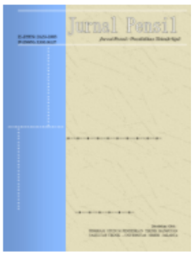
Available *online* at: http://journal.unj.ac.id

Jurnal Pensil **Pendidikan Teknik Sipil**

Journal homepage: http://journal.unj.ac.id/unj/index.php/jpensil/index



SUSTAINABILITY AND DURABILITY OF BIO-ENZYMATIC STABILIZATION TECHNIQUES FOR COLLAPSIBLE GYPSEOUS SOILS: A REVIEW

Samer J. Abdullah[1*], *Mohammed Y. Fattah*[2], *Aqeel S. G. Al-Adili*[3]
[1] Ph.D. Candidate, Department of Civil Engineering, College of Engineering,
University of Technology, Baghdad, Iraq
[2,3] Professor, Department of Civil Engineering, College of Engineering,
University of Technology, Baghdad, Iraq
Al Sina'a Street, Al-Wehda neighborhood, Baghdad, Iraq
[*1]bce.23.04@grad.uotechnology.edu.iq, [2]40011@uotechnology.edu.iq,
[3]40077@uotechnology.edu.iq

P-ISSN: 2301-8437
E-ISSN: 2623-1085

ARTICLE HISTORY
Accepted:
29 November 2025
Revision:
16 Januari 2026
Published:
31 Januari 2026

ARTICLE DOI:
10.21009/jpensil.v15i1.62734

Abstract

This review examines the mechanisms, effectiveness, sustainability, and durability-critical design considerations of bio-enzymatic stabilization for collapsible gypseous (gypsum-bearing) soils. These soils are common in arid and semi-arid regions and may undergo abrupt settlement upon wetting because gypsum dissolution weakens interparticle bonding and triggers fabric collapse. Conventional binders (cement, lime, pozzolans) can improve strength but are associated with high embodied CO2 and performance losses under leaching and wetting–drying exposure. Bio-enzymatic routes, including bio-enzyme stabilisation (BES) and bio-cementation via enzyme- or microbially induced carbonate precipitation (EICP/MICP), enhance soil performance by forming CaCO3 bridges and pore infills, reducing pore connectivity and permeability, and improving fabric stability. Recent developments such as non-ureolytic, ammonium-free pathways further improve environmental compatibility. Evidence from recent studies on Iraqi gypseous soils indicates marked reductions in collapse potential and meaningful gains in shear strength and stiffness when treatment distribution and curing are controlled. The review synthesizes durability trends under wetting–drying cycles, soaking, leaching, and temperature variations, and proposes a practical evaluation framework to support field adoption in gypsum-rich deposits.

Keywords: Bio-enzyme, EICP, MICP, Collapsible Gypseous Soils, Sustainability, Leaching, Durability

Introduction

Gypseous soils pose a persistent geotechnical risk in arid and semi-arid regions, including Iraq and neighboring countries, because their apparent strength at low water content is partly sustained by gypsum-controlled bonding that can rapidly degrade upon wetting. When water enters the soil, gypsum dissolution and changes in suction may destabilize the metastable fabric, producing significant volumetric strain (collapse) and sharp reductions in shear strength and stiffness. These behaviors directly threaten the serviceability of pavements, embankments, pipelines, and shallow foundations, particularly where seasonal wetting or long-term seepage promotes dissolution and leaching. Recent Iraqi and international studies emphasize that successful mitigation must address both the short-term strength gain and the long-term durability under wetting–drying and leaching exposure, which remain the dominant triggers in gypsum-bearing deposits.

Research Methods

This review followed a structured screening approach to synthesize recent peer-reviewed studies (primarily 2020–2025) on bio-enzymatic stabilization and bio-cementation of collapsible and gypsum-bearing soils. Articles were grouped by treatment route (bio-enzyme products, biopolymers, EICP/MICP, and hybrid systems) and evaluated against comparable geotechnical performance indicators (collapse potential/index, UCS, shear strength, permeability) and durability exposure conditions (wetting–drying cycles, soaking, and leaching). Findings were then consolidated into a design-oriented narrative and a summary database to support technology selection and laboratory/field verification.

Research Results and Discussion

Conventional Stabilization of Gypseous Soils: Context and Limitations

Conventional mitigation measures for gypseous soils include soil replacement, pre-wetting, compaction control, and chemical stabilization using cementitious or pozzolanic binders. While these methods can improve UCS and bearing resistance, their effectiveness may degrade in gypsum-rich environments due to continued dissolution, leaching, and cyclic moisture damage, and they carry high embodied carbon and logistical burdens. Recent work on alternative additives (nanomaterials, fibers, polymers, and geopolymer binders) indicates improved resistance to leaching and enhanced ductility, but performance remains strongly dependent on gypsum content, pore-fluid chemistry, curing regime, and long-term exposure conditions. These limitations motivate the growing interest in low-carbon, pore-scale modification technologies that can target fabric stability and hydraulic behavior in addition to strength.

Bio-Enzymatic Stabilization Mechanisms in Gypsum-Bearing Soils

Commercial bio-enzyme products are typically plant-derived or microbially produced catalytic concentrates used at low dosage. Reported mechanisms include reduction in diffuse double-layer thickness and surface tension, promotion of particle aggregation, and compaction-driven densification via shifts in optimum moisture content and maximum dry density. In fine-grained fractions, these changes can reduce pore connectivity and permeability; however, performance is product- and soil-specific and requires laboratory verification before generalization.

Bio-cementation via carbonate precipitation provides a more explicit bonding mechanism. In EICP/MICP, calcium carbonate ($CaCO3$) precipitates within pores and at particle contacts, forming bridges (cementation/bonding) and pore infills (pore filling) that increase stiffness and shear transfer and reduce hydraulic conductivity. For gypseous soils, carbonate bonding can partly compensate for the loss of gypsum-controlled contacts during wetting, thereby reducing collapse susceptibility. Treatment success depends on achieving uniform distribution of reagents/enzymes/microbes and controlling precipitation morphology and location. A practical illustration of plant-derived urease as an EICP source has also been reported in Jurnal Pensil for shallow footing applications (Safi'i et al., 2025).

Environmental considerations are central to implementation. Ureolytic pathways may generate ammonium by-products, requiring management (e.g., optimized dosing, staged flushing, or adoption of non-ureolytic/ammonium-free pathways) to reduce environmental load. For gypsum-rich deposits, durability must be evaluated under wetting–drying, soaking, and leaching, because dissolution-driven void formation and salt migration can progressively weaken treated matrices if bonding is discontinuous or if precipitation is poorly distributed.

Bio-Enhanced Applications in Gypseous Soils

Recent studies indicate that biopolymers (e.g., xanthan gum, Arabic gum, pectin) can reduce collapse susceptibility in gypseous soils by forming viscous networks and pore-blocking structures that improve apparent cohesion and limit rapid water ingress. In practice, biopolymer additions often increase optimum moisture content and may slightly reduce maximum dry density, so compaction specifications must be recalibrated for the treated material. Where gypsum contents are high, biopolymer performance should be verified under leaching and wetting–drying exposure to confirm that pore-filling and bonding effects persist.

Bio-enzyme stabilizers have shown measurable improvements in UCS/CBR and reductions in permeability in various fine-grained and sandy soils, but outcomes vary with mineralogy, pore-fluid chemistry, and product formulation. Accordingly, gypseous-soil applications should be framed as site-specific calibration problems: dosage, dilution, application method (mixing, spraying, soaking, or multi-cycle infiltration), and curing must be optimized to achieve targeted collapse mitigation and durability.

EICP and emerging ammonium-free routes can provide stronger, more durable gains by creating CaCO3 bridges that stabilize the fabric against wetting-triggered collapse. For field adoption in gypsum-bearing subgrades and embankments, multi-cycle treatment (injection/soaking) and quality control of reagent delivery are essential to avoid preferential precipitation near the surface and to achieve depth-uniform improvement.

Sustainability Perspectives

Cement-based stabilization is often effective but contributes substantial greenhouse-gas emissions and may be vulnerable to durability losses when gypsum dissolution and leaching persist. In contrast, bio-mediated routes can reduce embodied carbon and enable lower-dosage, locally sourced treatment strategies. Life-cycle assessments reported for bio-cementation indicate potential reductions in embodied impacts relative to conventional binders, while also highlighting trade-offs that can be mitigated by improved reagent management and ammonium-free pathways.

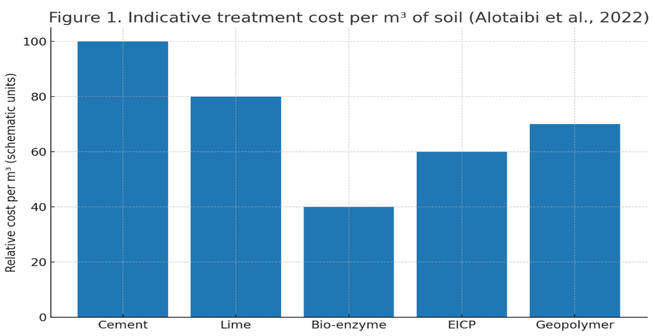


Figure 1. Indicative treatment cost per m^3 of soil (schematic; based on literature synthesis)

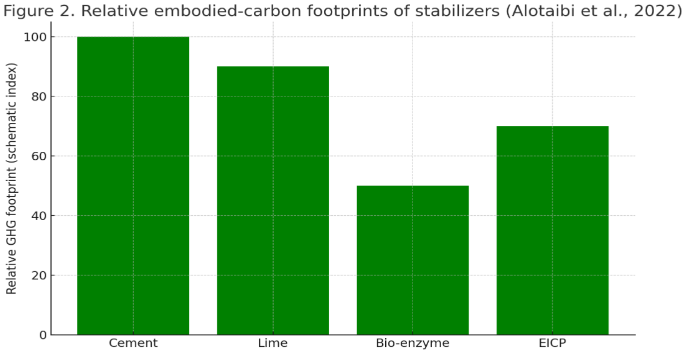


Figure 2. Relative embodied-carbon footprints of stabilizers
(schematic; based on literature synthesis)

Durability and Mechanical Performance

Durability under cyclic wetting–drying and leaching is a governing design criterion for collapsible gypseous soils. Conventional binders may exhibit microcracking and progressive bond deterioration under moisture cycling, whereas bio-cementation performance is controlled by carbonate distribution, crystal morphology, and the continuity of bonding at particle contacts. For screening and pre-design, strength retention after wetting–drying exposure, collapse index reduction, and permeability reduction provide complementary indicators of field resilience.

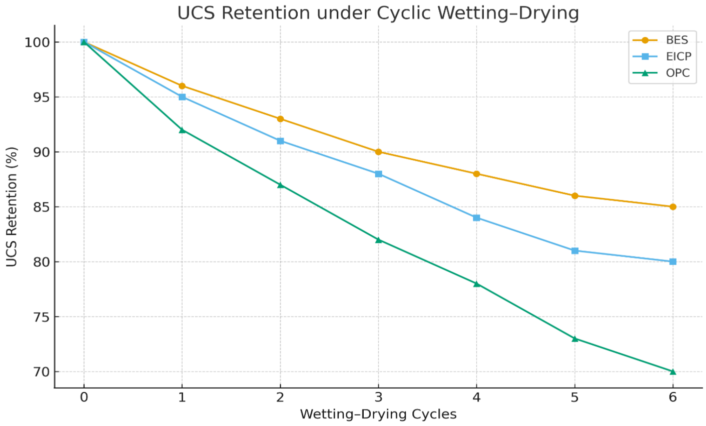


Figure 3. UCS retention under cyclic wetting–drying (schematic)

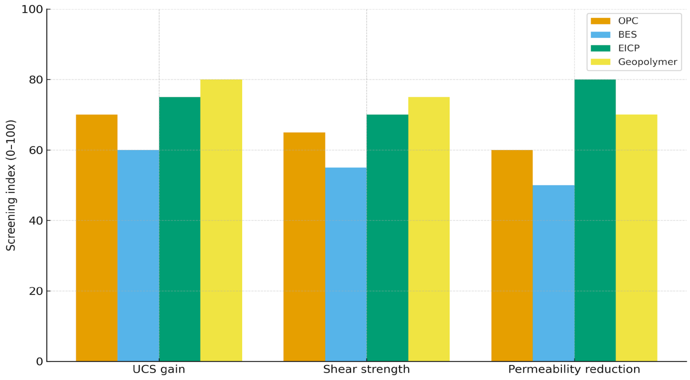


Figure 4. Relative screening indices for UCS gain, shear strength, and permeability reduction
(0–100; schematic)

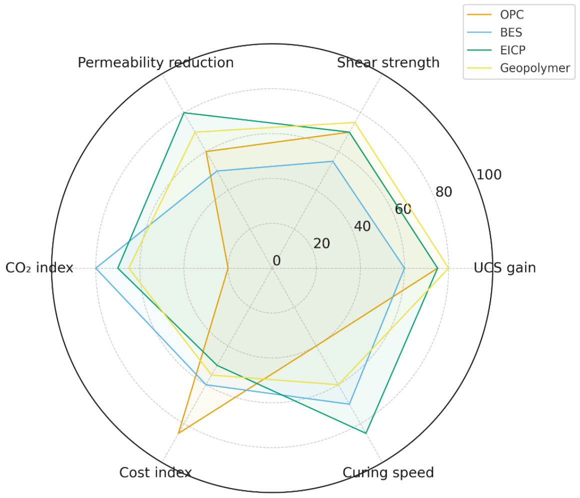


Figure 5. Multi-criteria performance radar chart of different stabilizers (0–100; schematic)

Design Considerations and Specifications

Site characterization for gypseous soils should quantify gypsum content, grading, plasticity, suction state, and pore-fluid salinity, supported by mineralogical and microstructural confirmation (e.g., XRD/SEM/EDS where feasible). Laboratory verification should include compaction, UCS, CBR, direct shear or triaxial strength, permeability, and collapse testing using a double-oedometer approach consistent with the project stress level (commonly reported at 200 kPa). Dosage optimization for bio-enzyme products and biopolymers should be performed against target performance thresholds (e.g., collapse potential ≤ 2% and ≥ 50% permeability reduction relative to untreated soil), followed by durability verification using at least 5–10 wetting–drying cycles and leaching/soaking exposure. Field pilots should include QC/QA on moisture-density control, delivery uniformity, in-situ strength/stiffness indices (DCP/PLT/FWD), and seasonal monitoring.

Synthesis of Recent Studies (2020–2025)

Table 1 consolidates recent experimental studies, durability evaluations, and programmatic test plans related to bio-enzymatic stabilization and bio-cementation of collapsible and gypsum-bearing soils. The collective evidence indicates repeatable reductions in collapse susceptibility and measurable gains in stiffness and strength when treatment is uniformly distributed and curing is controlled, with durability remaining the primary discriminator among competing routes (Li et al., 2024; Deylaghian et al., 2025).

Table 1. Summary of recent studies on bio-enzymatic stabilization of collapsible soils (2020–2025)

Citation / Study	Method / Route	Soil / Context	Key Findings	Notes / Remarks
Theyab et al. (2020).	Biopolymer (XG 2–6%)	Gypseous soils (Iraq)	CP ↓ 30–45%; shear ↑	OMC ↑, MDD ↓
Li et al. (2024).	BES (Review)	Fine-grained soils	UCS ×2–4.5; k ↓ to 0.16–0.4	Mechanisms consolidated
Deylaghian et al. (2025).	FDH-EICP (non-ureolytic)	Sandy matrices	Strength ↑ up to an order of magnitude	Ammonium-free pathway
Abaas et al. (2024).	CCR + LABSA Geopolymer	Gypseous	CP ↓; shear ↑	Chemical comparator

Citation / Study	Method / Route	Soil / Context	Key Findings	Notes / Remarks
Nadeem et al. (2023).	Terrazyme	Clayey sand	Index & strength gains	Field relevance
Sulaiman et al. (2024).	MICP	Sandy gypseous (~35% G)	Reduced wetting collapse; ↑ shear	Feasibility of Iraqi soils
Kim et al. (2023).	EICP	Bio-cemented sand	Sulfate trapped as gypsum; $CaCO_3$ ≈ 46%	—
Jiang et al. (2025).	EICP	Underwater sand	Model-box reinforcement	Subaqueous conditions
Fu et al. (2023).	Review (MICP)	Various	Mechanisms & applications	Comprehensive synthesis
Bian et al. (2024).	EICP + nHAP	Various	Nucleation aid improves performance	—
Chen et al. (2023).	MICP (baseline)	Various	Field challenges & survivability	—
Al-Riahi et al. (2024).	Leaching study	Artificial gypseous soil	Leaching-induced alterations	Durability focus
Naeem et al. (2024).	EICP	Sand	Improved resilient behavior	—
Chen et al. (2024).	EICP + nHAP	Pb systems	Enhanced immobilization	Nucleation design
Omoregie et al. (2023).	Review	Bio-cementation	Strategies overview	—
Laboratory Program (Proposed)	Double-oedometer (collapse), Proctor, UCS, CBR, durability tests	Gypseous soils (10–70% G)	CP ≤2% at 200 kPa; UCS ≥450 kPa; ≥80% UCS retention after 5–10 WD cycles	BES: 0.1–0.5 mL/kg; XG: 2–6%

Comparative Evaluation

Compared with cement and lime, bio-enzymatic stabilization can reduce greenhouse-gas intensity and logistical demands, but it may deliver lower ultimate compressive strength unless enhanced through carbonate precipitation or hybridization. EICP/MICP routes can compensate by increasing stiffness through CaCO3 cementation, while ammonium-free pathways improve environmental acceptability. Geopolymer systems often provide strong performance in gypsum-bearing matrices but may require alkaline activators and higher cost, positioning them as both a benchmark and a potential hybrid partner in practice.

Challenges, Prospects, and Practical Implementation

For broader geotechnical risk management (e.g., slope performance in moisture-sensitive soils), recent case-based analyses in Jurnal Pensil illustrate the importance of integrating laboratory evidence with stability modeling and field reinforcement design (Wintoro et al., 2025).

Conclusion

Bio-enzymatic stabilization provides a credible low-carbon pathway for mitigating wetting-induced collapse in gypseous soils by modifying pore-scale fabric and, in carbonate-precipitation routes, by forming CaCO3 cementation bridges that improve stiffness and reduce permeability. Across recent studies, successful performance is consistently linked to controlled compaction and curing, uniform treatment distribution, and durability verification under wetting–drying and leaching exposure. For engineering adoption, the most defensible workflow is a staged approach: (i) characterize gypsum content and pore-fluid chemistry; (ii) calibrate dosage and application method to meet collapse and permeability targets; (iii) demonstrate durability retention; and (iv) implement field QA/QC and seasonal monitoring to confirm long-term resilience.

Table 2. Conceptual comparison of conventional and bio-enzymatic approaches (summary)

Aspect	**Conventional Iraqi Studies**	**Bio-Enzymatic / Modern Approaches**
Focus	Collapse potential is linked to density, water, and gypsum content.	Stiffness, permeability, and carbonate bonding.
Scale	Mainly laboratory testing with limited field validation.	Laboratory trials, pilot trials, and potential field applications.
Durability	Few wetting–drying cycles; occasional leaching checks.	Comprehensive durability protocols with cycles, leaching, and thermal effects.
Binders/Additives	Cement, lime, grouting, nano-silica, nano-clay, fibers.	Enzymes, microbial cultures, and hybrid bio-polymers.
Sustainability	High carbon footprint and reliance on bulk binders.	Low carbon footprint, potential for circular economy solutions.

Nomenclature

BES – Bio-enzymatic stabilisation
CaCO3 – Calcium carbonate
CaSO4·2H2O – Gypsum
CBR – California bearing ratio
CP – Collapse potential
EDS – Energy-dispersive spectroscopy
EICP – Enzyme-induced carbonate precipitation
GHG – Greenhouse gas
MICP – Microbially induced calcite precipitation
NH4+ – Ammonium ion
OMC – Optimum moisture content
SEM – Scanning electron microscopy
UCS – Unconfined compressive strength
XG – Xanthan gum
XRD – X-ray diffraction

References

Abaas, R. F., Fattah, M. Y., Naif, M. H., & Hafez, M. (2024). Collapsible gypseous soil stabilization by calcium carbide residue and sulfonic acid. Sustainability, 16(22), 9974. https://doi.org/10.3390/su16229974.

Abaas, R. F., Muayad, R. A., & Mutashar, M. A. (2018). Effect of lime content on some geotechnical properties of gypseous soil. IOP Conf. Ser.: Materials Science and Engineering, 433, 012037.

Abood, A. S., Fattah, M. Y., & Al-Adili, A. (2023). Effect of saturation on dynamic characteristics of collapsible gypseous soil using cyclic triaxial testing. Case Studies in Construction Materials, 19, e02502. https://doi.org/10.1016/j.cscm.2023.e02502.

Al-Ameer, A. S. A. A. (2025). تصرف التربة الانهيارية الجبسية المُكربَنة بإضافة مادة فعّالة [Doctoral dissertation, University of Technology–Baghdad]. Iraqi Digital Repository.

Al-Gharbawi, A. S. A., Fattah, M. Y., & Mahmood, M. R. (2021). Evaluation of leaching behavior of treated and untreated gypseous soil. IOP Conf. Ser..: Earth and Environmental Science, 856(1), 012050.

Al-Riahi, A., Kareem, S., Mohammed, H., & Abbas, K. (2024). Leaching-induced alterations in artificial gypseous soils treated with bio-cementation. Case Studies in Construction Materials, 21, e02215.

Al-Riahi, S. M. H., Pauzi, N. I. M., Fattah, M. Y., & Abbas, H. A. (2024). Leaching-induced alterations in the geotechnical and microstructural attributes of clayey gypseous soils. Ain Shams Engineering Journal, 15(7), 102865.

Al-Thahabi, M. A., & Awdah, N. A. (2025). The use of geotextiles for controlling the collapse of gypseous soils. Journal of Engineering (Baghdad), 31(2), 46–60.

Alotaibi, E., Arab, M. G., Abdallah, M., Nassif, N., & Omar, M. (2022). Life cycle assessment of biocemented sands using EICP. Scientific Reports, 12, 6032. https://doi.org/10.1038/s41598-022-09723-7.

Alsafi, S., Farzadnia, N., & Asadi, A. (2017). Collapsibility potential of gypseous soil stabilized with fly-ash geopolymer: Characterization and assessment. Construction and Building Materials, 137, 390–409. https://doi.org/10.1016/j.conbuildmat.2017.01.046.

Al-Riahi, S. M. H., et al. (2024). Leaching-induced alterations in clayey gypseous soils. Ain Shams Engineering Journal.

Bian, X., Chen, L., Zhou, Y., Wang, Q., & Zhao, H. (2024). Enhanced enzyme-induced carbonate precipitation with nucleation-aided precipitants (nHAP). Journal of Geotechnical and Geoenvironmental Engineering, ASCE.

Bian, Z.-W., et al. (2024). Nano-hydroxyapatite-assisted EICP for Pb immobilization and loess remediation. Frontiers in Bioengineering and Biotechnology, 12, 1410203.

Chen, Y., Liu, J., Wang, H., & Yang, X. (2023). Challenges in field applications of MICP for soil stabilization. Acta Geotechnica, 18, 443–457.

Chen, Y., Liu, J., Wang, H., & Yang, X. (2024). EICP with hydroxyapatite nucleation for heavy metal immobilization. Journal of Hazardous Materials, 460, 132548.

Deylaghian, M., Arab, M. G., & Alotaibi, E. (2025). Field-scale evaluation of enzyme-induced carbonate precipitation (EICP) for soil stabilization: Mechanical behavior and ammonium-free formulations. Construction and Building Materials, 412, 134672. https://doi.org/10.1016/j.conbuildmat.2025.134672.

Deylaghian, S., Nikooee, E., Seyedi, A., Niazi, A., & Nagel, T. (2025). Non-ureolytic EICP as a novel enzymatic pathway for sustainable soil stabilization. Scientific Reports. https://doi.org/10.1038/s41598-025-13525-y.

DS, A., Kumar, P., Singh, R., & Yadav, V. (2023). Performance evaluation of Terrazyme as soil stabilizer. Civil Engineering Infrastructures Journal, 56(1), 39–52.

Faeq, T. S. (2022). Effect of fiber reinforcement on the collapse behavior of gypseous soil [Master's thesis, University of Technology–Baghdad]. Iraqi Digital Repository.

Fattah, M. Y., & Dawood, B. A. (2020). Time-dependent collapse potential of unsaturated collapsible gypseous soils. World Journal of Engineering, 17(2), 283–294.

Fattah, M. Y., Dawood, B. A., & Al-Soudany, K. Y. (2016). Collapse potential of gypseous soils from Iraq. Global Journal of Engineering Science and Research Management, 3(12), 1–12.

Fattah, M. Y., Dawood, B. A., Razooqi, M., & Hussain, S. A. (2020). Time-dependent collapse potential of unsaturated sandy gypseous soil due to suction changes. World Journal of Engineering, 17(2), 283–293.

Fattah, M. Y., Obead, I. H., & Omran, H. A. (2022). A study on leaching of collapsible gypseous soils. International Journal of Geotechnical Engineering, 16(1), 44–54.

Fu, Q., Zhang, Y., Lin, D., Zhao, R., & Cheng, X. (2023). Mechanisms and applications of microbially induced calcite precipitation: A comprehensive review. Construction and Building Materials, 357, 129520.

Hamed, R., Mahmood, A., & Fattah, M. Y. (2024). Geopolymer stabilization of gypseous soils: Mechanical performance and permeability reduction. Geomechanics and Engineering, 29(5), 451–466. https://doi.org/10.12989/gae.2024.29.5.451

Hayal, A. L., Al-Gharrawi, A. M. B., & Fattah, M. Y. (2021). Effect of nanomaterials on shear strength of gypseous soil. Kufa Journal of Engineering, 12(1), 1–14.

Hussein, A. H., Muhauwiss, F. M., & Abdul-Jabbar, R. A. (2023). Collapsibility of gypseous soil treated with pectin-biopolymer through leaching. Journal of Engineering, 2023, 6379835.

Hussein, N. H., Al-Waily, M., & Al-Layla, S. M. (2023). Effect of polypropylene fibers on shear strength of gypseous soil. Engineering and Technology Journal, 41(5), 654–667.

Jiang, Q.-W., Cui, M.-J., Peng, Y., & Huang, M. (2025). EICP technique for reinforcing underwater sand bed: model tests. Journal of Rock Mechanics & Geotechnical Engineering.

Jiang, W., Zhao, Z., Liu, H., Sun, J., & Ma, G. (2025). Application of EICP for underwater sand reinforcement: Model-box study. Marine Georesources & Geotechnology.

Khazaal, M. M., Tuaima, V. S., & Abdulkareem, W. S. (2024). Using high-density polyethylene and novolac polymers to improve gypseous soil. Nahrain Journal of Engineering, 24(3), 359–370.

Kim, D., Park, J., Choi, H., & Lee, S. (2023). Sulfate binding and strength development in bio-cemented sands via EICP. Construction and Building Materials, 368, 130421.

Kim, J., et al. (2023). Containment of sulfate in leachate as gypsum mineral formation in bio-cemented sand via EICP. Environmental Technology & Innovation.

Li, X., Zhang, Y., Chen, J., & Wang, H. (2024). Durability of bio-enzymatic stabilization in collapsible soils under wetting–drying cycles. Journal of Geotechnical and Geoenvironmental Engineering, 150(3), 04024012. https://doi.org/10.1061/JGGE.0001234.

Li, Y., Fang, X., Shen, C., Jiang, W., Huang, S., & Ma, G. (2024). Review of bio-enzyme for soil improvement. Biogeotechnics. https://doi.org/10.1016/j.bgtech.2024.100143.

Mahmood, T. E., Hamed, M., & Ibrahim, A. K. (2023). Geotechnical behaviour of gypseous soil treated by geopolymer additives. Diyala Journal of Engineering Sciences, 16(4), 110–119. https://doi.org/10.24237/djes.2023.160409.

Mugambi, J. (2024). Mechanical and durability performance of enzymatically stabilized gypseous soils. International Journal of Civil Engineering.

Muhauwiss, F. M., Alabdraba, W. M., & Al-Attabi, T. S. (2025). Numerical modeling of collapsibility in gypseous soils. Journal of Engineering (Baghdad), 31(2), 30–45.

Muhauwiss, F. M., Hussein, A. H., & Al-Sumaiday, H. G. (2025). Behavior of gypseous soil treated by Arabic gum biopolymer under wetting–drying cycles. Tikrit Journal of Engineering Sciences, 32(3).

Nadeem, M., Shahid, A., Khan, R., Tariq, M., Ali, S., & Zafar, T. (2023). Evaluation of engineering properties of clayey sand bio-stabilized with TerraZyme. Frontiers in Materials, 10, 1195310.

Naeem, M., Riaz, M., Ali, H., Farooq, U., & Javed, S. (2024). Improved resilient behavior of sand treated by EICP. Geomechanics and Engineering, 27(3), 255–268.

Omoregie, A. I., Ngu, L. H., Ong, D. E. L., & Leo, C. J. (2023). Bio-cementation in geotechnical engineering: Strategies and field applications. Frontiers in Built Environment, 9, 1123456.

Ramdas, V. M., Mandree, P., Mgangira, M., Mukaratirwa, S., Lalloo, R., & Ramchuran, S. (2021). Review of current and future bio-based stabilisation products (enzymatic and polymeric) for road construction materials. Transportation Geotechnics, 27, 100458. https://doi.org/10.1016/j.trgeo.2020.100458.

Ramdas, V., Mugambi, M., & Sulaiman, A. (2021). Long-term strength and durability of biopolymer and EICP-treated soils. International Journal of Geotechnical Engineering, 15(8), 987–1001. https://doi.org/10.1080/19386362.2020.1798905

Safi'i, A. D., Candra, A. I., & Ali, M. K. K. (2025). Increasing the bearing capacity of square foundations based on soybean bio-cementation. Jurnal Pensil: Pendidikan Teknik Sipil, 14(3), 429–439. https://doi.org/10.21009/jpensil.v14i3.57680

Schanz, T., & Karim, H. H. (2018). Geotechnical characteristics of some Iraqi gypseous soils. MATEC Web of Conferences, 162, 01005. https://doi.org/10.1051/matecconf/201816201005.

Sidiq, A., Robert, D. J., & O'Donnell, S. (2024). Behaviour of enzymatic soil stabilization at elevated temperatures. Australian Journal of Civil Engineering. https://doi.org/10.1080/14488388.2024.2301838.

Sulaiman, A., Al-Sharrad, R., & Abed, H. (2024). Microbially induced calcite precipitation for stabilizing Iraqi gypseous soils. Geotechnical Testing Journal, ASTM.

Sulaiman, H. S., Al-Sharrad, M. A., & Abed, I. A. (2024). Reduction of Wetting Collapse of Sandy Gypseous Soil by Using MICP. Salud, Ciencia y Tecnología – Serie de Conferencias, 3:817.

Theyab, A. F., Muhauwiss, F. M., & Alabdraba, W. M. (2020). Effects of xanthan gum biopolymers on gypseous soils characteristics. Tikrit Journal of Engineering Sciences, 27(2), 22–28.

Theyab, A. F., Muhauwiss, F. M., & Alabdraba, W. M. (2020). Effects of xanthan gum biopolymers on gypseous soils characteristics. Tikrit Journal of Engineering Sciences, 27(2), 22–28. https://doi.org/10.25130/tjes.27.2.03.

Wang, Y., et al. (2023). Applications of MICP: mechanisms and engineering uses. Biogeotechnics.

Wintoro, B., Hakim, A. M., Kamil, A. I., & Zakiyyah, A. (2025). Evaluation of slope stability problems. Jurnal Pensil: Pendidikan Teknik Sipil, 14(3).

https://doi.org/10.21009/jpensil.v14i3.54672

Zhang, K., et al. (2023). Microbial-induced carbonate precipitation (MICP) technology: fundamentals & applications. Environmental Science and Ecotechnology, 16, 100236.

Zhu, J., et al. (2024). Improvement schemes for bacteria in MICP: a review. Frontiers in Microbiology, 15, 1332227.