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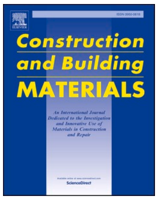

Review

Application of Microbially Induced Calcite Precipitation (MICP) technology in construction materials: A comprehensive review of waste stream contributions

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ABSTRACT

Waste generation is a growing concern in many countries across the world, particularly in urban areas with high rates of population growth and industrialization. The increasing amount of waste generated from human activities has led to environmental, economic, and health issues. Improper disposal of waste can result in air and water pollution, land degradation, and the spread of diseases. Waste generation also consumes large amounts of natural resources and energy, leading to the depletion of valuable resources and contributing to greenhouse gas emissions. To address these concerns, there is a need for sustainable waste management practices that reduce waste generation and promote resource recovery and recycling. Amongst these, developing innovative technologies such as Microbially Induced Calcite Precipitation (MICP) in construction materials is an effective approach to transforming waste into valuable and sustainable applications. MICP is an environmentally friendly microbial-chemical technology that applies microorganisms and chemical reagents to biological processes to produce carbonate mineral. This substance can be an energy-efficient, cost-effective, sustainable solution to environmental and engineering challenges. Recent research has shown that waste streams can replace several MICP-chemical components in the cultivation media of microorganisms and cementation reagents (calcium sources and urea). In addition to its effectiveness in treating hazardous waste streams, MICP has been found to be cost-effective and sustainable solution applicable to various waste media. This comprehensive review paper aims to provide a thorough understanding of the environmental advantages and engineering applications of MICP technology, with a focus on the contribution of waste streams. It also provides researchers with guidance on how to identify and overcome the challenges that may arise applying the MICP technology using waste streams.

1. Introduction

The generation of solid waste in Australia reached a record high of 75.8 million tons in 2020–21, with construction and demolition materials accounting for 33%, organics for 19 %, ash from coal-fired power generation for 16%, hazardous waste (mainly contaminated soil) for 10%, paper and cardboard for 8%, metals for 7%, and plastics for 3%. This shows a 10% increase in the statistics from that recorded for 2016–17 [1]. Waste management in Australia is a pressing issue due to the country's high population and expanding economy, both of which lead to a significant amount of waste generation. The government and local authorities have taken steps to address this issue by implementing policies and programs aimed at reducing waste and promoting sustainable waste management practices [2].

The waste management system encompasses strategies for preventing, decreasing, collecting, transporting, storing, and disposing of waste, as well as promoting its recycling [3]. Efficient waste management and disposal are imperative for safeguarding the environment and public health, as well as preserving natural resources. The proper management of waste streams typically involves minimizing the amount of waste

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produced, treating, and disposing of waste in a safe and responsible way, and recycling or reutilizing waste materials whenever feasible. Poor waste disposal practices can result in soil, water, and air pollution, attract pests, and produce unpleasant odors.

A critical component of waste streams is to recognize local factors such as waste characteristics and seasonal variations in climate, social aspects, cultural attitudes toward waste, and political institutions, as well as a prevalent limitation of resources [4]. As depicted in Fig. 1, the waste hierarchy categorizes waste management strategies based on their environmental impact and sustainability, with the aim of minimizing the waste generation rate [5].

Various methods of waste disposal include landfilling, incineration, recycling, composting, and converting waste to energy. Waste management methods vary amongst countries as a whole and, from another point of view, between developed and developing countries, among different regions such as urban and rural areas, and between residential and industrial sectors [4]. As depicted in Fig. 2, landfills, recycling, energy recovery, and exports are common methods of managing waste in Australia [1]. The collection and disposal of waste have become a growing concern and a costly issue for governments globally, leading to the adoption of alternative waste disposal methods [6].

The traditional methods of waste disposal, such as incineration and landfilling, have had significant impacts on human health and the environment, including the issue of landfill leachate [7]. Although recent research has indicated that energy recovery from waste can be an effective method, it still has some environmental emissions due to its carbon footprint [8].

Minimizing waste generation and promoting resource recovery and recycling through sustainable waste management practices are crucial to addressing these challenges. This is closely linked to environmental benefits and can be exemplified by the widespread popularity of recycling and repurposing waste as a waste management strategy. For example, waste materials have the potential to be reused in various engineering fields, including concrete mix design [9]. Construction and demolition waste constitutes large amounts of solid substances recently applied in the construction industry [10].

Table 1 shows a variety of waste materials that can be used in combination with biomineralization technology as a sustainable approach to waste management. This combination can effectively decrease the cost of process mechanisms for engineering applications in particular large-scale projects and provide an alternative to the conventional practice of solely reusing waste streams.

According to Fischer et al. [27], biomineralization is the natural process through which microorganisms produce minerals. This process involves two main types of precipitation: biologically controlled and biologically induced [28]. Biologically controlled mineralization occurs when the microorganism has a high level of control over the nucleation and growth of mineral particles and can synthesize minerals in a species-specific form, independent of environmental conditions. Conversely, biologically induced mineralization is heavily influenced by the surrounding environment. One key advantage of biologically induced processes is the production of valuable end products, including minerals, which can be utilized in various environmental and engineering applications. These processes are highly adaptable and flexible, functioning efficiently under a wide range of environmental conditions and with different types of microorganisms [29]. Moreover, biologically induced processes have the potential to be scaled up to industrial levels, offering a promising solution for addressing large-scale engineering and environmental challenges [30].Zhu et al. [31] noted that, sometimes, both processes are employed simultaneously to facilitate biomineralization.

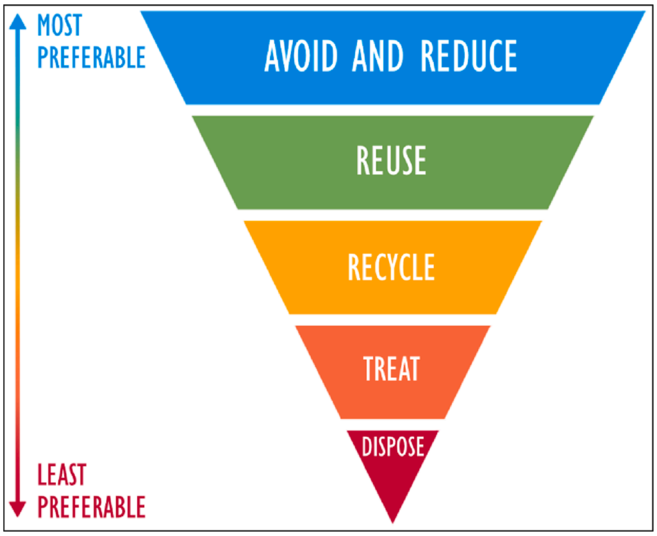

Fig. 1. Waste hierarchy [5].

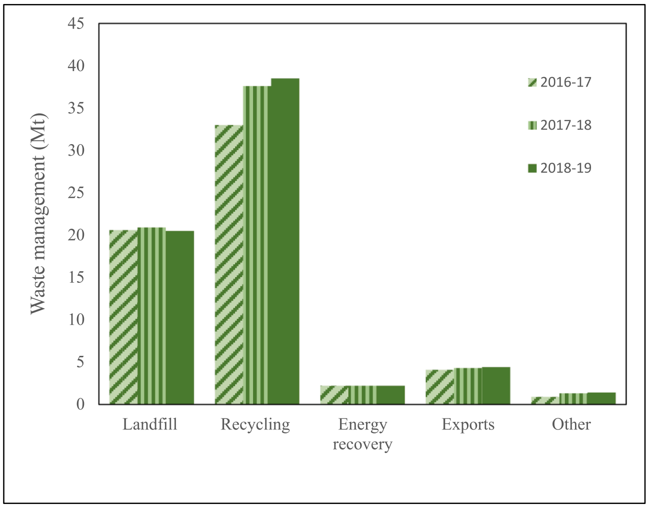

Fig. 2. Waste management types in Australia [1].

Microbially induced calcium carbonate precipitation (MICP) is a highly effective biomineralization technique that involves the production and deposition of calcium carbonate minerals by microorganisms, particularly bacteria, in specific environmental conditions [32]. In recent years, various studies have reported the successful implementation of the MICP technology for a wide range of potential applications, such as soil improvement [31–35], dust suppression [36–38], concrete remediation [39], and treatment of soil and water contamination [39,40].”

MICP involves biological processes such as urea hydrolysis, sulphate reduction, nitrate reduction, and photosynthesis [41]. Ureolytic microbial-induced calcite precipitation is a type of MICP, which involves the use of urea hydrolysis by microorganisms, typically bacteria, to produce and deposit calcium carbonate minerals. Ureolytic bacteria, e.g., Sporosarcina pasteurii, are ordinarily utilized in this technique to induce the precipitation of calcium carbonate minerals. This is achieved through the generation of the enzyme urease that acts as a catalyst to break down urea into carbon dioxide and ammonium ions, leading to the formation of calcium carbonate minerals [41–43]. Moreover, bacterial cells have been demonstrated to be highly efficient nucleation sites for mineral precipitation, primarily due to their negatively charged functional groups, including carboxyl, phosphate, and amine, which can then readily bond with carbonate ions [44]. This technique has been studied for various applications, such as soil stabilization and concrete remediation, and has shown potential as a sustainable and cost-effective solution to engineering challenges [45].

To control the MICP process in field applications, factors such as chemical reactant concentrations and methods of introducing bacteria and chemicals to the reaction medium must be considered. Calcium

Table 1
Application of waste stream to the MICP technology.

Reference	Bacteria Type	Waste Substitute	Cementation/Cultivation Media	Experiment
[11]	Sporosarcina pasteurii	Pig urine	Urea	Porosity, permeability, precipitation contents, monitoring calcium content, XRD, SEM-EDX, FE-SEM
[12]	Indigenous ureolytic bacteria	Cow urine	Urea	Precipitation contents, monitoring TOC, TN, TIC *, pH content
[13]	Sporosarcina pasteurii	Human urine	Urea	Compressive strength, precipitation contents, monitoring calcium and Ammonium content, pH, XRD
[14]	Bacillus Sp	Eggshell	Calcium chloride	Unconfined compression strength, permeability, precipitation contents, SEM
[15]	Sporosarcina pasteurii and L. fusiformis	Eggshell	Calcium chloride	Unconfined compression strength, permeability, precipitation contents, monitoring pH, SEM-EDX
[16]	Sporosarcina pasteurii	Limestone	Calcium chloride	Unconfined compression strength, tensile strength, permeability, precipitation contents,
[17]	Sporosarcina pasteurii	Calcareous sand	Calcium chloride	Unconfined compression strength, permeability, precipitation contents, dry density, XRD, SEM
[18]	Sporosarcina pasteurii	Oyster shells, Scallop shells, and Eggshells	Calcium nitrate	Unconfined compression strength, permeability, precipitation contents, dry density, XRD, SEM
[19]	Sporosarcina pasteurii	Lactose mother liquor	Standard culture media (nutrient and yeast extract media)	Compressive strength Precipitation contents, monitoring bacteria growth profile (OD 600), CFU count and Urease activity assay
[19]	indigenous bacteria	Molasses	–	Monitoring dissolved oxygen (DO), oxidation–reduction potential (ORP), DOC, PCR, ICP, temperature, pH, specific conductivity
[19]	Sporosarcina pasteurii	Dairy waste streams, brewery waste with urea fertilized	Urea-yeast extract medium	Monitoring bacteria growth profile (OD 600), CFU count, ATP, Urease activity assay
[19]	Sporosarcina pasteurii	Urea-corn steep liquor	Urea-yeast extract medium	Self-healing concrete experimental test
[20]	Indigenous bacteria	Vegetable	–	Compressive strength, shear strength, microbiological analysis, SEM-EDX
[21]	Sporosarcina pasteurii	Food grade yeast extract	Yeast extract	Monitoring biomass concentration, urease activity assay, precipitation contents, XRD
[21]	Sporosarcina pasteurii	Corn steep liquor, commercial yeast Extract, soy flour, whey with sea water	Culture media	Compression strength, precipitation content Bacteria growth profile, Urease activity assay,
[22]	Sporosarcina pasteurii	Fly ashes derived from municipal solid waste incineration	stabilization of ash	Fly ash characteristic analysis, monitoring heavy metal leaching toxicity, SEM-EDS
[23]	Lysin bacillus xylanolytic	Wastepaper	Utilizing as a fiber in Bio cementation	Unconfined compression strength, density, Freeze-thaw durability, precipitation content, SEM
[24]	Escherichia coli	Waste tyre rubber fibre	Concrete filler/additives mix design	Concrete experiment
[25]	Pararhodobactr sp.	Mine trail waste-Pb^{2+}	Mobilizing heavy metal in mine trail	Capillary water absorption, hydraulic conductivity, XRD, SEM
[26]	Indigenous bacteria	Wastewater-Cd^{2+}	Removal of heavy meatal from wastewater	————————

*TOC: Total organic carbon, TN: Total nitrogen, TIC: Total inorganic carbon.

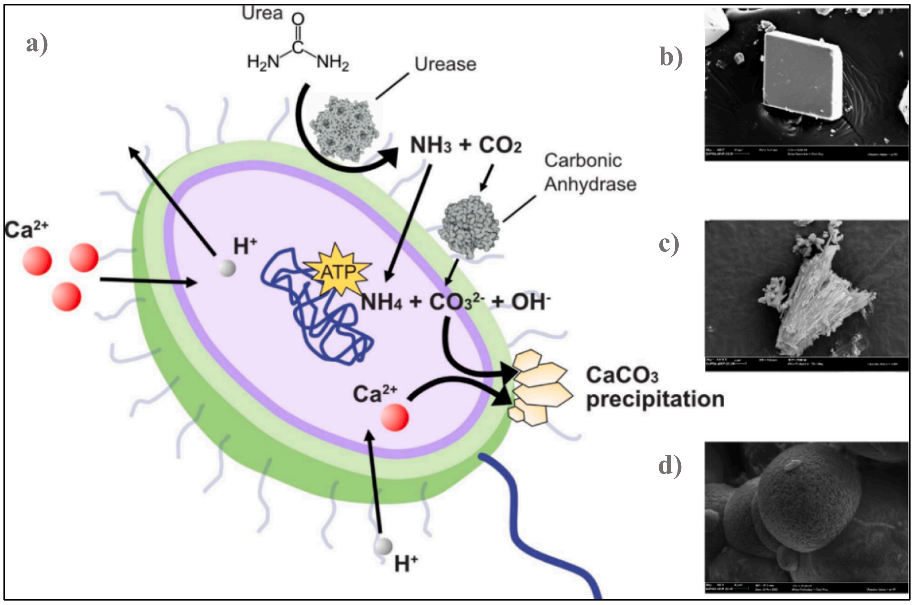

Fig. 3. Ureolytic microbially induced calcium carbonate precipitation a) schematic reaction modified after [43] and Scanning Electron Microscopy(SEM) images of a) Calcite crystal, b) Aragonite crystal, c) Vaterite crystal.

carbonate is created in an amorphous shape and different crystal polymorphs such as calcite, vaterite, and aragonite, depending on the environmental conditions [44,46,47]. Fig. 3 depicts the schematic representation of the process of microbial-induced calcium carbonate precipitation, along with Scanning Electron Microscope (SEM) images illustrating the different forms of calcium carbonate precipitation.

The MICP technology cost can vary depending on factors such as the project scale, the type of soil or substrate being treated, and the type of microorganisms and chemical additives used. Additionally, the cost can be influenced by the geographic location and availability of resources, labor costs, and equipment costs. In general, MICP can be a cost-effective method compared to other traditional soil stabilization methods, particularly for small-to-medium-sized projects. However, for large-scale ones, the cost-effectiveness may vary, and a more detailed cost analysis would be necessary. It is worth noting that while the initial costs of MICP may be higher than those of 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.

To date, various articles have been published in review journals, which concentrate on specific aspects of the MICP technology. For instance, some of these articles include exploring the use of microbial-induced carbonate precipitation in the construction materials industry, e.g., the use of biodeposition for protecting ornamental stone and biocementation [48], engineered applications of ureolytic biomineralization [45], microbial activity and factors impacting by-product formation [49], the applicability and challenges of MICP [50], comprehensive review of the progress and advancements made in the field of MICP since its initial implementation in 1995 [51], and the use of MICP for the transformation of heavy metals into heavy metal carbonates and elimination of calcium from contaminated environments such as polluted water [52]. To the best of our knowledge, no review paper has been published yet to investigate the challenges and potential for waste management associated with the MICP technology.

The primary objective of this review paper is to thoroughly evaluate the potential benefits and challenges associated with incorporating waste streams into the MICP technology. Certain types of waste have been suggested as possible substitutes for MICP ingredients, for example, calcium chloride and urea for cementation reagents and bacterial cultivation media, respectively. By utilizing waste in the MICP technology, large-scale projects, such as soil stabilization and water treatment, can be significantly reduced in cost. Moreover, this technique promotes waste management by repurposing strategy. By combining the MICP technology with waste streams, it is possible, particularly for governments, to develop cost-effective and environmentally friendly approaches for future large-scale MICP projects, thereby reducing carbon footprints, preserving natural resources, and managing waste more efficiently.

2. Environmental advantages and engineering applications of the MICP technology

The innovative and eco-friendly MICP technology utilizes natural phenomena to induce calcium carbonate precipitation. This technology has significant potential to provide environmental benefits and engineering applications, specifically in the fields of soil stabilization and self-healing concrete, which could contribute to carbon sequestration [51,52].

One of the innovative applications of MICP is soil stabilization. Soil stabilization refers to the process of enhancing the physical properties of soil to increase its strength, stability, and durability [53]. To this end, various techniques are used, including mechanical and chemical stabilization; both have advantages and disadvantages. For instance, mechanical stabilization can be executed swiftly and efficiently, making it a preferred method for large projects with tight schedules. Moreover, it can be applied to stabilizing different soil types. However, it may lead to high energy consumption and, consequently, increase greenhouse gas emissions, making it harmful to the environment. On the other hand, chemical stabilization provides long-term soil stabilization that can endure for years. It can be customized to suit specific soil conditions and engineering requirements, which makes it a viable option. Nevertheless, it can be expensive and may require specialized knowledge and expertise to apply correctly. Additionally, if not appropriately utilized, it can have adverse environmental impacts. The choice of a soil stabilization method depends on factors such as soil properties, the intended use of the stabilized soil, and the cost-effectiveness of the technique. Compared to traditional mechanical and chemical stabilization methods, bio soil stabilization techniques generally consume less energy and produce less greenhouse gas emission. This is because such methods rely on the natural metabolic processes of microorganisms instead of heavy machinery or chemical treatments. The biomineralization process, involving the creation of $CaCO_3$ crystals, acts as an effective bridge between soil particles (Fig. 4), while the precipitation of calcium carbonate can also fill the pores, increasing the density of the soil matrix. Introducing MICP to modify soil involves several simple methods such as surface percolation, premixing, and injection [54]. According to numerous researchers, the unconfined compressive strength (UCS) is widely used to characterize the strength of biocemented soils. Table 2 provides information on the mechanical strength of some experimental samples treated using the MICP technology. The efficacy of MICP for soil cementation depends on several factors such as the type of bacteria utilized, the method of achieving the necessary concentration, the pH and temperature during urea hydrolysis, the flow rate and concentration of the cementation solution (including calcium concentration and input flow rate), and soil properties (such as the availability of nucleation sites, degree of saturation, soil gradation, particle size, and pore throat size). Deng et al. [55] reported that the environmental impact of MICP is more significant than previously assumed. Compared to traditional stabilization methods such as cement and lime, the current MICP process consumes fewer non-renewable resources; however, it has a significant environmental impact due to the production of smoke and ash, associated with some secondary impacts, including global warming, photochemical ozone creation, acidification, and eutrophication. Carbon emissions and energy consumption of MICP are 3–7 times and 15–23 times greater, respectively, than those of traditional methods. The high energy consumption in the process is primarily due to the use of chemical reagents. Therefore, exploring alternative commercially available eco-friendly sources, such as waste streams, is crucial in this regard.

Self-healing concrete is a highly advanced and resilient form of concrete, which incorporates MICP to sustain its structural integrity and extend its longevity. This exceptional technique not only guarantees the enduring performance of concrete structures, but also helps mitigate the CO_2 release into the atmosphere by reducing the need for cement production [63].

In addition, the MICP technology can capture carbon dioxide from the atmosphere and convert it into calcium carbonate, which is stored permanently as a solid mineral [64]. This process helps to reduce greenhouse gas emissions and combat climate change. Overall, the use of the MICP technology has the potential to provide significant environmental benefits while addressing various concerns related to soil stabilization and carbon sequestration.

MICP soil stabilization methods can utilize waste streams such as agricultural waste, food processing waste, or wastewater treatment byproducts as stabilization agents. This reduces waste disposal rates and can provide a valuable utilization for materials that might otherwise be discarded.

3. Utilizing waste stream with the MICP technology

The utilization of waste streams in conjunction with the MICP technology can provide several environmental benefits and cost

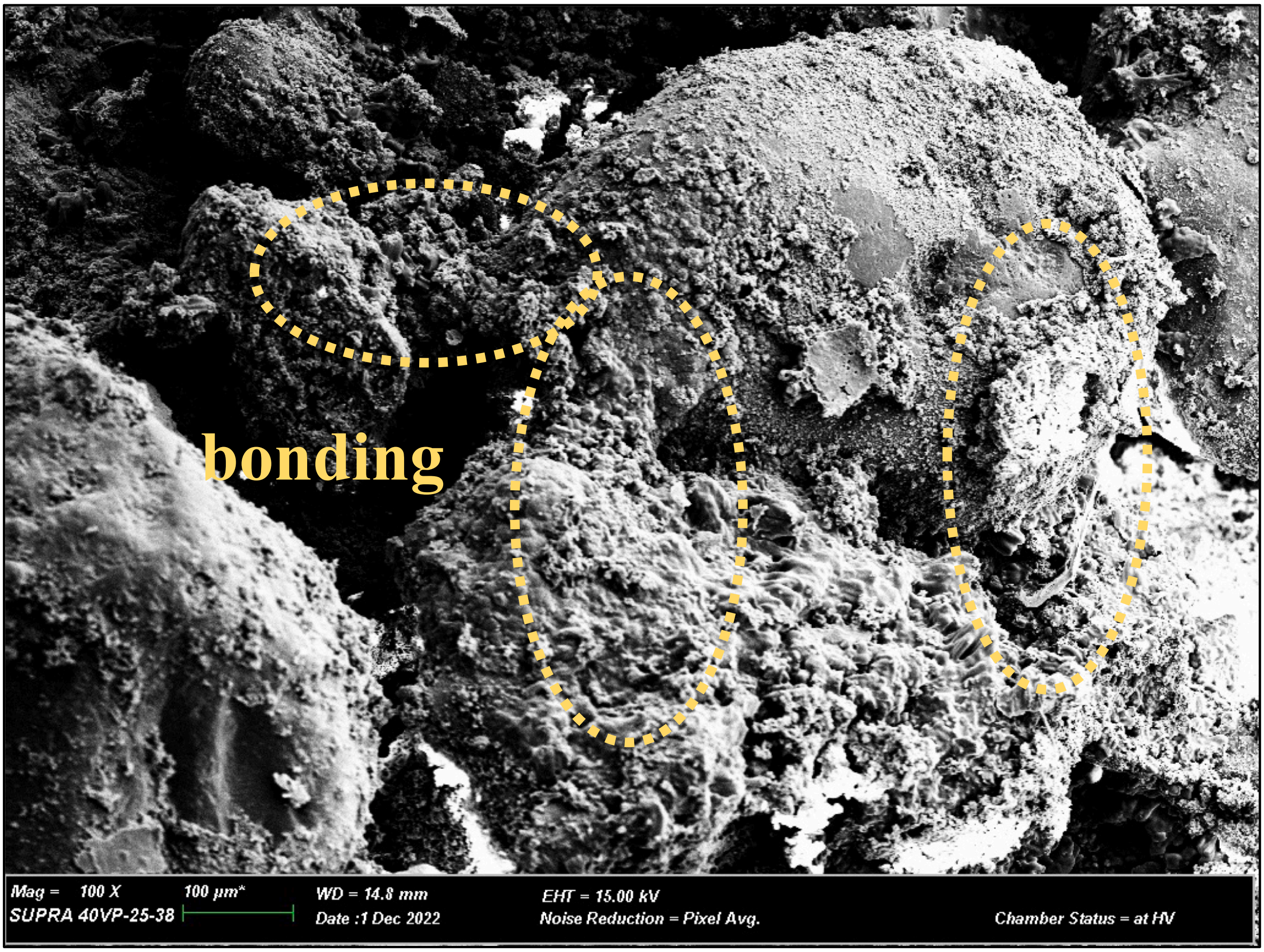

Fig. 4. Scanning Electron Microscopy (SEM) images of biocemented sand.

Table 2
Mechanical strength of MICP soil stabilization.

References	Soil Type	Bacteria Type	Urea; Ca (M)	UCS (kPa)
[56]	Poorly graded silica sand	Bacillus sphaericus	1;1	1114
[57]	Poorly graded Ottawa sand	Sporosarcina pasteurii	0.5:0.5	1200
[58]	Fine, medium and gravel grained sand	Sporosarcina pasteurii	0.25;0.25	600–2300
[59]	Poorly graded silica sand	Sporosarcina pasteurii	1;1	1760
[60]	Quartz sand	Bacillus megaterium	0.5:0.5	1002
[61]	Poorly graded sand	Sporosarcina pasteurii	1:1	1500
[62]	Silt	Sporosarcina pasteurii	1;1	895

reductions in particular engineering applications. The subsequent sections will describe in detail how the MICP technology can play a crucial role in transforming waste into a valuable resource.

3.1. *Waste streams as a cementation reagent*

3.1.1. *Urea alternative*

Urea is a critical chemical needed for the ureolytic MICP process, and it is also a nitrogen fertilizer widely applied to the agriculture industry. When urea is deposited into the soil, plants use the nitrogen in the form of ammonium or nitrate to grow, which occurs as a result of microbial activity in the soil or plant enzymes hydrolyzing the urea [65].

The process of creating urea components ($CO(NH_2)_2$) involves reacting ammonium (NH_3) and carbon dioxide (CO_2) under high temperature and pressure, which is achieved through burning fossil fuels. This process generates heat and leads to an increase in temperature, contributing to climate change. According to estimates, the production of one kilogram of urea results in greenhouse gas (GHG) emission of 4.02 kg of carbon dioxide [66].

As a result of the significant demand for urea in the agricultural industry, as well as the production costs and environmental considerations, it is critical to replace synthetic urea in the MICP technology with other commercial and environmentally friendly urea sources, particularly in large projects in the future. In recent times, biological wastes such as pig urine, cow urine, and human urine have been extensively studied as viable alternatives to synthetic urea in the MICP technology process.

In a study conducted by Chen et al. [11], the feasibility of using waste pig urine as an alternative to synthetic urea in the MICP technology was investigated due to the high environmental concerns associated with pig farms pollution. The researchers collected waste pig urine from a pig farm in Taiwan and subjected it to centrifugation at 8049×*g* and 4 °C for 20 min. The study found that changes in the NH_4^+ content and the visual appearance of white powder formed on the bonding of sand particles, as well as improvements in the stabilized sand column, provide compelling evidence indicating waste urine is a successful substitute for synthetic urea in the process of MICP technology. The permeability and porosity of the stabilized column sand (7 cm in diameter and 11 cm in height) treated with waste pig urine were 0.135–0.150 cm/s and 32.10–33.96%, respectively, while a non-stabilized sample had 0.236 cm/s and 35%. The researchers focused on studying waste pig urine in the MICP technology, but there is limited research on the chemical characteristics of waste pig urine, the impact of different concentrations of waste pig urine and urea, storage and transfer conditions, and the chemical stability of waste pig urine for the MICP technology. The study also did not consider sand column strength, which is a crucial factor in geotechnical engineering. To ensure reliable engineering design and predictable outcomes, sand column strength should be considered. To compare the effectiveness of waste pig urine and other types of urine, a series of samples using synthetic urea as a benchmark should be used for index comparisons when replacing with waste pig urine.

Carla et al. [12] conducted a systematic investigation on the potential use of waste cow urine in the MICP technology. The researchers obtained waste cow urine from dairy farms and stored it at −20 °C to evaluate its chemical stability. The analysis revealed that sterilized waste cow urine had a total organic carbon of 976 mM (millimolar), total inorganic carbon of 107 mM, total nitrogen of 559 mM, and urea concentration of 224 mM, at pH 8.37. The researchers reported that the urea concentration in both fresh and thermal sterilized waste cow urine remained stable for four weeks with average concentrations of 136 + 9.5 and 103 mM, respectively.

Udert et al. [67], however, reported the opposite based on the results of their investigation. The lengthy duration of stability provides ample time for applications involving MICP. In this particular investigation, waste cow urine adjusted to a specific pH level was subjected to chemical analyses after passing it through a sand column up to six times. The sand columns were infused with cultivation media in order to encourage the growth of native soil bacteria. The study's methodology demonstrated that urea found within both sterilized and unsterilized waste cow urine with pH levels of 7 to 9 underwent natural hydrolysis by the native soil bacteria. In addition, the chemical analysis showed an increased carbonate content (4.1–5.3 mM) with adjusting the initial pH level of the waste cow urine to 9.

Similar to those proposed in previous studies, the approach introduced by Carla et al. [12]suggests that waste human urine could potentially replace synthetic urea in the MICP technology. In a recent study conducted by Lambert et al. [13], waste human urine was effectively used to cement a brick (222 × 106 × 73 mm) through Sporosarcina pasteurii-induced calcification. Additionally, Lambert used calcium hydroxide to stabilize the waste human urine for an extended duration, in contrast to a previous study that reported waste cow urine to be stable for only a month. Prior research achieved stabilized urine by increasing the medium's pH with calcium hydroxide [68]. The comparison strength test demonstrated 2.7 mPa, which is comparable to the strength achieved through MICP treatment of sand as reported in previous studies. The study also investigated on manufacturing bioremediated bricks. To create a single bio-brick, 31 L of urine solution was necessary, but only 1% of this solution was used to produce calcium carbonate. Chemical analysis revealed that waste human urine at pH 11.2 was more stable than urea-hydrolyzing media at pH 9.25 due to lower enzyme activity. The quantity of urea hydrolyzed in waste human urine over four days was low, suggesting that it remained stable during that time without adding calcium hydroxide.

The concentration of urea, stability, and conditions during transport and storage are critical factors that pose challenges when considering urine as a replacement for synthetic urea in the MICP technology. Despite this, urine as a waste material, particularly coming from cattle farms, is a feasible option to substitute synthetic urea. However, replacing synthetic urea with waste urine could result in the release of ammonium into the atmosphere, which may lead to air pollution, especially in large quantities. Nitrogen can also cause groundwater pollution and greenhouse gas emissions such as nitric oxide [65]. In response to the issue of ammonia gas emissions exceeding regulations in MICP-based biocement, Chu et al. [69] proposed a new microbially-induced struvite precipitation biocement. This method involves the reaction of NH3 with magnesium and calcium phosphate to create struvite, which traps the NH_3. Comparison experiments were conducted on sand using both methods, which showed a 75% reduction in ammonia gas emissions and a total mass of ammonium (NH_4^+) in the effluent of twice the amount in the MICP-treated sample. Additionally, a recently proposed approach is to replace urea with carbon dioxide influx. Although this method does not use waste, it is promising as it can reduce carbon dioxide emissions during biocementation. The carbon dioxide influx has been shown to effectively replace urea in Bacillus megarterium-induced calcification, improving the durability of concrete [70] and potentially reducing the need for synthetic urea in the biocementation technology in the future.

3.1.2. *Calcium alternatives*

Calcium is a crucial chemical used to produce calcium carbonate precipitation in biomineralization technology. However, it has been reported that not only calcium ions, but also other divalent cations, such as magnesium ions, could be potentially useful to the biocementation technology [71]. Furthermore, during the precipitation of carbonate minerals, heavy metal ions, such as strontium (Sr^{2+}), lead (Pb^{2+}), cadmium (Cd^{2+}), and copper (Cu^{2+}), can potentially be incorporated into the calcium carbonate crystal by substituting the Ca^{2+} ions [72].

Different chemical sources of calcium, including calcium chloride, calcium hydroxide, calcium nitrate, and calcium acetate, are commonly used in the biocementation technology media. However, these sources have been found to provide varying levels of capability and effects on the crystallization of biominerals [70,71].

Generally, calcium chloride is the primary chemical used in biomineralization due to its high solubility and availability, as reported in various studies [43,72,73]. However, the industrial use of calcium chloride is not limited to biocementation, as it has several other applications as well [74]. Nonetheless, the use of calcium chloride in the MICP process can cause the release of chloride, leading to corrosion of metals and concrete. Various researchers have asserted that this can result in damage and increased costs, especially when large amounts of calcium chloride are used near a concrete construction [75–78]. Additionally, chloride can contaminate underground water in soil stabilization projects.

To address the challenges associated with using calcium chloride in the biocementation technology, waste materials can be utilized as a replacement for calcium sources. One such waste material is eggshells that have been found to effectively replace calcium chloride in biocementation [14]. To prepare the calcium media, in the study of Choi [14], waste eggshells were powdered and dissolved in diluted vinegar (5%) at different preparation times, with and without the waste eggshell membrane. It was determined that the extraction of the membrane had no significant effect, and the waste eggshell and membrane should be dissolved in a 1:8 ratio. Furthermore, it was found that calcium carbonate precipitation was higher in the samples using waste eggshells compared to the control samples, possibly due to uneven calcium concentration.

Kulanthaivel et al. [15] also reported that waste eggshells can potentially replace calcium ions. The eggshell cementing chemical was made by dissolving waste eggshells using 5% white vinegar, which breaks down the 94% calcium salts they contain. After being washed and dried, the eggshells were crushed into a powder and mixed with white vinegar in a 1:8 wt ratio. The mixture is then shaken mechanically for a week. This process was first described by Choi [14]. The researchers reported that using waste eggshells resulted in an unconfined compression strength of 650 kPa, permeability ranging from 6.3×10^{-3} to 3.2×10^{-5} cm/s, and an appropriate level of precipitation (17.9%).

Choi et al. [16] conducted a study on using waste limestone powder derived from aggregate quarries as an alternative to calcium ions in the MICP technology. To create a calcium-rich medium, waste limestone powder was dissolved in waste acetic acid, which is a waste stream of the cellulosic biofuel industry produced through the fast pyrolysis of lignocellulosic biomass. The study found that dissolving 100 g of waste limestone powder in 200–1200 ml of waste acetic acid (7 % W/V acetic acid) led to 0.83–0.64 M calcium ions with pH 5.2–4.8 after 5 days. The authors prepared a centrifuged (4000 rpm, 20 min) diluted mixture of the waste limestone powder and waste acetic acid (100:800) with water to create a 0.3 M solution, adjusted the pH from 5 to 7.5, and used it for biocementation experiments. In sand column samples (5 cm in diameter and 10 cm in height), microbially-waste calcium-induced precipitation (5.67–8.19% calcium carbonate precipitation contents) resulted in permeability ($8.17–1.52 \times 10^{-6}$ m/s), unconfined compression strength (800–1100 kPa), and tensile strength (120–200 kPa). Unlike chloride, which is released in the common MICP process and is harmful to the environment, acetate is less toxic and can be easily degraded by microorganisms. Similarly, Calcareous sand can also be used in the MICP process when dissolved in an appropriate acetic acid [17].

In a recent study carried out by Liang et al. [18], the potential use of kitchen waste such as oyster shells, scallop shells, and eggshells as a source of calcium for the biocementation technology was investigated. The experiment also included the use of lab-grade calcium nitrate for comparison purposes. The waste material was washed, dried, and crushed before being dissolved in a pH-adjusted (6.5–7) calcium media, which was then mixed with 10% nitric acid in a ratio of 1:6 for 36 h. The results showed that oyster shells, scallop shells, and eggshells contained significant concentrations of calcium, with values of 0.56, 0.42, and 0.4 M, respectively. Oyster shells were found to be particularly effective in biocemented sand columns (39.1 × 80 cm), resulting in permeability (1.12×10^{-4} m/s), unconfined compression strength (1455 kPa), and precipitation (15%). The SEM image analysis was also conducted to evaluate the microporosity index, with oyster shells (9.12%), scallop shells (14.52%), and eggshells (12.88%), with the latter two items outperforming calcium nitrate (9.53%).

Based on the research findings, it is important to identify an optimal ratio for effectively activating and utilizing calcium rich waste with acid, while ensuring high effectiveness and appropriate pH levels. In addition, it is crucial to consider the cost-effectiveness of waste materials, as the waste materials should be suitable for both laboratory and large-scale industrial purposes. Sorting kitchen waste may not be practical for commercial use. The release of chloride ions during biocementation can have negative effects on the surrounding water and concrete erosion structures. Therefore, using rich calcium source waste instead of calcium chloride can provide significant environmental benefits. However, it is important to further study the productivity and availability of such waste materials, as not all waste sources are suitable to large-scale biocementation projects, aside from waste limestone.

3.2. *Waste stream as culture media*

In biomineralization technology, bacteria cells play a crucial role in generating enzymes for catalysing the biocementation process and providing a nucleation site for mineralization [79]. Sporosarcina pasteurii, previously known as Bacillus pasteurii, is a gram-positive bacterium with a high level of enzyme activity, which has been widely used in the ureolytic MICP technology [80]. For bacteria to grow at an optimal rate, it is essential to provide them with a suitable culture medium containing necessary nutrients such as carbon, nitrogen, phosphorus, and other essential minerals. Additionally, the pH and temperature of the culture medium should be appropriate to the specific type of bacteria used, and sufficient time should be considered for growth to occur. It is important to note that different types of bacteria have different requirements for growth; thus, the specific conditions needed for cultivation will depend on the type of bacteria you are trying to grow. The cultivation of bacteria is considered the most expensive part of biocementation technology based on a cost analysis [18,79]. In the MICP technology, Sporosarcina pasteurii is mostly cultivated using ammonium yeast extract and urea, nutrition broth, Luria Bertani, and tryptic soy broth [80,81].

Waste products with high protein content, particularly those generated by the food industry, have the potential to be utilized as alternative nutrient sources in biotechnological processes. However, the large-scale release of such waste products can pose a threat to the environment. Despite this, there are various potential benefits to using them effectively as a nutrient source for different applications. In the development of biocementation technology, there has been extensive research into using waste streams as a replacement for cultivation media. Nevertheless, in searching for alternatives to waste streams, it is crucial to consider factors such as cost-effectiveness, the possibility of sterilization, and the performance of the culture media. Waste products such as brewery waste yeast, corn steep liquor, torula yeast, vegemite, dairy waste whey and buttermilk, and lactose mother liquor are examples of waste industrial streams that can be used as substitutes for cultivation media [82,83]. This section will explore suitable culture media derived from waste streams for the biocementation technology.

According to Reddy [84], the waste lactose mother liquor derived from the dairy industry can be utilized as a substitute for lab-grade cultivation media (which typically includes urea-yeast extract) for the cultivation of Sporosarcina pasteurii on a commercial scale. The lactose mother liquor contains 15.4% lactose (carbon sources), 8% proteins (nitrogen sources), and 353 mg/l calcium, 186 mg/l potassium, and 90 mg/l chloride, with a pH of 6.20. When compared with common cultivation media, a similar growth pattern and pH change were observed, and no significant differences in CFU/ml were noted through Sporosarcina pasteurii cultivation. In the study of biocementation processes, the urease activity is a crucial factor to consider [85,86]. After a 168-hour monitoring, the maximum urease activity was observed in nutrient broth-urea medium, yeast extract-urea medium, and lactose mother liquor-urea medium at 412, 366, and 353 U/ml, respectively.

Delwiche and Smith [87] reported that molasses can act as a nutrient additive to promote urea hydrolysis and can be utilized in water remediation applications containing ions. Cuzman et al. [88] conducted a systematic investigation into the feasibility of using dairy waste streams and brewery waste streams as alternative media for Sporosarcina pasteurii cultivation. The authors also explored whether urea fertilizer could replace lab-grade urea in the cultivation process. The study revealed 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 examined as a potential replacement for lab-grade urea-yeast extract medium [19]. Bacterial growth profiles in Urea-corn steep liquor were found to be comparable to those in urea-yeast extract medium. However, zeta potential experiments indicated that bacteria grown in urea-corn steep liquor had significantly lower surface charges (-29 in corn steep media compared to −46 in urea-yeast extract medium). Liang et al. [89] suggested that the negative charge on bacterial surfaces is influenced by phosphate, carbonate, and sulphate groups. The type of bacteria and the concentrations of urea and calcium chloride components may also affect the zeta potential. Therefore, the ingredients of alternative culture media may be able to reduce the zeta potential. Whilst this effect may not be significant in self-healing concrete, it could be crucial to consider reducing bacteria surface charges in other MICP applications such as water remediation [90].

Omar et al. [20] reported that vegetable waste could potentially be used for biocement applications, particularly to replace chemicals in the MICP process. The waste was collected from various vegetables, including cabbage, long beans, cucumbers, and spinach, and then was fermented for one month in a tightly sealed container with urea added throughout to promote the growth of ureolytic bacteria. The analysis of the filtered substrates showed the presence of 253.4 mg/ml carbon, 9236.27 mg/ml nitrogen, as well as 42 mg/l Si, Fe, and Ca, which are suitable to indigenous bacteria nutrition. The microbiological analysis revealed the presence of bacteria such as Escherichia coli, Salmonella, Staphylococcus aureus, Clostridium perfringens, Pseudomonas aeruginosa, and Enterococcus/Streptococcus, commonly found in soil and water from the environment. The unconfined compression strength of soils treated with the soul-fermented vegetable waste was up to 60 kPa. However, the low strength might be due to a single-cycle treatment, whereas most studies report multiple cycles treatment [91]. The study did not clarify whether the soil indigenous bacteria or fermented vegetables caused the chemical reaction. The viscosity of the fermented vegetable waste and precipitation tests require further study to understand their effects on crystal morphology and reaction rate analysis.

Armstrong et al. [82] comprehensively investigated the use of commercial yeast extract as a substitute for lab-grade yeast extract in Sporosarcina Pasteurii cultivation. Although the food-grade yeast is not typically obtained from waste stream sources, their study is of benefit for the bacteria nutrient replacement technology. The results showed that the maximum optical density (OD) for the food-grade yeast was 1.04 after 54 h, while the lab-grade yeast achieved an OD of 1.21 after 42 h, demonstrating that the food grade yeast can be a cost-effective replacement for expensive lab-grade yeast extract.

Kahani et al. [21] adopted an approach similar to that of previous studies to investigating the use of corn steep liquor, commercial yeast extract, soy flour, and whey to reduce the MICP process cost. Kahani and colleges also explored the possibility of using seawater instead of pure water, which is critical in drought-stricken areas where the MICP technology is being researched. The researchers also examined a non-sterile, sanitized media condition, which reduced energy consumption and was found suitable to large-scale MICP projects. Dairy waste, in the form of whey powder leftover from primary cheese-making processes, contains 497 g/kg organic carbon and 22.9 g/kg nitrogen. Although the growth profile of the bacteria (OD 600) in whey nutrition media was lower than in other nutrition media, it exhibited the highest urease activity. Moreover, when seawater with a salinity of 1.06% was used as a solvent in the culture medium, the urease performance of the bacteria was not significantly affected. Additionally, it has been reported that the addition of waste activated sludge to yeast extract media as an additive could potentially enhance the urease activity of Sporosarcina pasteurii bacteria [92].

Kitchen waste is a potential source of nutrients for microbial growth as it contains various ingredients such as starch, polysaccharides, proteins, cholesterol, lipids, vitamins, and inorganic salts. Sporsarcina pasteurii can use kitchen waste as an alternative nutrient source, with carbohydrates and proteins making up 53% and 16%, respectively. To enhance the nutrient availability in kitchen waste, neutral proteases were used for protein pre-treatment. Enzymatic hydrolysis with a commercial enzyme broke down long-chain protein molecules into small peptones and peptides or free amino acids that can be utilized by bacteria for growth [93]. The composite substrate was stored at 4 °C prior to enzymatic pre-treatment and bacterial cultivation. Results showed that treated kitchen waste media had high nutrient content and released soluble organic nitrogen significantly within 6 h. The growth profile of bacteria using treated kitchen waste media showed a similar trend to that exhibited by yeast extract, while it was more effective than nutrition broth media. A high urease activity (14.32 mM Urea min^{-1}) and biomass concentration ($OD_{600} = 4.19$) support the use of kitchen waste as an alternative nutrition media [94].

Previous research suggests that waste streams may have the potential to serve as a replacement for lab-grade cultural media. In this regard, factors such as bacteria strain and enzyme activity, as well as cost-effectiveness, should be taken into consideration. Future research should focus on determining the optimal concentration and storage conditions. Note that waste nutrients cannot be expected to be more effective than lab-grade materials, as they are inherently with less effectiveness. Therefore, acceptance limitations are required in future studies. Additionally, future research is recommended to examine the impact of using waste streams to replace cultivation media on calcium carbonate morphology. It is also important to acknowledge that these waste streams may contain other contaminants that could affect the process of biomineralization.

3.3. MICP treatment of waste stream

MICP has been extensively researched in engineering, especially in the context of construction applications and cementing porous media. The earlier part of this review paper primarily discussed the use of waste materials, instead of chemical agents, as a cementation reagent and culture media in the biocementation process. This approach not only allows for the reuse of waste streams, but also reduces the MICP cost in large projects. Furthermore, the MICP technology can be leveraged to support three key engineering applications, while also managing waste streams. The technology has the potential to contribute to these applications in an advanced manner, aligned with engineering goals.

The disposal of fly ash, a hazardous waste product derived from municipal solid waste incineration, poses a significant challenge to the industry due to its high pH (10–13) and heavy metal content (>500 mg/kg), which make it an environmental hazard [95]. However, Sporosarcina Pasteurii induced precipitation has been found to have the potential to solidify the highly alkaline fly ash and effectively embolize hazardous metal ions, as demonstrated by Chen et al. [22]. The researchers reported that MICP can be achieved without the need for additional calcium chemicals, as fly ash already contains appropriate levels of calcium oxide (44.1%) to prepare calcium sources. Chemical analysis showed that the stabilization rates of various heavy metals in the fly ash ranged from 6.9% to 93.5%. Based on these findings, MICP appears to be a promising technique for treating fly ash and reducing its environmental impacts, as long as it is stored or reused properly.

The particle size of the fly ash is an important factor in the solidification of granular particle soil during the MICP treatment [96]. Two types of fly ash were studied, with average particle sizes of 0.108 mm and 0.021 mm, respectively. The MICP stabilization and calcium silicate hydration through fly ash activity for a week resulted in an unconfined compression strength of 0.709 MPa for cylindrical samples (36 mm in diameter and 70 mm in height) of the finer ash. The MICP treatment effectively bonded the ash particles.

During the recycling process in a paper mill, wastepaper is generated containing cellulose fibres ranging in size from 20 to 500 μm. Chen et al. [23] found out that these wastepaper fibres can be used as an additive to enhance the mechanical strength of stabilised sand using MICP. The addition of just 1% wastepaper fibre can increase unconfined compression strength by 20%, as well as improve failure strain behaviour and ductility. These results are similar to those achieved in studies using synthetic fibres, such as polypropylene fibre, in MICP-treated sand [97]. In general, wastepaper fibres can retain more bacteria and increase the chance of biomineralization. However, the presence of too much fibre content can also reduce the mineral bonding spots between sand particles, which has a negative effect.

While MICP and recycled materials can generally have many positive impacts, there are instances where they do not have a positive effect. For example, Espinal et al. [98] reported that the MICP treatment of waste plastic fibre does not improve the performance of interfacial bonding fibres. This is because the biomineral produced by MICP covers the fibre surface with a thick and inconsistent layer, which prevents an increase in bond strength.

MICP has the potential to enhance the quality of construction materials and recycled aggregates in concrete. When the latter are treated with MICP, the pores and cracks in the particles can be filled, resulting in reduced water absorption and modified interfacial transition zones (ITZs) [99]. Similarly, Joshi et al. [100] reviewed the effects of MICP on waste materials-amended concrete and found out that applying MICP through bioprecipitation can be a sustainable approach to improving the concrete durability properties. Furthermore, MICP has been shown to successfully improve waste tire rubber fibre in cement mortar by reducing pore spaces and enhancing the performance and durability of the mortar [24].

Another challenge is the release of dissolved heavy metals into the environment from waste rock and tailings impoundments. It can occur slowly depending on specific environmental conditions, ultimately impacting groundwater, soils, and surface water. Proudfoot et al. [101] conducted a study focusing on the use of indigenous bacteria to promote the generation of $CaCO_3$ coating on waste rock particle surfaces. They also discussed the use of MICP technology, which shows promise for filling void spaces and coating particles in fine-grained media. The authors found out that this process contributed not only to the reduction of acid and dissolved metals in leachate, but also to the stabilization of mine waste.

Mwandira et al. [25] explored the potential of MICP technology in reducing the mobility of Pb^{2+} in mine waste through the stabilization of Pb-contaminated kiln slag and leach plant residue. The Pb-contaminated kiln slag and leach plant residue have the average particle sizes of 1000 and 9 µm; density of 2.88 and 2.39 g/cm3; and Pb concentration of 5.40 and 7 mg/L, respectively. Different immersion and flow methods were employed to achieve an estimated unconfined compression strength of 8 and 4 MPa for the treated samples (25 mm in diameter and 70 mm in height). The unconfined compressive strength was measured using a needle penetration device. In addition, hydraulic conductivity was significantly reduced by the urea hydrolysis and calcium carbonate precipitation. Following the MICP treatment, the leaching ability of Pb^{2+} from mine waste was less than 0.001 mg/L. Moreover, indigenous bacteria were found to control heavy metal contamination in both water and soil. Kim et al. [102] investigated the urea-hydrolysing abilities of three indigenous bacterial strains to be used as a biomineralizing agent for heavy metal immobilization in heavy-metal-contaminated soils and mine tailings. The schematic treatment of soil contaminated with heavy metals, waste from mines, and leachates is depicted in Fig. 6.

MICP has the potential to effectively remediate toxic metals, including lead and cadmium, in landfill leachates [103]. Furthermore, in the study of [104], the toxic precipitates remained stable even under continuous acid degradation at a pH of 5.5, with only 1.76% of the lead released after two weeks.

Another application of application of the MICP technology involves the use of carbonate precipitation to eliminate heavy metal contamination from wastewater. Recent studies have reported highly effective removal of cadmium from wastewater using bacteria-induced cadmium carbonate precipitation through MICP methods [25,40]. This suggests that waste materials can be effectively repurposed through the MICP technology, but further research is required to determine the optimal concentrations, ratios, cost-effectiveness, and conditions for bacteria activity. In the near future, the use of the MICP technology to treat the construction and demolition waste is expected to become a significant research area, especially for concrete and geotechnical applications (Fig. 5).

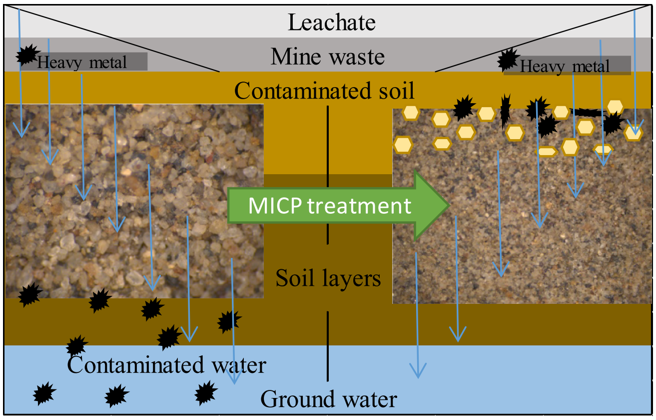

Fig. 6. MICP treatment of contaminated soil and ground water.

4. Conclusion

Microbially Induced Calcite Precipitation (MICP) through ureolytic bacteria has been considered as the most straightforward and energy-efficient process for engineering applications. In this paper, the potential of utilizing the waste stream technology along with MICP was discussed. This detailed study concluded that waste streams could substitute synthetic chemicals in cementation reagent as well as in culture media compatible with lab-grade materials and more commercial. Specifically, by incorporating waste stream technology into MICP, waste can be reused in a wide range of engineering applications, which greatly reduces the waste input into landfills. To utilize waste streams for the MICP technology, some preparation is required. This involves storing urine waste in appropriate storage conditions and reactivating waste streams as calcium sources with suitable acids. The risk of contamination with pathogenic bacteria must be minimized during the production process. Moreover, the substitution of nutrition waste requires autoclave capability and adequate levels of carbon and nitrogen. Accordingly, it is worth mentioning that the application of waste should be considered depending on materials obtainable locally. The use of waste materials as a local resource can reduce transport costs [12]. Furthermore, the stabilization of waste through MICP is a highly energy-efficient activity with several eco-friendly effects. Additionally, MICP has great potential for purifying wastewater, and its efficiency in this regard needs to be compared to other methods.

Ensuring uniformity is a significant challenge when it comes to achieving strong biocemented sand. To overcome this challenge, certain techniques have been developed, including the use of a single “all-in-one” solution, which holds promise in enhancing the uniformity of cemented sands [105]. However, the size of soil particles poses another significant challenge, with coarser aggregates proving difficult to biocement successfully [91]. This emphasizes the need for further research to develop methods that can overcome this limitation of MICP technology, particularly when introducing waste streams to MICP technology.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Arul Arulrajah, PhD reports financial support was provided by Australian Research Council.

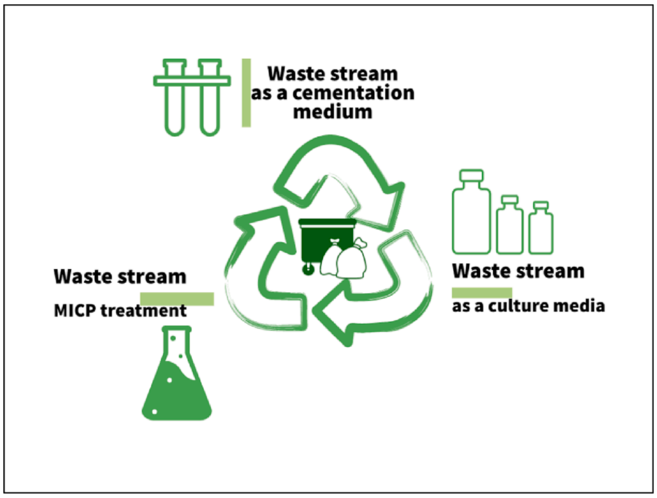

Fig. 5. Utilizing waste stream with the MICP technology.

Data availability

Data will be made available on request.

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