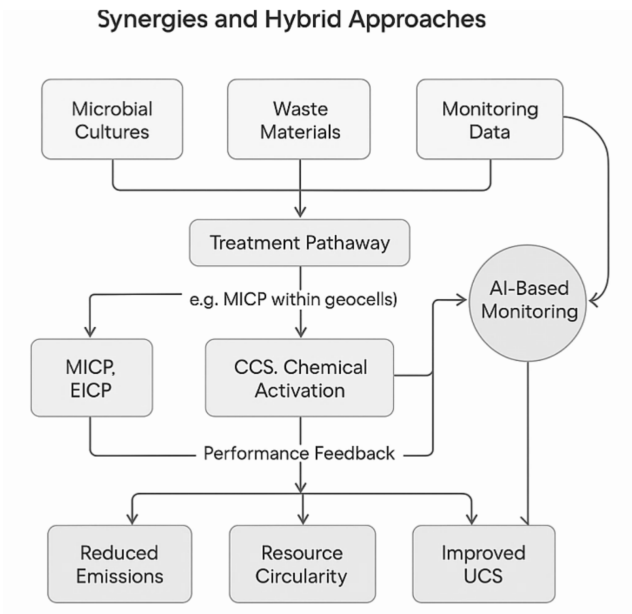

Figure 2 – Integrated Framework for Sustainable Soil Stabilisation: Synergies and Hybrid Approaches.

Another crucial research need involves performance evaluation under extreme climate conditions, including high salinity, freeze–thaw cycles, and arid or highly saturated environments. Long-term field monitoring in such contexts is essential to validate the durability and reliability of these sustainable methods beyond laboratory settings [50].

Policy development and standardisation are also critical. The lack of clear technical guidelines, performance criteria, and regulatory frameworks currently limits the adoption of green ground improvement techniques. National and international codes must evolve to incorporate sustainability metrics and recognise alternative binders and bio-based technologies. Additionally, the integration of artificial intelligence (AI) and smart monitoring systems offers transformative potential. AI-driven optimisation of mix design, microbial selection, and field deployment can accelerate innovation, while real-time monitoring using IoT-based sensors and machine learning can provide early warnings of performance degradation and enable adaptive maintenance [51]. Ultimately, future research must be interdisciplinary, combining insights from microbiology, materials science, environmental engineering, and computational modelling to create robust, scalable, and context-specific solutions that address the multifaceted challenges of sustainable soil stabilisation [52].

CONCLUSIONS

Sustainability is no longer a peripheral concern in geotechnical engineering; it is a central driver of innovation and design. This review has examined three promising pathways toward greener ground improvement: bio-mediated soil stabilisation, cellular confinement systems (CCS), and waste-based soil improvement. Each technique offers unique advantages—whether through carbon footprint reduction, resource efficiency, or performance enhancement—but also presents challenges in terms of scalability, field variability, and regulatory acceptance. Bio-mediated approaches excel in environmental compatibility but are still in the early stages of development in terms of commercial readiness. CCS provides mechanical robustness and ease of deployment, while waste-based stabilisation offers a practical, cost-effective route toward circularity in construction. To advance these solutions, a collaborative, interdisciplinary approach is essential—bridging engineering, microbiology, policy, and data science. Innovation in materials science, AI integration, and the establishment of global sustainability standards will be key to widespread adoption [11]. As the civil engineering community moves toward a carbon-neutral future, the transition from traditional to sustainable geotechnical practices must be both intentional and evidence-based, ensuring not just environmental compliance but also long-term performance, resilience, and societal benefit.

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