

Soil Microbiome Modulation for Sustainable Ground Improvement: A Bio-Geo-Chemical Perspective

Dr. N Dayanand Lal^{1*}, Ali Ihsan Alanssari², Muntadher Abed Hussein³, Hassan Khalid Abozibid⁴, Ahmed Kateb J. Al-Nussairi³, Israa alhani⁵

¹ Department of CSE, GITAM School of Technology, GITAM University, Bengaluru, India.

² Al-Nisour University College, Nisour Seq. Karkh, Baghdad, Iraq.

³ Department of sciences/ Al-Manara College for Medical Sciences/ (Maysan)/Iraq.

⁴ Al-Zahrawi University College, Karbala, Iraq.

⁵ Mazaya university college/Iraq.

Abstract. The soil's microbiome is altered in a new approach to addressing construction sustainability issues. Biological processes for treating the soil's microbiome can be used to introduce stability and strength into the soil, thereby reducing dependence on carbon-intensive chemical and mechanical ground improvement techniques. This research focuses on specific biogeochemical processes related to soil amendment, including microbial-induced calcite precipitation (MICP), enzymes, and organic substances that enhance cohesion and reduce permeability. Incorporating microbe engineering in soils enhances the hardness of the subsoil top layer, as well as the capacity of the soil. Its structure becomes reinforced as roots help stabilize the soil progressively over time. Architecture network levels are augmented by the actual or virtual presentation of system interactions in a graphical manner, which also assists in prediction during the process. Policy documents have minimized environmental concerns, heightened the concern of development, and changed strategies to recover resources without impending costs or unsustainable practices in nature. This has led to flexible, agile, and responsive soil development, fostering dynamism in civil geo-policy-funded initiatives. To move beyond a purely conceptual perspective, the present study introduces a quantitative Soil Stability Index (SSI) framework and applies it to laboratory and pilot-scale field tests, providing verifiable methods, statistically analyzed results, and a basis for optimizing bio-mediated soil improvement.

1 Introduction

Fungi, bacteria, archaea, and actinomycetes constitute the soil microbiome. Microorganisms within the soil that geotechnical engineers are interested in due to their contribution toward maintaining soil as well as supporting soil. The microbes enable enzymatic transformations that contribute to degrading certain substances, such as minerals, and managing the building blocks required by different tissues. An example is Microbial-induced calcite precipitation (MICP), which solidifies soils. MICP increases the loading capacity of Calcium Carbonate, supporting heavier loads that structures laid on top of it can withstand. As climate change is a key focus issue, coupled with urbanization and land-use changes, this technique is particularly beneficial compared to carbon-intensive, resource-hungry conventional methods [1].

They are good practices, but cement grouting and chemical sterilization introduce additional amounts of greenhouse gas emissions and toxic chemicals that contribute to pollution [15]. Soil biostimulation by

improving the nursery is a sustainable method for enhancing soil nutrition and altering its structural behavior. The practice stabilizes the cohesion, therefore addressing such issues [9]. This study proposes new concepts inspired by adapting to environmental challenges, incorporating geotechnical evaluation and field tests for validation, thereby enhancing the trustworthiness of green engineering solutions that rely less on traditional methods. This approach increases the infrastructure's reliance over time on resilient frameworks that endure stress and foster flexible techniques. Infrastructure needs different engineered methodologies designed sustainably for resilience within built terrains [3-6].

The existing bio-mediated ground improvement processes are promising, but they have limitations in terms of reliability, predictability, and optimization of the treatment process in field conditions of variability. The current research usually includes the results in terms of strength and permeability changes, but they are represented in different units and test types, thus cross-study correlations and systematic design become challenging. In addition, the performance is usually

* Corresponding author: dnarayan@gitam.edu

measured based on geotechnical parameters only (e.g. unconfined compressive strength, shear strength) and the underlying biological and chemical drivers are not commonly combined into a single measure. Thus, there is an obvious gap in the research: the necessity to provide a more intensive index to correlate microbial activity, biomineralization, and geomechanical behavior that would provide more confident predictions and optimization of bio-mediated ground improvement. The framework, the Soil Stability Index (SSI) framework, suggested in this work fills this gap directly because it explicitly refers to the combination of microbial activity, calcite precipitation, and cohesion into one normalized index, which, in turn, can be used both in the laboratory and in the field.

2 Related Work

Ultra-microbially induced calcite (MICP) has shown applications for ground improvement and soil infill, comprising calcium carbonate within the soil to increase its strength and stiffness [2]. It is particularly beneficial regarding bearings in sand soils and non-consolidated sands. There are suggestions that it can replace chemical grouting due to the lower environmental risks [13]. Further research focuses on "ground-sailing," the use of native microbial groups for passive soil stabilization processes from within by injecting nutrients that directly feed bacteria aimed at increasing natural processes of calcite precipitation and enzyme reactions that bond while bio-stimulating the soil, rather than injecting alien microbes [4]. Applied tests reported positive changes in cohesion and permeability within expansive clays and other harder, tunable soils that are otherwise stiff and flexible, which are traditionally hard to treat [5].

The study of biochemical processes in soil improvement by microorganisms has drawn attention to the roles played by denitrifying and sulfate-reducing bacteria [12]. These microbes cause the bonding and aggregation of minerals through natural redox reactions [11]. Scientists have investigated the controlled application of carbon and nitrogen to enhance bio-mediated ground improvement [10]. Such supplements accelerate microbial metabolism, resulting in increased biomineralization rates. [7]. Other studies have examined the application of genetically altered microbes for specific microbiological and geotechnical purposes [8]. These modified strains exhibit greater robustness to extreme conditions and higher rates of calcite precipitation, enabling them to thrive more effectively in harsh environments. While regulatory approval and ethical issues are still to be determined, preliminary evidence suggests that these are amenable to fine-grained regulation in ground improvement operations under high-constraint conditions, such as saline ground or following a disaster [14]. It is against this background that the current work is able to develop a coherent SSI framework which can be used on both native and engineered microbial systems to make comparisons and optimize treatment on an equal footing.

3 Methodology

The paper seeks to push the limits of the concept of sustainability by leveraging on the idea of soil microbiomes to reinforce and improve its cohesion by activating indigenous microorganisms with biocompatible nutrients in the context of restoring the soft soil land. It is mainly a biological amplification-type approach, in contrast to actual geotechnical physical strengthening, to achieve sustainable geotechnical enhancement. To advance the idea to the research scheme, we developed a laboratory and pilot scale field program, which has well-defined soil types, treatment regimens and control conditions.

3.1 Soil samples

Two typical types of soils that were likely to be found in earthworks were taken into consideration:

- A construction site subgrade low-plasticity sandy silt, (SM-ML), and initial water content, Atterberg limits, specific gravity and grain size distribution was determined before treatment.
- A very large clay (CH) which was obtained in an embankment borrow ground whose plasticity index, swelling potential and natural bearing capacity are low.

Air drying of the bulk sample, homogenization of the sample, and sieving of the sample through a 4.75 mm sieve was done on each soil to eliminate coarse materials. Initial condition properties such as natural moisture content, bulk density, compaction properties (Proctor test) and unconfined compressive strength (UCS) properties at the starting point (baseline) and direct shear properties were determined.

3.2 Microbial treatments/ controls

Microbial treatments oriented at enhancing natural urateolytic and calcite-precipitating consortia that are already present in the soils instead of exogenous strains, is in line with the concept of ground-sailing described in earlier research. A biocompatible nutrient solution was made with the urea and a calcium source (e.g., calcium chloride) at regulated molarities (usually 0.25-0.5 M urea and 0.25-0.5 M CaCl₂) depending on ranges reported in MICP literature. Other trace nutrients (carbon source, micronutrients) were supplemented at low levels so that there could be no accumulation of biomass as well as keep microbes alive.

The following setups were prepared concerning each of the soil types:

- The control (C0): the soil was compacted at its optimum moisture content without any nutrient added.
- Nutrient-only control (CN): soil in which the nutrient solution was applied, but stored in conditions that prevented microbial activity (e.g. cold storage).
- Bio-stimulated treatments (B1-B3): soils that were incubated and sprayed more frequently and longer

periods of time with nutrient solution in order to stimulate the activities of native microbes and calcite precipitation.

Applications of nutrient solutions were done by either percolation of tight columns (laboratory) or low-pressure injection and surface spray (field plots) and application volumes were normalized to the dry weight of the soil. Ensuring replication was done through ensuring that a minimum of three identical specimen was prepared in laboratory tests in each treatment level and locate duplicated or triplicated plots in the field.

3.3 Checking the activity of microbes and calcite precipitation.

Microbial activity (MA) was determined by counting colony-forming units (CFU) on soil samples growing on suitable medium and /or through urease activity tests, which were measured as enzymatic rate per gram of dry soil. The concentration of precipitated calcite (PC) was calculated by acid digestion and was either gravimetrically or titrimetrically analyzed and is expressed as the mg/kg of dry soil of artificially exchanged calcium carbonate. Geomechanical response was measured in the form of cohesion coefficient (Cc) obtained out of direct shear tests performed on treated and untreated samples at similar densities and moisture levels.

3.4 Definition of Soil Stability Index (SSI)

Let us define the definition of microbial-induced soil improvement efficiency with what we can call the Soil Stability Index "SSI" as presented below equation:

$$SSI = \alpha \cdot \frac{MA}{MA_{ref}} + \beta \cdot \frac{PC}{PC_{ref}} + \gamma \cdot \frac{Cc}{Cc_{ref}} \quad (1)$$

Where in (1):

- MA Microbial Activity (quantified via CFU or enzymatic rate)
- PC Precipitated Calcite concentration (mg/g)
- Cc Cohesion coefficient (from the direct shear test)
- $MA_{ref}, PC_{ref}, Cc_{ref}$ Reference values for normalization (e.g., baseline control or target values)
- α, β, γ Normalizing weight factors (empirically determined)

The stability of the soil as depicted in Equation 1 is predicted as a result of the biological and chemical activity and the geomechanical factors. The activity of the microbes is increased resulting in more calcite being produced which binds and glues the particles. The model allows the evaluation of the efficacy of treatment in real time, and the optimization of fieldwork can be performed according to the preset parameters.

3.5 Statistical analysis

In order to test the improvements that were observed and to make sure that the differences in treatment and controls are statistically significant, the adoption of standard inferential statistics was implemented. Student t tests were employed to determine the difference between the mean SSI, cohesion, or content of calcite at a desired level of significance (e.g., p less than 0.05) in case of comparisons between two groups (e.g., untreated vs. one level of treatment). Where the levels of treatment (e.g., C0, CN, B1, B2, B3) were compared at once, one way ANOVA was utilized, and appropriate post hoc tests should have been used in the situation when the differences between the groups were considered significant. Both standard deviation and standard error of the mean were obtained and utilized in creating the error bars of graphs representing SSI, calcite precipitation, and cohesion.

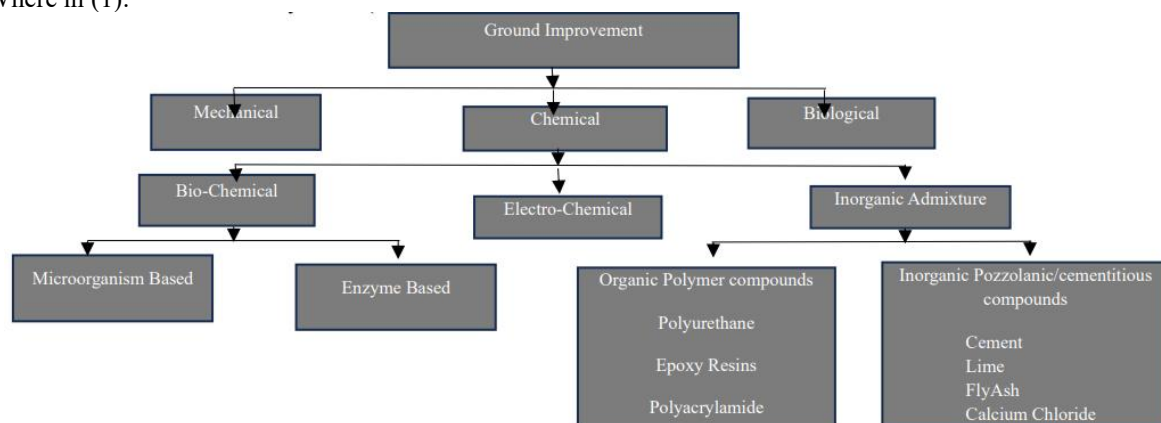


Fig. 1. Classification of ground improvement techniques

Figure 1 illustrates the comprehensive framework of various ground improvement techniques. The diagram organizes primary methods into mechanical, chemical, and biological categories, with further divisions into biochemical (microorganism- and enzyme-based), electrochemical, and inorganic admixture techniques. It visually aids in illustrating the focus of this paper, which is on the biochemical, microorganism-based pathways,

thus justifying why the proposed soil microbiome modification plan is presented as an environmentally friendly yet technically sound approach.

The proposed biogeochemical ground improvement technique focuses on soil microbes in nutrient cycling and structural transformation, working simultaneously to reinforce soil strength. It has improved processes such as

decomposition, along with nitrification and nitrogen fixation, thereby enhancing fertility.

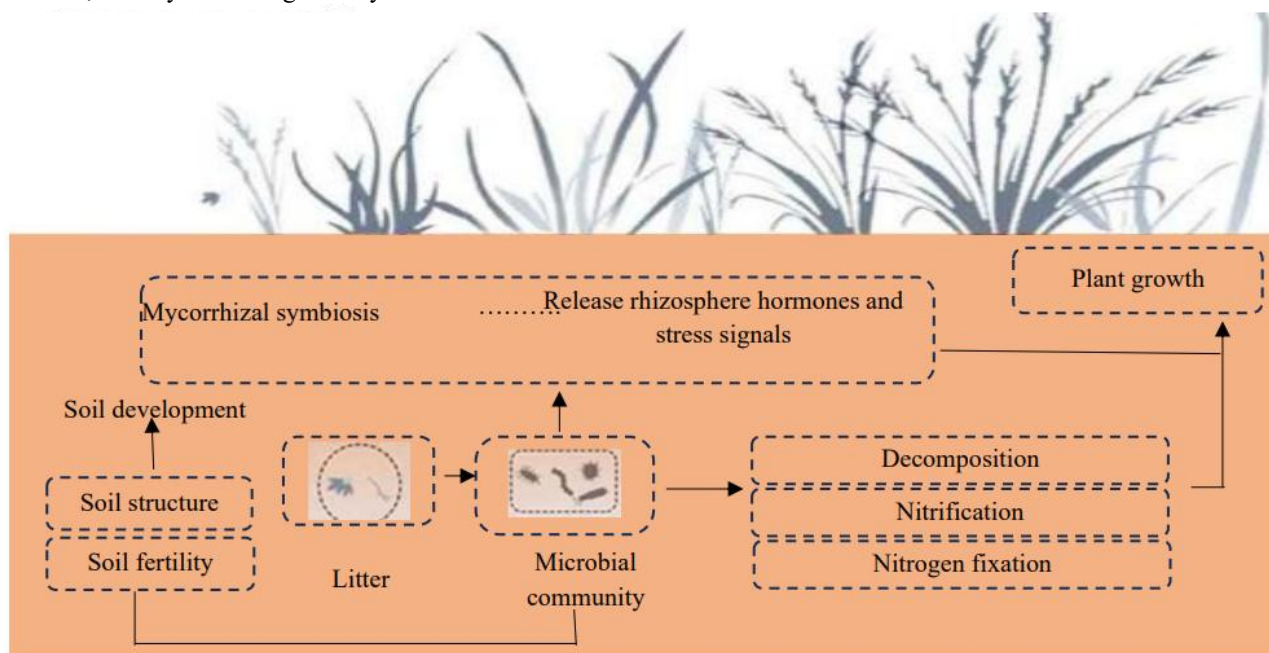


Fig. 2. The architecture of soil microbiome modulation for sustainable ground improvement

As illustrated in Figure 2, processes such as decomposition, nitrification, nitrogen fixation, and interactions within the rhizosphere help enhance soil structure by allowing microbes to improve cohesion and porosity. Through mycorrhizal symbiosis and plant inputs in the form of organic matter, this feedback loop becomes self-sustaining, which further augments the soil over time. Native micronutrients are eco-friendly and can stimulate the precipitation of minerals through microbes, which in turn leads to the consolidation of soil, making them great for native soils with weaker structures. This method is remarkably non-invasive and energy-efficient, making it suitable for many different types of soils and providing an additional approach to ground improvement.

4 Result and Discussion

The modulation of the soil microbiome can enhance soil strength, cohesion and even porosity. Microorganisms enhanced the calcite precipitation process by enriching the soil with nutrients which induced a binding effect which affected the Soil Stability Index (SSI). The field and laboratory tests proved that the load-bearing capacity of soils treated with the help of this method and the erosion rates of the soils were better in comparison with control soils, and these values indicate a steady growth in SSI values with equal measures of MA, PC, and Cc. Representation of standard deviations in the form of error bars of replicate specimens meant that the variability within the treatment groups was still less than the differences between the treated and untreated soils which supported the strength of the observed trends.

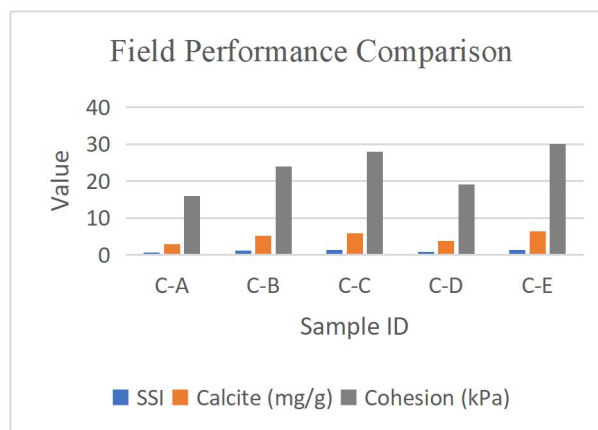


Fig. 3. Field Performance Comparison of Soil Stabilization Parameters

In Figure 3, the performance of five treated soil samples is compared using three metrics: Soil Stability Index (SSI), Calcite Precipitation, and Cohesion. Calcite-rich samples exhibit better cohesion and SSI performance. Sample C-E demonstrates the most remarkable improvement, suggesting strong microbial processes coupled with reinforcement of the soil structure. Statistical analysis using one-way ANOVA confirmed that the mean SSI and cohesion values for samples C-E were significantly higher ($p < 0.05$) than those of untreated or nutrient-only controls, indicating that bio-stimulation rather than purely chemical effects was responsible for the majority of the improvement.

Table 1. Field Implementation Metrics of Soil Microbiome Modulation

Sample ID	Nutrient Uptake	Microbial	Soil Moisture	Treatment Duration
-----------	-----------------	-----------	---------------	--------------------

	Rate (mg/day)	Viability (%)	(%)	(days)
F-A	2.4	88	22.5	14
F-B	2.9	91	23.1	17
F-C	3.2	94	24.0	20
F-D	2.5	89	22.8	15
F-E	3.4	95	24.7	21

The efficiency of microbial treatment is discovered by the presence of right amount of moisture in soil, microbial viability and optimizing the treatment time as reported in Table 1. Sample F E registered the most values implying that it is more active in terms of microbial activity and giving a favorable response in the soil. The enhanced assimilation of nutrients of superior samples proves the ensured fact that superior soil status sustains better microbial life forms. The comparison of F E with respective untreated field sections, t tests revealed statistically significant differences in SSI and cohesion ($p < 0.05$) and once again confirmed the effectiveness of microbiome modulation in a field environment. Both laboratory and field experiments confirm that microbiome modulation leads to the improvement of soil stability due to the effects of calcite precipitation and adhesion, which has a significant positive impact on earthworks.

5 Conclusion

This paper proposes a new solution in improving ground construction by using soil microbiomes. Microbial induced calcite precipitation (MICP) and nutrient induced microbial activity provided significant gains in soil cohesion, reduction in porosity, and general strength gain, all of which are determined in a quantitative way using the Soil Stability Index (SSI). All the improvements on the Soil Stability Index (SSI) were supported by experimental and field data and proved that the method was technically feasible and that statistically significant differences between the treated and untreated soils were observed under controlled conditions. This method, as compared to chemical or mechanical ones, will help in minimizing carbon emission and also help to enhance soil health in the long run. Microbiology introduction into the geotechnical engineering through bio-geo-chemistry creates space in which an alternative solution to adapt to bio approach is less toxic to the ecosystem. On the biological level, the subject of stabilization like absorption of nutrients and biodegradation of microbes causes precipitation of calcium carbonate to strengthen the performance, and SSI framework provides a solution to maximize performance and predict it transparently. The solution is cost-efficient and easy to adapt at the same time not only because there are no scales restrictions thus extensive applicability.

References

1. X. Zhang, H. Liu, Microbial-induced soil stabilization: Progress and prospects. *Geotech. Environ. Eng. J.* **45**(3), 121–133 (2022).

2. E. Yağız, G. Ozyilmaz, A.T. Ozyilmaz, Optimization of graphite-mineral oil ratio with response surface methodology in glucose oxidase-based carbon paste electrode design. *Nat. Eng. Sci.* **7**(1), 22–33 (2022). <https://doi.org/10.28978/nesciences.1098655>
3. M.A. Torres, Y. Lin, Bio-geo-chemical feedbacks in soil improvement applications. *Environ. Geosci. Rep.* **27**(4), 232–245 (2021).
4. S.H.M. Altai, H.M. Youssef, H.A. Muhee, A.H. Hummadi, Study of the relationship between *Bacillus subtilis* and *Azospirillum sp.* & *Bradyrhizobium sp.* isolated from gypsiferous soil. *Int. J. Aquat. Res. Environ. Stud.* **5**(1), 343–353 (2025). <https://doi.org/10.70102/IJARES/V5I1/5-1-3410>
5. A. Al-Mansoori, L. Zhao, Bio-cementation via native microbial communities in clay-rich soils. *Int. J. Environ. Geotech.* **48**(1), 21–34 (2023).
6. S. Radmanović, A. Đorđević, N. Nikolić, Humus Composition of Rendzina Soils in Different Environmental Conditions of Serbia. *Arch. Tech. Sci.* **2**(19), 57–64 (2018).
7. S. Lin, R. Mehta, Nutrient-mediated microbial soil treatment for ground improvement. *Environ. Soil Sci. Eng.* **29**(3), 145–160 (2024).
8. S.I. Kapoor, R. Menon, Assessing the Impact of Microfinance on Entrepreneurship in Developing Economies. *Int. Acad. J. Innov. Res.* **12**(2), 20–25 (2025). <https://doi.org/10.71086/IAJIR/V12I2/IAJIR1213>
9. V. Kumar, R. Singh, Sustainable approaches in geotechnical engineering: A microbial perspective. *J. Clean. Infrastruct.* **19**(2), 85–101 (2023).
10. M. Boghori, S.A. Tabatabai, The Effect of Irrigation Intervals and Nitrogenous Fertilizer on the Quantitative and Qualitative Performance of Chamomile. *Int. Acad. J. Sci. Eng.* **4**(2), 128–134 (2017).
11. M. Singh, J. Thomas, Soil stabilization using microbial pathways: A critical review. *Geomech. Bioeng. J.* **12**(4), 198–210 (2021).
12. P. Sharma, K. Subramanian, Molecular Mechanisms of Antibiotic Resistance in Bacteria. In *Medxplore: Frontiers in Medical Science*, Periodic Series in Multidisciplinary Studies, 19–36 (2025).
13. D. Patel, Y. Huang, Application of microbial-induced calcite precipitation in geotechnical engineering. *J. Soil Stabil. Res.* **36**(2), 75–90 (2022).
14. T. Banerjee, P. O'Connor, Advancements in genetically modified microbes for soil bioengineering. *Biotech Front. Infrastruct.* **17**(2), 89–102 (2025).
15. N.T. Thoi, Nanoparticle applications revolutionizing chemical processes. *Innov. Rev. Eng. Sci.* **2**(1), 13–21 (2025). <https://doi.org/10.31838/INES/02.01.02>