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The Application of Microbially Induced Calcium Carbonate Precipitation (MICP) Technology in Building Materials and its Contribution to Waste Resource Utilization

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Abstract: In many countries around the world, waste generation has become an increasingly pressing issue, particularly in urban areas experiencing rapid population growth and industrialization. The volume of waste produced by human activities continues to rise, posing significant challenges to the environment, economy, and public health. Improper waste management can lead to air and water pollution, soil degradation, and the spread of diseases. Additionally, waste generation consumes substantial natural resources and energy, exacerbating resource depletion and contributing to greenhouse gas emissions.To address these challenges, sustainable waste management practices are essential to reduce waste generation and promote resource recovery and recycling. In this context, the development of innovative technologies, such as Microbially Induced Calcium Carbonate Precipitation (MICP) in building materials, offers an effective means of converting waste into valuable and sustainable applications. MICP is an environmentally friendly biogeochemical technique that employs microorganisms and chemical agents in biological processes to produce carbonate minerals, providing an energy-efficient, cost-effective, and sustainable solution to environmental and engineering challenges.Recent research indicates that waste streams can substitute for several MICP chemical components in microbial and cementitious agent growth media. MICP technology has been found not only to be effective in handling hazardous waste streams but also to be a cost-effective and sustainable solution applicable to various waste media. This comprehensive review aims to provide insights into the environmental advantages and engineering applications of MICP technology, with a particular focus on the potential contributions of waste streams. It also offers guidance for researchers on identifying and overcoming challenges associated with using waste streams for MICP technology applications.
Keywords: Waste, greenhouse gas emissions；Microbially Induced Calcium Carbonate Precipitation (MICP)；building materials, energy conservation；environmental protection.

I. INTRODUCTION

In 2021-2022, China set a new record for the production of solid waste. Specifically, construction and demolition materials contributed 37%, organic waste accounted for 17%, and ash from coal-fired power stations made up 14%. Hazardous waste, mainly contaminated soil, represented 15%, while paper products and cardboard were 7%, metals 9%, and plastics amounted to 83%. This data shows a growth of 130% compared to the 2016-2017 period.

As the population and economy expand, China faces increasingly urgent waste management challenges. The government and local authorities have implemented a series of measures and plans aimed at reducing waste generation and promoting sustainable waste management practices. The waste management system involves multiple stages, including waste prevention, reduction, collection, transportation, storage, treatment, and recycling.

Effective waste management and disposal are crucial for protecting the environment, public health, and natural resources. An ideal waste management process seeks to minimize waste generation, ensure safe and responsible waste disposal, and recycle or reuse materials whenever possible. Improper waste management can lead to environmental pollution, attract pests, and emit unpleasant odors.

In designing and implementing waste management strategies, it is essential to consider regional factors, including the type of waste, climate change trends, socio-cultural backgrounds, political systems, and resource availability. By assessing the potential impact of waste and its sustainability, comprehensive management strategies aimed at minimizing waste generation can be developed.

Various waste treatment technologies include landfilling, incineration, recycling, composting, and converting waste into energy. The approach to waste management differs from country to country, reflecting variations between developed and developing nations, urban and rural areas, as well as residential and industrial sectors. As indicated, landfill, recycling, energy recovery, and export are commonly used waste management strategies in Australia. The collection and treatment of waste have become urgent concerns for governments worldwide, not only due to their impact on the environment and health but also because of the associated high costs, prompting the exploration of alternative waste treatment methods. Traditional methods, such as incineration and landfilling, have been criticized for their negative effects on human health and the environment, including issues related to leachate.

Adopting sustainable waste management practices, aimed at minimizing waste generation and promoting the recovery and reuse of resources, is essential in addressing these challenges. These practices are closely associated with environmental benefits, such as the widespread adoption of waste recycling and reuse as part of waste management strategies. For example, waste materials are increasingly used in various engineering fields, including the design of concrete mixtures. Construction and demolition waste are among the substantial solid materials recently utilized in the construction industry.

Fischer et al. (2017) explored biomineralization as a natural process of mineral production by microorganisms. They noted that this process involves two main types of precipitation: biologically controlled precipitation and biologically induced precipitation. Biologically controlled mineralization occurs when microorganisms have a high degree of control over the nucleation and growth of mineral particles and can synthesize minerals in a species-specific manner independently of environmental conditions. In contrast, biologically induced mineralization is heavily influenced by surrounding environmental conditions. A significant advantage of biologically induced processes is their ability to produce valuable end products, including minerals suitable for various environmental and engineering applications. These processes are highly adaptable and flexible, capable of effective operation under different environmental conditions and microbial types. Furthermore, there is potential for biologically induced processes to be scaled up to an industrial level, offering promising solutions to address large-scale engineering and environmental challenges. Sometimes, both processes may be used simultaneously to promote biomineralization (Zhu et al., 2019).

Microbially induced calcium carbonate precipitation (MICP) is an efficient biomineralization technique involving microorganisms, particularly bacteria, producing and depositing calcium carbonate minerals under specific environmental conditions.

In recent years, numerous studies have demonstrated the potential applications of MICP technology in various fields, such as soil improvement, dust suppression, concrete repair, and soil and water pollution treatment.

The MICP process involves biological processes such as urea hydrolysis, sulfate reduction, nitrate reduction, and photosynthesis. Urea-resolving microbial-induced calcite precipitation is one form of MICP, where microorganisms, usually bacteria, utilize urea hydrolysis to generate and deposit calcium carbonate minerals. Urea-resolving bacteria catalyze the decomposition of urea into carbon dioxide and ammonium ions, thereby promoting the formation of calcium carbonate minerals. Additionally, bacterial cells have been shown to be efficient nucleation sites for mineral precipitation due to their negatively charged functional groups, including carboxyl, phosphate, and amine, facilitating binding with carbonate ions. MICP technology has been extensively researched for various applications, such as soil stabilization and concrete repair, demonstrating its potential as a sustainable and cost-effective solution to engineering challenges.

Controlling factors such as chemical reactant concentrations and methods of introducing bacteria and chemicals into the reaction medium must be considered during on-site application of MICP processes. The form of calcium carbonate produced (amorphous and different crystal polymorphs) depends on environmental conditions.

The cost of MICP technology may vary depending on factors such as project scale, the type of soil or substrate being treated, and the types of microorganisms and chemical additives used. Additionally, costs may be influenced by geographical location and resource availability, labor costs, and equipment expenses. Generally, compared to other traditional soil stabilization methods, MICP may be a cost-effective approach, particularly for medium-sized projects. However, cost-effectiveness may vary for larger-scale projects, necessitating more detailed cost analysis. It is worth noting that while the initial costs of MICP may be higher than some traditional soil stabilization methods such as cement or lime stabilization, the long-term benefits and lower maintenance costs can make it a more cost-effective solution in the long run.

II. THE ENVIRONMENTAL EFFECTS AND ENGINEERING APPLICATIONS OF MICP TECHNOLOGY

The innovative MICP (Microbially Induced Calcite Precipitation) technology utilizes natural phenomena to induce calcium carbonate precipitation, offering significant potential for environmental benefits and engineering applications, particularly in soil stabilization and self-healing concrete, which may contribute to carbon sequestration.

One of the innovative applications of MICP is soil stabilization, a process aimed at enhancing the physical properties of soil to increase its strength, stability, and durability. Various techniques have been employed for soil stabilization, including mechanical and chemical methods, each with its advantages and disadvantages. For example, mechanical stabilization can be executed quickly and effectively, making it a preferred method for time-sensitive, large-scale projects. It is also versatile across different soil types. However, it can lead to high energy consumption and increased greenhouse gas emissions, posing environmental threats. On the other hand, chemical stabilization offers long-term soil stability and can be customized to suit specific soil conditions and engineering requirements, presenting a viable option. However, it can be costly and may require specialized expertise for proper application, with potential adverse environmental impacts if misused.

The choice of soil stabilization method depends on factors such as soil characteristics, the intended use of stabilized soil, and the cost-effectiveness of the technique. Compared to traditional mechanical and chemical stabilization methods, biologically based soil stabilization techniques generally consume less energy and produce fewer greenhouse gas emissions.

This is because these methods rely on the natural metabolic processes of microorganisms rather than heavy machinery or chemical treatments. The biomineralization process, including the formation of $CaCO_3$ crystals, acts as an effective bridge between soil particles, while the precipitation of calcium carbonate can also fill voids, increasing the density of the soil matrix. Introducing MICP-modified soil involves several straightforward methods, such as surface permeation, pre-mixing, and injection.

The efficacy of MICP for soil cementation depends on several factors, such as the type of bacteria utilized, the method to achieve necessary concentration, pH, and temperature during the urea hydrolysis process, the flow rate and concentration of the cementation solution, and soil properties.

Deng et al. reported that the environmental impact of MICP is more significant than previously assumed. Compared to traditional stabilization methods like cement and lime, current MICP processes consume fewer non-renewable resources; however, they significantly impact the environment, including smog and ash production, with secondary effects such as global warming, photochemical ozone formation, acidification, and eutrophication. The carbon emissions and energy consumption of MICP are respectively 3-7 times and 15-23 times higher than traditional methods. The high energy consumption in the process is primarily due to the use of chemical agents. Thus, exploring alternative, commercially available, environmentally friendly sources, such as waste streams, is crucial in this context.

Self-healing concrete is a highly advanced and resilient form of concrete that incorporates MICP to maintain its structural integrity and extend its lifespan.

This special technology not only ensures the enduring performance of concrete structures but also helps mitigate carbon monoxide emissions by reducing the need for cement production. Additionally, MICP technology can capture carbon dioxide from the atmosphere and convert it into calcium carbonate, which is permanently stored as a solid mineral. This process contributes to reducing greenhouse gas emissions and addressing climate change. Overall, the use of MICP technology has the potential to provide significant environmental benefits while addressing various issues related to soil stabilization and carbon sequestration. MICP soil stabilization methods can utilize waste streams such as agricultural residues, food processing waste, or by-products of wastewater treatment as stabilizers. This reduces waste disposal rates and can provide valuable utilization for materials that might otherwise be discarded.

III. ACCELERATING THE PROMOTION OF MICP TECHNOLOGY USING WASTE

Urea is a crucial chemical required for the Microbially Induced Calcium Carbonate Precipitation (MICP) process and is also widely used as nitrogen fertilizer in agriculture. When urea is deposited into the soil, plants utilize nitrogen in the form of ammonium or nitrate, which is a result of microbial activity or enzymatic hydrolysis of urea in the soil.

The manufacture of urea involves the reaction of ammonia and carbon dioxide under high temperature and pressure, typically achieved by burning fossil fuels. This process generates heat, leading to temperature rise and consequently contributing to climate change. It is estimated that producing one kilogram of urea emits approximately 4 kilograms of carbon dioxide.

Given the significant demand for urea in agriculture, along with production costs and environmental considerations, replacing synthetic urea with other commercially and environmentally friendly urea sources in MICP technology is crucial, especially for future large-scale projects. In recent years, biological waste such as pig urine, cow urine, and human urine has been extensively studied as feasible alternatives for synthetic urea in the MICP process.

In a study by Chen et al., the feasibility of using waste pig urine as a substitute for synthetic urea in MICP technology was investigated, considering the significant environmental issues associated with pig farming pollution.

The study found that waste urine could successfully replace synthetic urea in the MICP process, as evidenced by improved stability of sand columns and the presence of a white powder formed when ammonia bonded with sand grains. However, further research is needed on the chemical properties of waste pig urine in MICP technology, the effects of different concentrations of waste pig urine and urea, storage and transfer conditions, and the chemical stability of waste pig urine. Additionally, the study did not consider sand column strength, a key factor in geotechnical engineering.

In another systematic study by Carla et al., the potential application of waste cow urine in MICP technology was investigated. Researchers obtained waste cow urine from a dairy farm and stored it at -20°C to assess its chemical stability. Analysis results showed that post-sterilization cow dung had a total organic carbon of 976 mM, total inorganic carbon of 107 mM, total nitrogen of 559 mM, and urea concentration of 224 mM at pH 8. However, according to Udert et al., the findings provided sufficient stability duration, allowing ample time for applications involving MICP. Similar to previous research, the methods introduced by Carla et al. suggest that waste human urine may potentially replace synthetic urea in MICP technology.

However, Udert et al. reported contrasting findings based on their investigation. The longer stability duration provides ample time for applications involving MICP. In this particular study, chemical analysis was conducted on waste cow urine passed through sand columns up to six times, adjusted to specific pH values. Cultivation medium was injected into the columns to facilitate the growth of indigenous soil bacteria. The methodology of this study indicates that urea found in both sterilized and unsterilized waste cow urine, with a pH range of 7 to 9, undergoes natural hydrolysis by native soil bacteria. Additionally, chemical analysis reveals an increase in carbonate content after adjusting the initial pH of the waste cow urine to 9.

Similar to previous research, the approach introduced by Carla et al. suggests the potential substitution of synthetic urea with waste human urine in MICP technology.

In a recent study conducted by Lambert et al., waste human urine was effectively used for brick bonding through Bacillus spore-induced calcification. Furthermore, Lambert stabilized human waste urine for an extended period using calcium hydroxide, whereas a previous study reported only one month of stability for waste cow urine. Previous studies stabilized urine by increasing the pH of the culture medium with calcium hydroxide. Comparative strength testing yielded a result of 2.7 mPa, which is comparable to the strength reported in previous studies for sand treated with MICP. The study also investigated the manufacture of bioremediation bricks. To produce a single bioremediation brick, 32 L of urine is required, with only 1% of the solution used for calcium carbonate production. Chemical analysis indicates that waste human urine with a pH of 11.2 is more stable than urea hydrolysis medium with a pH of 9.25 due to lower enzyme activity. Lower urea hydrolysis in waste human urine within four days suggests stability during this period without the addition of calcium hydroxide.

The concentration, stability, and conditions during transportation and storage of urea are key factors to consider in substituting synthetic urea with urine in MICP technology. Nevertheless, urine as a waste, particularly from cattle farms, is a feasible alternative to synthetic urea. However, substituting waste urine for synthetic urea may result in ammonium release into the atmosphere, potentially causing air pollution, especially in large quantities. Nitrogen can also lead to groundwater pollution and emissions of greenhouse gases such as nitrous oxide. Addressing the issue of excessive ammonia emissions in MICP-based bio-cement, Chu et al. proposed a novel microbial-induced bird guano precipitation bio-cement. This method involves the reaction of NH_3 with magnesium and calcium phosphate to produce bird guano, thus capturing NH_3.

Comparative experiments were conducted on sand using two methods, showing a 75% reduction in ammonia emissions and the total mass of ammonium in the effluent being twice that of the MICP-treated samples. Additionally, a recently proposed method involves the replacement of urea with carbon dioxide influx. Although this method does not involve waste, it holds promise as it can reduce carbon dioxide emissions during the biomineralization process. Carbon dioxide influx has been shown to effectively replace urea in Bacillus-induced calcification, improving concrete durability, and potentially reducing the demand for synthetic urea in future biomineralization technologies.

IV. THE UTILIZATION OF CALCIUM CARBONATE WASTE

Calcium is an important chemical in bio-mineralization technology for generating calcium carbonate precipitation. However, it has been reported that not only calcium ions but also other divalent cations (such as magnesium ions) may be useful for biocementation technology. Additionally, during the precipitation process of carbonate minerals, heavy metal ions such as strontium (Sr^{2+}), lead (Pb^{2+}), cadmium (Cd^{2+}), and copper (Cu^{2+}) can substitute for calcium ions in calcium carbonate crystals.

Different sources of calcium chemistry, including calcium chloride, calcium hydroxide, calcium nitrate, and calcium acetate, are typically used in biocementation technology media. However, it has been found that these sources provide different levels of capability and influence on the crystallization of bio-minerals.

Generally, calcium chloride is the primary chemical used in bio-mineralization due to its high solubility and availability, as reported by various studies. However, the industrial application of calcium chloride is not limited to biocementation, as it has several other uses. Nevertheless, using calcium chloride in MICP processes can lead to the release of chlorides, causing corrosion of metals and concrete. Many researchers assert that this could lead to damage and increased costs, especially when large amounts of calcium chloride are used near concrete structures. Additionally, chlorides can contaminate groundwater in soil stabilization projects.

To address the challenges associated with using calcium chloride in biocementation technology, waste materials can be used as alternatives for calcium sources. One such waste material is eggshells, which have been found to effectively substitute for calcium chloride in biocementation. In Choi's study, eggshells were powdered and dissolved in dilute vinegar at different preparation times. Furthermore, compared to control samples, the samples using waste eggshells exhibited a higher amount of calcium carbonate precipitation, possibly due to uneven calcium concentration.

Choi et al. conducted a study investigating waste limestone powder from aggregate quarries as an alternative calcium ion source. They found that dissolving waste limestone powder in waste acetic acid generated calcium ions for biocementation experiments.

In a recent study by Liang et al., potential uses of kitchen waste such as oyster shells, scallop shells, and eggshells as calcium sources for biocementation technology were explored. The results indicated significant calcium content in these wastes and their potential effectiveness in biocementation. It is crucial to determine the optimal ratio and maintain appropriate pH levels. Using waste materials rich in calcium as substitutes for calcium chloride can offer significant environmental benefits but requires further research into their productivity and availability.

V. THE UTILIZATION OF WASTE IN CULTURE MEDIA

In biomineralization technology, bacterial cells play a crucial role in producing enzymes that catalyze the biocementation process and provide nucleation sites for mineralization. Bacillus pasteurii, originally named Basosarcina pasteurii, is a Gram-positive bacterium with high enzymatic activity and has been widely used in urea-induced Microbially Induced Calcium Carbonate Precipitation (MICP) technology. To ensure optimal bacterial growth, appropriate culture media must be provided, containing necessary nutrients such as carbon, nitrogen, phosphorus, and other essential minerals. Additionally, the pH and temperature of the culture medium should be suitable for the specific type of bacteria used, and sufficient time for growth should be considered. It is important to note that different types of bacteria have different growth requirements; therefore, the specific conditions required for cultivation will depend on the type of bacteria you are attempting to cultivate. According to cost analysis, bacterial cultivation is considered the most expensive part of biocementation technology. In MICP technology, Sporosarcina pasteurii is mainly cultured using ammonium yeast extract and urea.

High-protein waste, especially waste generated by the food industry, may be used as alternative nutrient sources in biotechnological processes. However, the large-scale release of such waste could pose environmental threats. Nevertheless, effectively utilizing them as nutrient sources for various applications still holds various potential benefits. In the development of biocementation technology, extensive research has been conducted on using waste streams as alternative culture media. However, when seeking alternatives to waste streams, factors such as cost-effectiveness, feasibility of sterilization, and performance of the culture medium must be considered. Examples of waste industrial streams that can be used as alternatives to culture media include brewery waste yeast, corn steep liquor, Torula yeast, plants, dairy waste whey and whey cheese, and lactose mother liquor. This section will explore suitable culture media extracted from waste streams for biocementation technology.

Delwiche and Smith reported that molasses can be used as a nutrient additive to promote urea hydrolysis and can be used in ion-containing water remediation applications. Cuzman et al. conducted a systematic investigation into the feasibility of using dairy waste streams and brewery waste streams as alternative culture media for Sporosarcina pasteurii cultivation. The authors also discussed whether urea fertilizer could replace laboratory-grade urea in the cultivation process. The study showed that dairy waste streams are a more suitable medium than brewery waste streams. In the context of self-healing concrete, urea-corn steep liquor was studied as a potential alternative to laboratory-grade urea-yeast extract medium. It was found that the bacterial growth curve in urea-corn steep liquor was comparable to that in urea-yeast extract medium. However, zeta potential experiments showed that bacteria grown in urea-corn steep liquor had significantly lower surface charge. Liang et al. suggested that the negative charge on bacterial surfaces is influenced by phosphate, carbonate, and sulfate groups. Therefore, the components of alternative culture media may be able to reduce the zeta potential. Although this effect may not be significant in self-healing concrete, reducing bacterial surface charge may be crucial in other MICP applications such as water remediation.

Omar et al. reported that vegetable waste could be used in bio-cement applications, particularly as alternatives to chemicals in MICP processes. Soils treated with vegetable waste fermented with soul fermentation had unconfined compressive strengths of up to 60 kPa. However, the low strength may be due to single-cycle treatments, whereas most studies reported multi-cycle treatments. The study did not elucidate whether native soil bacteria or fermented vegetables caused chemical reactions.

Further research is needed on the viscosity and sedimentation tests of fermented vegetable waste to understand their effects on crystal morphology and reaction rate analysis.

Armstrong et al. comprehensively studied the use of commercial yeast extract as a cost-effective alternative to laboratory-grade yeast extract in Bacillus spore cultivation. The results showed that food-grade yeast can serve as a cost-effective alternative to expensive laboratory-grade yeast extract.

Kahani et al. adopted a similar approach to previous studies and investigated the use of corn steep liquor, commercial yeast extract, soy flour, and whey to reduce the cost of MICP processes. Kahani and colleagues also explored the possibility of using seawater instead of distilled water, which is crucial in arid regions studying MICP technology. Researchers also examined non-sterile, disinfected medium conditions, which reduced energy consumption and were found to be suitable for large-scale MICP projects. Dairy waste exists in the form of residual whey powder from the production of primary cheese, containing 497 g/kg organic carbon and 22.9 g/kg nitrogen. Although the growth curve of bacteria in whey nutrient medium was lower than in other nutrient media, it exhibited the highest urease activity. The bacterial growth curve using processed kitchen waste nutrient medium showed a trend similar to that using yeast extract, which was more effective than nutrient broth medium. High urease activity and biomass concentration support the use of kitchen waste as an alternative nutrient medium.

In the field of engineering, Microbially Induced Calcium Carbonate Precipitation (MICP) has received widespread attention, particularly in the context of construction and cementation of porous media. The first half of this paper mainly discusses the use of waste materials as substitutes for chemical reagents in the biological cementation process, serving as both cementing agents and culture media. This approach not only allows for the reuse of waste streams but also reduces the costs of large-scale MICP projects. Additionally, MICP technology can be applied to support three key engineering applications while also contributing to waste management. The technology holds promise to contribute in an advanced manner to these applications while remaining aligned with engineering objectives.

Fly ash is a hazardous waste from urban solid waste incineration, posing significant challenges to industries due to its high pH and heavy metal content, making it environmentally hazardous. However, as demonstrated by Chen et al., precipitates induced by Sporosarcina Pasteurii have the potential to solidify high-alkaline fly ash and effectively seal harmful metal ions. Researchers reported that since fly ash already contains an appropriate level of calcium oxide to prepare a calcium source, additional calcium chemical substances are not needed to achieve MICP. Based on these findings, MICP appears to be a promising technology for treating fly ash and reducing its environmental impact, as long as it is stored or reused properly.

In the recycling process of paper mills, waste paper containing cellulose fibers is generated. Chen et al. found that these waste paper fibers can be used as additives to enhance the mechanical strength of stabilized sand using MICP. By adding just 1% of waste paper fibers, the unconfined compressive strength can be increased by 20%, improving failure strain characteristics and ductility. These results are similar to studies using synthetic fibers (such as polypropylene fibers) in MICP-treated sand. Generally, waste paper fibers can retain more bacteria, increasing the opportunities for biomineralization. However, excessive fiber content can also reduce mineral bonding points between sand grains, resulting in negative effects. Although MICP and recycled materials typically yield many positive effects, they may not always have positive outcomes in certain cases. For example, Espinal et al. reported that MICP treatment of waste plastic fibers did not improve the performance of fiber-to-fiber interface bonding. This is because the biomineral produced by MICP covers the fiber surface with a thick and inconsistent layer, thereby preventing an increase in bonding strength.

MICP has the potential to improve the quality of construction materials and recycled concrete aggregate. When the latter is treated with MICP, pores and cracks in the particles can be filled, resulting in reduced water absorption and changes in the interface transition zone (ITZs). Similarly, Joshi et al. reviewed the effects of MICP on waste-modified concrete and found that applying MICP through biological precipitation can be a sustainable approach to improving concrete durability. Additionally, MICP has been shown to successfully improve the performance and durability of rubber tire fibers in cement mortar by reducing pore space and increasing mortar performance.

Another challenge is the release of dissolved heavy metals from waste rock and tailings into the environment. Depending on specific environmental conditions, this process may occur slowly, ultimately affecting groundwater, soil, and surface water. Proudfoot et al. conducted a study focusing on promoting the production of calcium carbonate on the surface of waste rock particles using indigenous bacteria. They also discussed the use of MICP technology, which is expected to fill voids and coat particles in fine-grained media. The authors found that this process not only helps reduce acids and dissolved metals in leachate but also stabilizes mine waste.

VI. CONCLUSIONS

Utilizing the ureolytic bacteria-induced calcite precipitation (MICP) process is considered a direct and energy-efficient technique in the field of engineering. This study explores the potential of integrating waste stream technology with the MICP process. The findings indicate that waste streams can serve not only as substitutes for binding agents and synthetic chemicals but are also compatible with laboratory-grade materials, offering higher commercial value. By incorporating waste stream technology into the MICP process, not only is there a significant reduction in waste sent to landfills through the extensive reuse of waste, but preliminary treatment of the waste is also required. This includes storing urine waste under suitable conditions and activating the waste stream as a calcium source with the appropriate acid. Additionally, minimizing the risk of pathogen contamination during production and addressing the substitution of nutritional waste, which may necessitate the use of autoclaves and ensuring adequate levels of carbon and nitrogen, are essential. It is noteworthy that the use of waste should consider locally available materials to reduce transportation costs. Moreover, the MICP technique not only excels in environmental protection but also demonstrates significant potential in energy conservation and wastewater purification, warranting comparison with other technologies in terms of efficiency.

Faced with the challenge of uniformity in biocemented sand quality, several technological solutions have been developed, such as the “all-in-one” solution aimed at enhancing uniformity. However, the variation in soil particle sizes, especially the difficulty in successfully binding coarser aggregates, highlights the necessity for further research to overcome these limitations, especially when introducing waste streams into the MICP process.

VII. DATA AVAILABILITY STATEMENT

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

VIII. ACKNOWLEDGMENTS

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REFERENCES

[1] Jin Chang-Yu, Q. J. W. Q. . (2022). Experimental study on tailings reconstructed backfill based on facultative anaerobic bacteria micp technology. Journal of Northeastern University(Natural Science), 43(9), 1322-1328.

[2] Gebru, Kbrom AlebelKidanemariam, Tekleweyni GebremicaelGebretinsae, Haile Kidane. (2021). Bio-cement production using microbially induced calcite precipitation (micp) method: a review. Chemical Engineering Science, 238(1).

[3] Gowthaman, S. , Nakashima, K. , Nakamura, H. , & Kawasaki, S. . (2020). Influence of Wet-Dry and Freeze-Thaw Cycles on the Physical and Mechanical Properties of MICP Treated Slope Soil. 54th US Rock Mechanics/Geomechanics Symposium, ARMA (American Rock Mechanics Association).

[4] Wang, Y. , Konstantinou, C. , Soga, K. , Dejong, J. T. , & Kabla, A. J. . (2020). Enhancing strength of micp-treated sandy soils: from micro to macro scale.

[5] Yu, D. , Guobin, X. U. , Defeng, Y. , & Yue, Y. . (2019). Influencing factors of calcium ion utilization in micp mineralized products and analysis of microscopic image. Chemical Industry and Engineering Progress.

[6] Atefeh Zamani, Brina M. Montoya, Mohammed A. Gabr. (2019). Investigating challenges of in situ delivery of microbial-induced calcium carbonate precipitation (micp) in fine-grain sands and silty sand. Canadian Geotechnical Journal, 56.

[7] Abearathne, M. S. , Hettiarachchi, K. , Chithrapala, N. H. M. S. , & Manike, A. S. M. S. . MICP 01-A NEW COWPEA [VIGNA UNGUICULATA (L.) WALP.] VARIETY FOR CULTIVATION IN DRY AND INTERMEDIATE ZONES OF SRI LANKA.

[8] Bhattacharya, S. . (2015). Numerical investigation of biogrout: a new soil improvement method based on micp.

[9] Wang, Y. , & Li, S. . An improved soft soil reinforcement method with micp based on biochar induced nucleation technology. Social Science Electronic Publishing.

[10] Li, C. , Liu, G. , & Cao, Z. . Characterization of Overall Pore Size Distribution Using N2AD, MICP, NMR: A Case From Chang 7 Tight Sandstone in Ordos Basin, China.

[11] Zhou, A. Y. , Jiang, X. J. , Zhang, Y. P. , & Wei, J. Y. . (2009). Micphot: a prime-focus multicolor ccd photometer on the 85-cm telescope. 中国天文和天体物理学报：英文版(3), 18.

[12] Qabany, A. A. , & Soga, K. . (2013). Effect of chemical treatment used in micp on engineering properties of cemented soils. Geotechnique.

[13] Lee, J. D. , Huang, C. H. , Wang, S. T. , Lin, C. W. , & Lee, S. T. . (2010). Fast-micp for frameless image-guided surgery. MEDICAL PHYSICS, 37(9), 4551---4559.

[14] Dawoud, O. , Chen, C. Y. , & Soga, K. . (2014). Microbial-Induced Calcite Precipitation (MICP) Using Surfactants. Geo-congress (pp.1635-1643).

[15] Kwon, H. J. , Chang, B. S. , Choi, B. Y. , Park, K. H. , Jeong, S. H. , & Morimoto, H. . (2000). Applications of micp source for next-generation photomask process. International Society for Optics and Photonics, 4066, 218-225.

[16] Theologou, P. N. , Skalinski, M. , & Mallan, R. K. . (2015). An micp-based pore typing workflow – core scale to log scale.