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REVIEW PAPER

Erosion mitigation with biocementation: a review on applications, challenges, & future perspectives

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Abstract Soil erosion is a complex natural process that occurs by either individual or combined actions of wind, hydraulic currents, waves, and rain. This study comprehensively reviews biocementation-based soil stabilisation techniques for developing erosion-resilient landforms through an ecologically conscious strategy. The different pathways for biocementation occurring in nature are discussed with a focused view on the microbially induced carbonate precipitation (MICP) technique. MICP relies on biogenic calcium carbonate ($CaCO_3$) precipitation via the urea hydrolysis route to bind the soil grains. The kinetics and factors affecting MICP are succinctly discussed to highlight the practical challenges associated with biocementation. This study emphasises the influence of MICP on erosion resistance (aeolian and hydraulic) and geotechnical properties of soils. The critical assessment of the previous studies revealed that aeolian and hydraulic erosion can be effectively controlled with a small to moderate quantity of biogenic $CaCO_3$ (2% to 10% of soil weight). MICP marginally influences the hydraulic conductivity of soils with a substantial improvement in compressive strength, making it desirous over traditional soil cementation agents for erosion control due to the limited intervention to natural groundwater flow. However, the scientific design and findings of the previous laboratory-scale and pilot-scale research are still inconsistent for standardising biocementation techniques to transition towards upscaling. This study presents critical insights to the researchers of the environmental, geotechnical and geoenvironmental engineering domains to design their upcoming studies to tackle the challenges required for upscaling biocementation technology.

Keywords Soil erosion control · Bio-mediated soil improvement · MICP · Aeolian erosion · Coastal erosion · Riverbank erosion

1 Introduction

Preserving our terrestrial ecosystem against degradation and desertification is identified as one of the most challenging sustainable development goals (SDG15) by the United Nations (Economic and Social Council; United Nations 2022). Soil is one of the most vital resources for life in conjunction with air and water (García-Ruiz et al. 2015). A drastic soil loss of greater than 24 billion tonnes per year is reported around the globe (United Nations 2019). Aeolian, coastal and riverbank erosion are caused by natural and anthropogenic processes.

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The majority of the deserts around the globe are vulnerable to aeolian erosion (D'Odorico et al. 2013). Around 12% of the dryland is found vulnerable to degradation, accounting for an area of around 5 million square kilometres (Burrell et al. 2020). The desert soil consists chiefly of dry and cohesionless loose sand and silts, which are subjected to surface erosion due to high-velocity winds. The aeolian processes are also liable to the formation of some of the majestic aeolian landforms such as crescent sand dunes and pinnacle Karst. In Fig. 1a, the pinnacle karst of Nambung National Park, Western Australia, is shown. The pinnacles have formed in the limestones due to cyclic aeolian erosion processes (Lipar and Webb 2015). However, the dust and sand particles released into the air due to the aeolian erosion adversely impact human health and essential infrastructural services such as transportation, telecommunication, and electricity.

On the other hand, around 40% of the global population is impacted by coastal erosion, and Mentaschi et al. (2017) recorded an overall surface loss of 28,000 square kilometres over a period of 32 years (1984–2015). The coasts are enduring severe erosion, leading to loss of land and infrastructure. One such coastal bank is situated near Eagle Bay, Rottnest Island, Australia. The photo of the beach is shown in Fig. 1b. The marks of erosion induced by the sea waves can be observed clearly in the photograph. Riverbank erosion also contributes significantly to global land degradation. The majority of the banks along the mega rivers lose substantial land due to erosion (Latrubesse 2008). One such mega river is the Brahmaputra, which has caused a land loss of around 2400 square kilometres in the Assam valley in eight decades (1912 to 1996) in India (Sarma 2005). The mega rivers around the world contribute significantly to land loss (Das et al. 2014).

Aeolian, riverbank, or coastal erosion initiates with the detachment of soil particles from the surface. Figure 2 demonstrates the micro-mechanics of surficial erosion initiation. The detached particles are entrained and transported by wind or water. Typically, the constitutive relationship between erosion rate ($\acute{Z}$) and shear stress (τ) is represented as illustrated in Eq. (1). Erosion at the soil surface initiates when the erosive stress (τ) applied on the soil–water or soil-air interface by flowing water or wind exceeds the critical stress, as illustrated in Eq. (2). Critical stress (τ_c) is the threshold stress that the granular material can withhold in its innate state. The critical stress of soil grains majorly depends on the interparticle electrical forces (f_e), interparticle contact forces (f_c), pore water pressure ($-u_w$), and weight of the particles (Briaud 2008). Therefore, soil erosion can be controlled either by minimising the erosive stress or improving the critical stress of the soil particles.

Fig. 1 **a** Aeolian erosion-induced pinnacles karst in Nambung National Park, Western Australia; and **b** Coastal erosion at Eagle Bay, Rottnest Island, Australia. (Photographs taken by Authors)

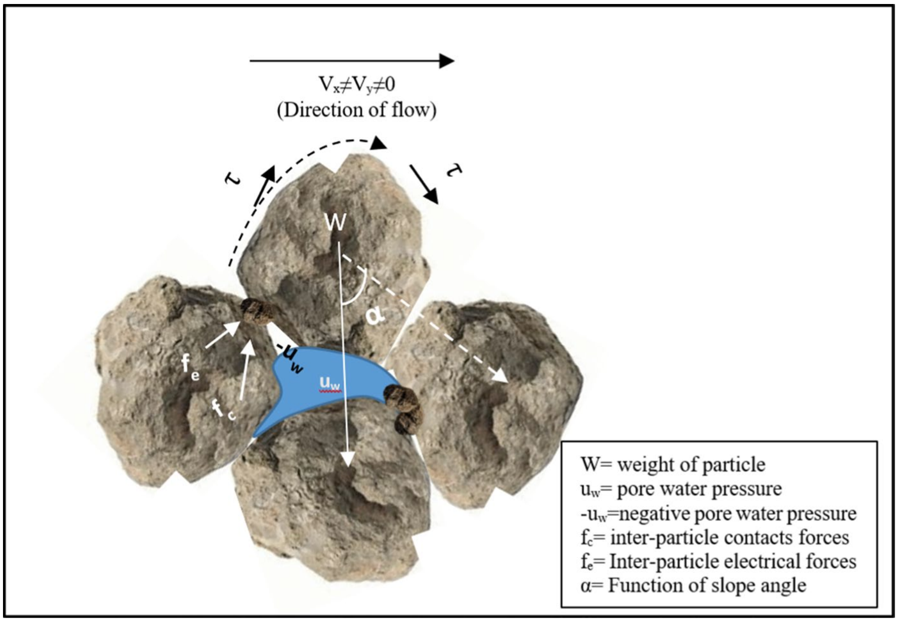


Fig. 2 Schematics demonstrating micro-mechanics of surficial erosion initiation

$$\dot{Z} = f(\tau) \tag{1}$$

$$\dot{Z} > 0 \text{if} \tau \geq \tau_c \tag{2}$$

The surficial detachment of soil grains can progress to different erosion modes depending upon the type of soil and angle of slope (bank or flat land) of the different terrestrial landforms (deserts, riverbanks, coasts and farmlands) against the erosive forces induced by rainfall, wind, river currents, coastal waves, or groundwater motion. The flatlands are expected to undergo scour (localised erosion), surficial erosion, internal erosion or piping and sinkhole formation. On the other hand, soil slopes, such as riverbanks and seashores near water bodies, can also undergo sudden collapse due to mass/slab failure caused by shear and tension apart from scour and surficial erosion (Nardi et al. 2012). The wet-dry cycle near water bodies leads to loss of matrix suction, resulting in erosion and collapse (Nardi et al. 2012). The different modes of soil erosion are illustrated in Fig. 3.

Consequently, erosion control measures can be classified broadly into two categories, including- 1. Deviating/attenuating the erosive stresses with rigid structures; or 2. Improving the soil erosion resistance by chemical binders/mechanical compaction. The existing erosion control engineering practices, including mechanical compaction, cement-based rigid structures, chemical-based synthetic binders and soil replenishment techniques, are barely viable in terms of their environmental impact and cost-effectiveness.

The attenuation of erosive forces such as wind, river currents and hydraulic waves is accomplished by means of cement-based rigid structures. These countermeasures are costly and counterproductive as they lead to sediment imbalance and harm the ecology (Florsheim et al. 2008; D'Odorico et al. 2013). The cement industry contributes more than 7% to global anthropogenic CO_2 emissions, which are increasing rapidly (Ali et al. 2011). Around 0.92 tonnes of CO_2 is emitted into the environment for each tonne of clinker produced in the cement-making process (Habert et al. 2010). With the target of controlling global warming, the United Nations has proposed a "net zero" carbon footprint by 2050 (Intergovernmental Panel on Climate Changes; United Nations 2018). Therefore, an alternative erosion mitigation strategy with an ecologically conscious approach is urgently required.

The other method to improve soil resilience includes chemical and cementitious binders that improve the critical stress of the sediments. However, it is to be noted that artificial grout materials, including lime, micro-fine cement, silicates, and epoxy,

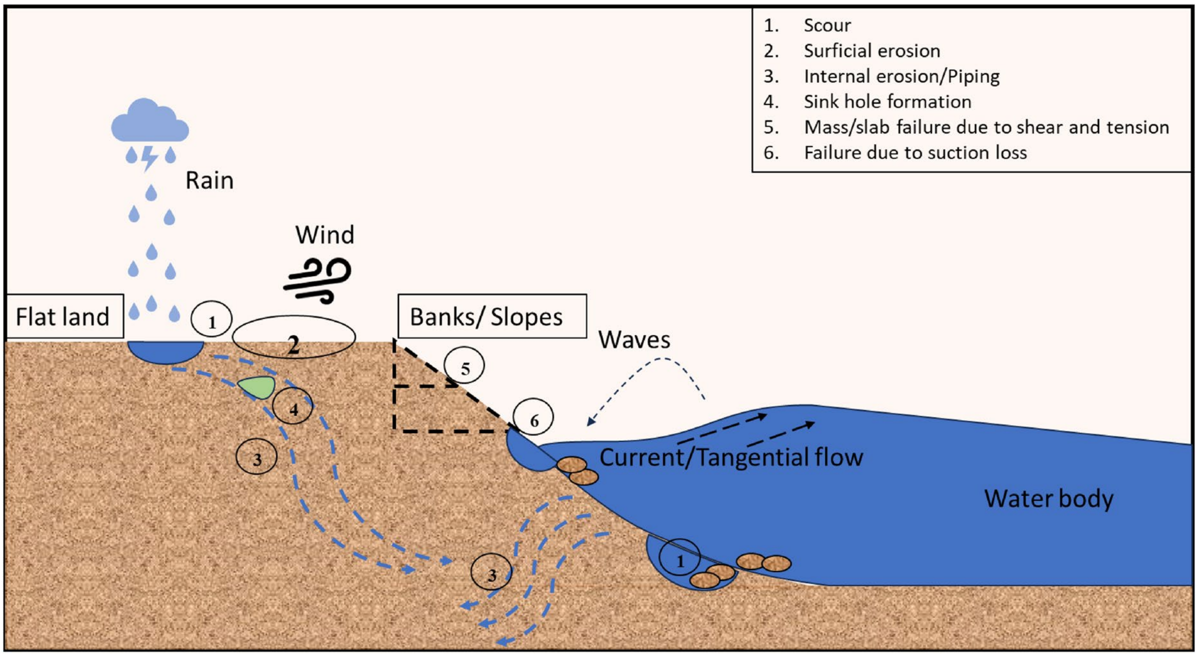


Fig. 3 Different erosion modes for flat land and banks

have been reported to be toxic to the geo-environment (Karol 2003; DeJong et al. 2010) and, hence, they can adversely impact the flora, fauna, and crop productivity of the soil. River embankments (artificial banks to prevent flooding-induced erosion) made with alternative materials such as slag to improve their strength and resilience against erosion can impart irretrievable damage to river ecology due to their hyperalkalinity (Dubey et al. 2022d). Therefore, there is a critical need to find next-gen sustainable materials that perform not only superior but also impart minimal ecological harm.

Extensive research is ongoing on different biostabilisation techniques in pursuit of sustainability, including biocementation, biopolymerisation, phytostabilisation and enzyme-induced cementation. Phytostabilisation (vegetation-based soil stabilisation) techniques are known to be the most appreciable sustainable erosion mitigation technique (Zhu and Zhang 2016; Bordoloi and Ng 2020). However, their influence on the erodibility of soil is too complex to predict due to its uncertain life cycle and dense root structures, which are dependent on the type of vegetation, available nutrition, and climatic conditions (van Dijk et al. 2013; Krzeminska et al. 2019). Enzyme-induced carbonate precipitation (EICP) and algae/cyanobacteria-based biocrust formation techniques are also getting attention due to their considerable potential in soil stabilisation with minimal environmental impact (Chandra and Ravi 2020; Fattahi et al. 2020; Patil et al. 2021, 2023). EICP is a comparatively convenient technique in terms of control over treatment strategy due to water-like consistency and straightforward application. However, purified enzyme (urease) is expensive and current research is extending towards finding cheaper sources from native plants (Rahman et al. 2023). Biocrust is a shallow (in millimetres) plant-promoting biological layer for antidesertification purposes; However, the biocrust formation has a slower growth rate and is easily disturbed with human intervention (Patil et al. 2023). Biopolymer treatment is not suitable for wet environment as the treated soils lose substantial strength upon moisture interaction due to the hydrophilic nature of biopolymers (Ramachandran 2022; Patwa et al. 2023).

On the other hand, biocementation involves mimicking microbial mineralisation techniques that occur in nature (De Muynck et al. 2010; Dhami et al. 2013a). Biocementation technique has shown potential in their geotechnical applications because- 1. Soil is rich in microbial diversity (Mitchell and Santamarina 2005), 2. Biocementation solution has water-like consistency, ensuring easy and controllable in-depth penetration (Ivanov and Chu 2008), and 3. Biocementation has the healing capacity upon the availability of nutrients (Castro-Alonso et al. 2019; Kaur et al. 2023). The recent work has demonstrated the potential of biocementation in erosion control in diverse environments such as deserts, riverbanks, and seashores (Salifu et al. 2016; Bibi et al. 2018; Nayanthara et al. 2019; Zomorodian et al. 2019; Shahin et al. 2020; Behzadipour and Sadrekarimi 2021; Dubey et al. 2021b, 2022b). Moreover, biocementation is reported to be effective in mitigating various types of erosion, such as rainfall-induced erosion, internal erosion, and tangential-flow/current-induced erosion (Amin et al. 2017; Jiang and Soga 2017; Jiang et al. 2019; Devrani et al. 2021; Clarà Saracho et al. 2021a). Although extensive studies have been conducted, the upscaling and field-scale application is limitedly explored due to challenges such as difficulty in controlling the microbial viability/efficiency, uniformity of precipitation, by-product ammonia generation and cost. Therefore, this study is aimed to consolidate and critically assess the gained knowledge in erosion control via biocementation techniques and challenges to direct future research.

2 Biocementation as a potential erosion control solution

Nature has been forming biominerals and cemented aggregates for millions of years, as discovered by previous researchers in the case of anthills, cave speleothems, beach rocks and corals (Baskar et al. 2009; Dhami et al. 2013a). A few of such mesmerising nature-forming structures have been illustrated in Fig. 4. Figure 4a demonstrates a natural beach rock at Eagle-bay of the Rottenest Island, Western Australia, withstanding the wave-induced erosion forces. Figure 4b shows an anthill formed near the Department of Civil Engineering, which withholds against heavy rains, while Fig. 4c illustrates speleothems from Mawsmai Caves, Meghalaya, India.

Naturally formed karsts and beach rocks are observed to resist the erosive actions of wind and water up to a great extent when compared with naturally available loose soil. Emulating these techniques in the laboratory could provide the key to an eco-friendly technique for controlling soil erosion. Previous literature has discovered the biogenic and abiogenic cementation processes occurring in nature and mimicked them in the laboratory (van Paassen et al. 2010a; Gomez et al. 2017; Ramachandran et al. 2020).

The biominerals present in nature are classified as biologically induced mineralisation and biologically controlled mineralisation (Lowenstam 1981). The

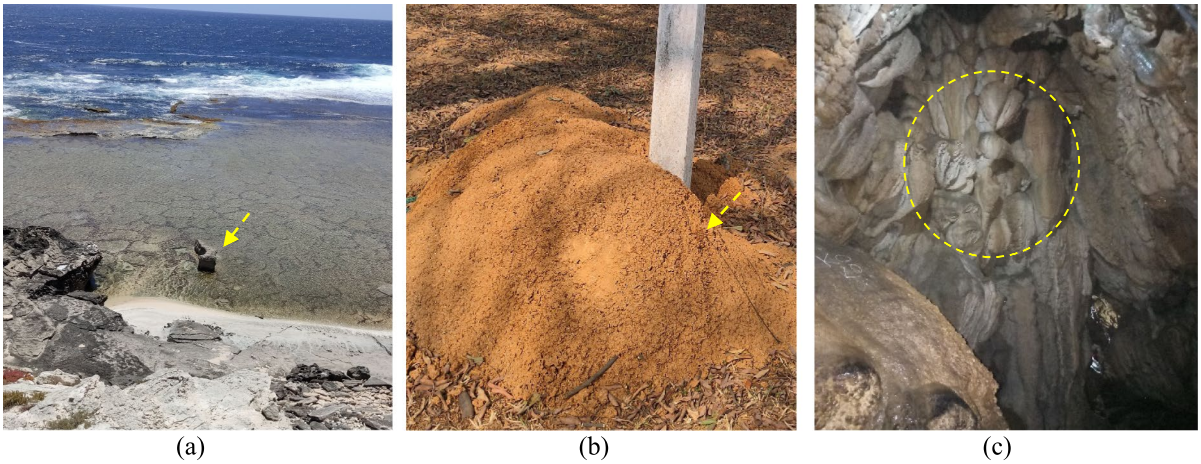

(a) (b) (c)

Fig. 4 Example of naturally formed minerals, **a** Erosion-resilient beach rock at Eagle Bays of Rottenest Island, Australia; **b** Anthills near the Civil Engineering Department, IIT Guwahati campus; and **c** Speleothems from Mawsmai Caves, Meghalaya, India. (Photos taken by Authors) biologically induced minerals are developed extracellularly through the metabolic activities of the microorganisms, while the biologically controlled minerals are precipitated inside or around their cells. In nature, several chemical reactions govern the biologically induced mineralisation process that demonstrate potential for engineering applications, as illustrated in Table 1. The commonly observed natural biocementation pathways can be subdivided into autotrophic and heterotrophic pathways. Autotrophic microorganisms do not require external sources for their nutrition and energy, and these reactions are observed to be slow. Through one of such autotrophic pathways, i.e., photosynthesis, Nature has been forming stromatolites for billions of years using cyanobacteria (Arp et al. 1999; Altermann et al. 2006; Rodríguez-Martínez et al. 2012). On the other hand, the heterotrophic pathways require external sources for nutrition. It is to be noted that in Table 1, calcium sources have been considered for the precipitation. However, these chemical reactions can be harnessed to precipitate most of the divalent metal ions. Several studies have reported the application of biologically induced mineralisation for the bioremediation of soil by immobilising heavy metals such as Pb^{2+}, Sr^{2+}, and As^{2+}(Fujita et al. 2010; Achal et al. 2012; Yang et al. 2017). It is critical to comprehend their advantages and limitations to select the most favourable biocementation pathway for engineering applications.

The autotrophic pathways are underexplored for engineering applications due to the challenges observed during the laboratory simulations. The major reason for the limited studies on photosynthesis pathway for biocementation can be attributed to the substantially slow rate of precipitation along with the continuous requirement of light and CO_2 for the metabolic activity of cyanobacteria. However, it is to be noted that almost three-quarters (70%) of the carbonate rocks of the earth's crust are formed via photosynthesis (Altermann et al. 2006). On the other hand, in the methane oxidation pathway, complex microbial/enzymatic activity results in the production of formate ($HCOO^-$), which eventually leads to the generation of CO_3^{2-} in alkaline conditions (Ganendra et al. 2014; Caesar et al. 2019). The CO_3^{2-} ions precipitate with Ca^{2+} and Mg^{2+}. Further research in a controlled environment is required to determine the most suitable strategies for their emulation for in situ engineering applications.

The most common heterotrophic pathways, urea hydrolysis and denitrification, have particular advantages and limitations. Urea hydrolysis is quicker than the other heterotrophic biocementation pathways but leads to generation of harmful ammonia/ammonium (Keykha et al. 2019; Lee et al. 2019; Yu et al. 2022). The denitrification pathway is largely anaerobic, and therefore, it is viable for deep geotechnical applications; however, denitrification is a multi-step process utilising four kinds of enzymes, and the intermediate products such as nitric oxide (NO_2^-) and nitrous oxide (NO_2) are toxic (DeJong et al. 2010; van Paassen et al. 2010a). Moreover, the accumulation of the intermediate products must be carefully managed by maintaining lower concentrations of reagents. In the case of denitrification, calcium acetate and calcium nitrate are considerably soluble and have a similar precipitation rate and yield in comparison to the urea hydrolysis pathway; however, there are only a few studies based on denitrification (van Paassen et al. 2010a; Gao et al. 2022). In a recent study by Gao et al. 2022, a large-volume circulation strategy was used following the denitrification pathway and the formation of cavities due to gas bubbles was reported. The other heterotrophic pathways, including Sulphate reduction, aerobic oxidation and ammonification, are not recommended for ground improvement due to the poor solubility of reagents (van Paassen et al. 2010a; Jain et al. 2021).

Therefore, the urea hydrolysis pathway is recommended as the most suitable candidate for erosion control applications, as oxygen availability is not a concern at shallow depths. In aerobic conditions, the urea hydrolysis path has been established for its high precipitation rate, carbonate yield and ease of control (DeJong et al. 2010; van Paassen et al. 2010a).

3 Biocementation via urea hydrolysis and its potential in erosion control

The principle of biocementation via urea hydrolysis is to catalyse calcium carbonate ($CaCO_3$) precipitation with the help of microbial urease (Stocks-Fischer et al. 1999). Therefore, the urea-hydrolysis-based biocementation process is often termed microbially induced calcium carbonate precipitation (MICP). Over 5,000 microbial species are reported to possess urease enzyme and are capable of

Table 1 Biocementation pathways and the governing chemical reactions

	S.N	Pathways	Governing chemical reactions	Reported mediating microbial species	Key references
Autotrophic	1	Photosynthesis	$CO_2 + H_2O \rightarrow CH_2O + O_2$ $HCO_3 \rightarrow CO_2 + OH^-$ $Ca^{2+} + 2HCO_3^- \rightarrow \mathbf{CaCO_3}\downarrow + CO_2 + H_2O$ $Ca^{2+} + HCO^{-2} + OH^- \rightarrow \mathbf{CaCO_3}\downarrow + 2H_2O$	Cyanobacteria such as *Nostoc punctiforme, Microcoleus vaginatus, Synechococcus sp.* PCC 7002	Arp et al. (1999); Rodríguez-Martínez et al. (2012); Colica et al. (2014); Fattahi et al. (2020); Heveran et al. (2020)
	2	Methane Oxidation	**Aerobic** $CH_4 + O_2 \leftrightarrow CH_3OH + H_2O$ $CH_3OH \rightarrow CHOH$ $CHOH + H_2O \rightarrow HCOO^- + H^+$ $HCOO^- + H_2O \leftrightarrow HCOOH + OH^-$ $HCOOH \rightarrow CO_2 + 2\,H^+$ $Ca^{2+} + CO_2 + 2OH^- \leftrightarrow \mathbf{CaCO_3} + H_2O$ **Anaerobic** $CH_3^{2-} + H_2O \leftrightarrow HCO_3^-$ $CH_4 + SO_4^{2-} \rightarrow HCO_3 + HS^- + H_2O$	*Methylocystis parvus* OBBP	Arp et al. (1999); Ganendra et al. (2014); Caesar et al. (2019)
Heterotrophic	3	**Urea Hydrolysis**	$NH_2\text{-}CO\text{-}NH_2 + 2H_2O + CaCl_2 \rightarrow \mathbf{CaCO_3}\downarrow + 2NH_4Cl$	*Sporosarcina pasteurii, Bacillus Megaterium, Sporosarcina Ureae, Bacillus sphaericus, Bacillus sp.*	Stocks-Fischer et al. (1999); Ivanov and Chu (2008); Dhami et al. (2013b); Montoya and DeJong (2015); Nassar et al. (2018)
	4	Nitrate Reduction	$5Ca(C_2H_3O_2)_2 + 8Ca(NO_3)_2 \rightarrow 13\mathbf{CaCO_3}\downarrow + 8N_2 + 7CO_2$	*Pseudomonas denitrifican, Diaphorobacter nitroreducens*, *Castellaniella denitrifican*	van Paassen et al. (2010a); Erşan et al. (2015)
	5	Sulphate Reduction	$6CaSO_4 + 4H_2O + 6CO_2 \rightarrow \mathbf{CaCO_3}\downarrow + 4H_2S + 2S + 11O_2$	*Desulfovibrio sp.*, Sulphate-reducing bacteria/SRB (Anaerobic)	Alshalif et al. (2016); Tambunan et al. (2019)
	6	Aerobic Oxidation	$Ca(C_2H_3O_2)_2 + 4O_2 \rightarrow \mathbf{CaCO_3}\downarrow + 3CO_2 + 3H_2O$	*Halomonas pacifica, Halomonas venusta*	Sánchez-Román et al. (2011), van Paassen et al. (2010a)
	7	Nitrogen Cycle	$\text{Amino acid} + O_2 + CO_2 + H_2O + Ca(C_2H_3O_2)_2 \rightarrow \mathbf{CaCO_3}\downarrow + H^+$	*Myxococcus xanthus, Alcanivorax borkumensis*	Rodriguez-Navarro et al. (2003), (2012); Ben Chekroun et al. (2004)

biocementation (Tamayo-Figueroa et al. 2019). Most of these microbes are abundantly available in the soil (Hammes et al. 2003; Burbank et al. 2011).

It is to be noted that for the engineering application of MICP, the strategy for employing exogenous ureolytic microbes in soil is termed bio-augmentation, while stimulating the indigenous microbial community for biocementation is known as bio-stimulation. One of the most popular bacteria used for bio-augmentation-based MICP is *Sporosarcina pasteurii* (SP).

The mechanism of soil binding is demonstrated in Fig. 5. The ureolytic microbes get attached to soil particles due to their surface-charge characteristics and extracellular polymeric substances (Jain and Arnepalli 2020; Datta et al. 2022). The attached microbes activate upon the availability of nutrients. In the presence of a cementation media (urea and calcium source), the microbes precipitate $CaCO_3$ crystals on the surface of the soil or in the pores of the soil.

The binding of the soil usually occurs with surface coating, particle bonding/bridging and pore filling (Xiao et al. 2022). With surface coating, the interlocking and friction between soil particles improve, which provides resistance against movement and deformation. Apparent cohesion is induced with the grain bridging, and the soil densifies with pore filling, increasing the critical stress of the soil grains. Therefore, the erodibility of soil is expected to be controlled against the flow of the wind/water with biocementation treatment. Figure 6 demonstrates the micrographs from recent studies highlighting the microbes producing $CaCO_3$ crystals and soil aggregation through MICP on a micro-scale.

The efficiency of the MICP process is assessed with- 1. The rate of urea hydrolysis (k_u); 2. The rate of $CaCO_3$ precipitation (Quantity) along with their quality; and 3. Urease activity of microbe. The rate of urea hydrolysis is evaluated with a first-order differential equation, assuming that the biomass (bacterial density) doesn't vary during the urea hydrolysis as illustrated in Eq. (3) (Ferris et al. 2004; Mitchell et al. 2019).

$$\frac{d\left[\mathrm{CO}\left(\mathrm{NH}_2\right)_2\right]}{dt} = -k_U\left[\mathrm{CO}\left(\mathrm{NH}_2\right)_2\right][B] \tag{3}$$

Here $[CO(NH_2)_2]$ implies the concentration of urea, k_u denotes the first-order rate coefficient, and $[B]$ is the concentration of biomass (bacterial density). It is necessary that the saturation index (SI)

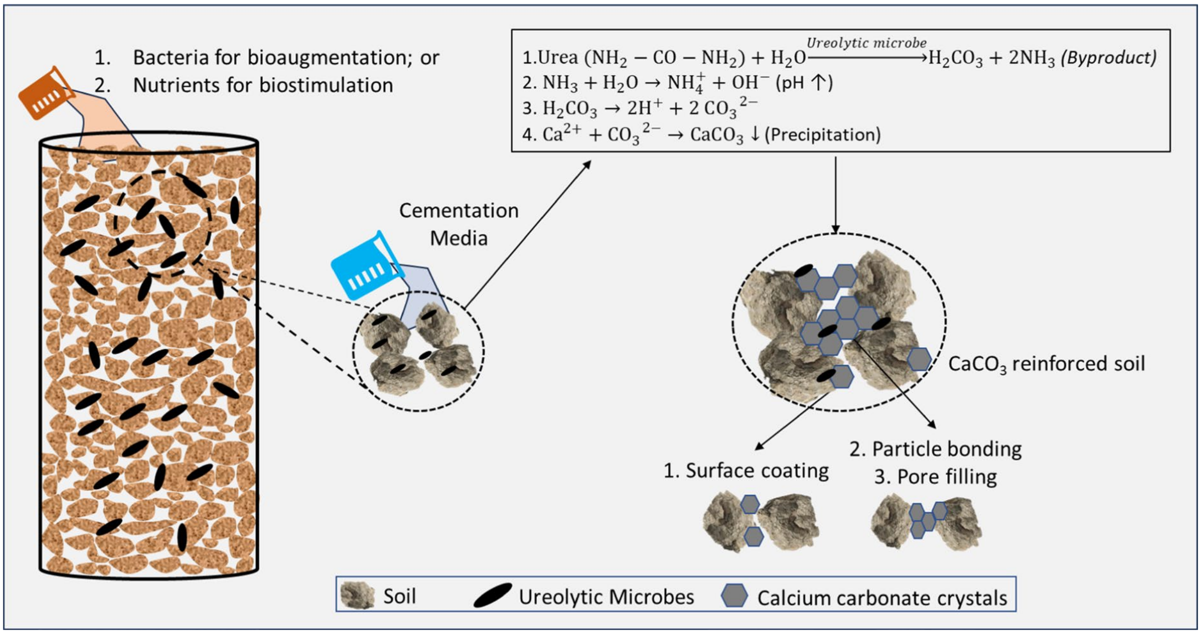
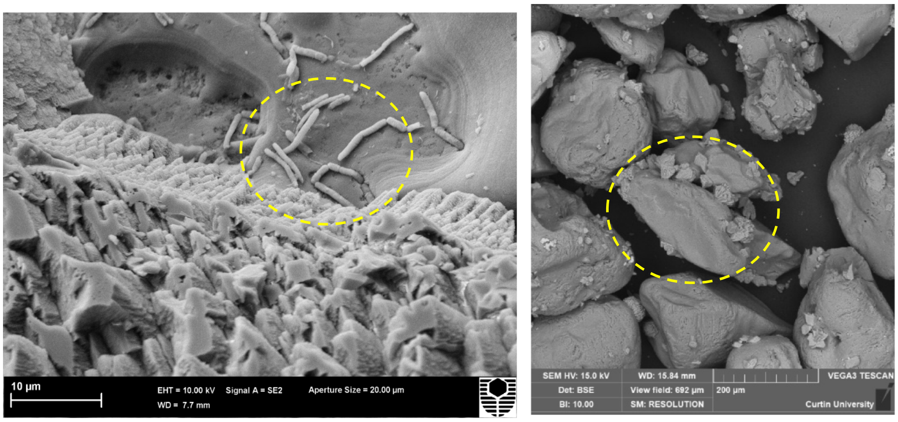


Fig. 5 Soil stabilisation with MICP



(a) (b)

Fig. 6 Soil grain bridging with MICP (Extended from Dubey et al. 2021a, b)

is greater than 1 for $CaCO_3$ precipitation (Arp et al. 1999; Dhami et al. 2013a). The saturation index is defined in Eq. (4).

$$SI = \log\Omega = \log\frac{IAP}{K_s} \tag{4}$$

IAP stands for ionic activity product, and K_s stands for solubility product.

The rate of $CaCO_3$ precipitation relies on the threshold activation energy required to move the chemical reaction forward. The rate and quantity of $CaCO_3$ precipitation is evaluated with titration method, acid washing, thermogravimetric analysis, inductively coupled plasma (ICP), X-ray diffraction (XRD), thermogravimetric analysis (TGA) and ASTM method (Choi et al. 2017). The quality of precipitates implies their morphology, microstructure, and strength. Biogenic precipitation of calcite, vaterite and aragonite polymorphs is recorded (Cizer et al. 2012; Rodriguez-Navarro et al. 2012). Calcite is identified with rhombohedral shape and epitaxial growth (Hammes et al. 2003; Cizer et al. 2012; Cuthbert et al. 2012). Vaterite is often found in cauliflower-like spheroid and is a relatively less stable polymorph than calcite (Dubey et al. 2022c). In contrast, morning-star-shaped aragonite, identified with curved prismatic faces (Mayorga et al. 2019), is rarely reported with MICP.

Ureolytic microbes reduce the threshold energy barrier through the excreted "urease enzyme" out of their cell membrane or cytoplasm. The microbial activity increases the rate of reaction up to 10^{20} times by reducing the energy barrier (Mitchell and Santamarina 2005). The reduction in the energy barrier is primarily because of the (a). metabolic activity of microbes that secretes enzymes and catalyse the reaction, and (b). the negatively charged cell walls, leading the microbes to act as nucleation sites. Urease activity is defined as the quantity of enzyme hydrolysing unit micromole of urea per minute per millilitres (Dhami et al. 2013b; Dubey et al. 2022a). Urease activity is assessed by evaluating the quantity of generated ammonia by phenol-hypochlorite method, Nessler method and electric conductivity method (Whiffin 2004; Whiffin et al. 2007; Dhami et al. 2013b).

The factors influencing the MICP process in terms of the rate of urea hydrolysis, quantity and quality of precipitates are summarised in Table 2.

The key findings from the literature recommend that MICP has the potential to work well in coarse-grained soil (0.075 mm to 4.75 mm) in environments in a pH range varying from 6 to 10 and temperature 10 °C to 50 °C. The types of microbes and their specific urease must be assessed before their application in the soil to predict their efficiency in $CaCO_3$ precipitation. However, the MICP application strategy can be strategised according to the type of soil, desired depth of penetration and rate of precipitation to overcome the limitation of geometric incompatibility of the soils with the microbes.

The majority of the proposed strategies for MICP application include injection/grouting and surface percolation/spraying for coarse-grained soils. Soon et al. (2014) investigated injection strategies with

Table 2 Factors affecting the efficiency of MICP

S.N	Factors	Key findings	Key references	Remarks
1	Type of microbes and urease activity	High urease-producing microbes precipitate smaller crystals with lower strength moduli Low urease-producing microbes precipitate larger crystals with higher strength moduli Urease activity can be controlled with microbial population	Heveran et al. (2019); Mujah et al. (2019); Konstantinou et al. (2021); Wang et al. (2021)	Bacteria with similar urease activity but different origins precipitate distinct polymorphs of $CaCO_3$ The precipitates by different microbes need to be investigated in a systematic interdisciplinary approach for better control of MICP
2	Concentration of cementation media	For equivalent $CaCO_3$ content, a lower concentration of cementation media results in higher strength Maximum precipitation efficiency and strength were observed at 0.5 M Retarding influence of concentration of cementation media above 1 M At 2.5 M, the precipitation ceases	Al Qabany and Soga (2013); Mujah et al. (2019); Lai et al. (2021); Dubey et al. (2022c)	1 L of 0.5 M cementation media can produce only 50 g of $CaCO_3$ stoichiometrically, assuming 100% conversion of reagents Optimisation of biocementation at higher concentrations of cementation media is needed to lower the number of treatment cycles for a reduction of the implementation cost and time
3	Temperature and pH	Precipitation ceases below 5 °C and above 60 °C due to the reduction in the population of microorganisms Urea hydrolysis favours an alkaline environment, optimum growth of SP was observed at pH 9.25 and maximum specific activity of the resuspended cells was observed in a pH range of 7–8	Ferris et al. (2004); Whiffin (2004); Rebata-Landa (2007); Cheng et al. (2014)	Biocementation techniques must be reconfigured, considering the native extremophiles and hyper-acidic/hyper-alkaline soil environments and site-suitable temperature ranges
4	Availability of oxygen	There is obscurity on standard biocementing microbe on being facultative anaerobic or aerobic The adaptability of the microbe to precipitate in anoxic conditions also depends on their species	Mortensen et al. (2011); Martin et al. (2012); Mitchell et al. (2019)	Facultative anaerobic and microaerophilic microbes are desired (Ivanov and Chu 2008) as they can grow and precipitate under low oxygen or anoxic (without oxygen compounds) conditions in the subsurface
5	Type of soils	The size of ureolytic bacteria is 0.5 to 3 µm (Konhauser 2007) Therefore, the biocementation technique is restricted to coarse and fine sands due to geometric incompatibility	DeJong et al. (2010); Mortensen et al. (2011); Zhu et al. (2019)	Different treatment strategies such as surface percolation, injection/grouting, mixing and spraying need to be standardised based on soil types

different pressures (0.2, 1.1 and 2 bar) for sandy soils and proposed a 1.1 bar pressure for 0.5 M cementation reagent flow for 48 h for uniform precipitation. At lower pressure, the precipitation is reported to occur close to the inlet and prohibits the flow of the reagents. Surface percolation is another method for the application of bacteria to the soil without disturbing the soil matrix. Cheng and Cord-Ruwisch (2014) reported with large-scale laboratory experiments that the surface percolation strategy is suitable for coarse-grained soil ($D_{50} > 0.3$ mm) due to its high permeability, which leads to uniform precipitation for shallow target depth. In contrast, there are limited studies on spraying strategies (Wang et al. 2018b; Zomorodian et al. 2019; Jiang et al. 2019; Chek et al. 2021) that have shown potential in mitigating the surficial erosion against wind and rainfall.

Contrarily, most of the studies on fine-clayey soil have considered a mixing strategy for the application of MICP. The field application of mixing techniques tends to be costly and non-feasible as the soil is disturbed. Cheng and Shahin (2016) utilised the bacterial suspension with urea and calcium sources and formed a bio-slurry. A high amount (more than 95%) of bio-slurry was reported to be retained in the soil, providing uniform precipitation. In a recent study, Won et al. (2021) demonstrated that a kaolinite suspension along with a biocementation solution facilitates uniform precipitation of $CaCO_3$ as the kaolinite acts as a nucleation site. Similar observations were reported with bentonite-assisted MICP (Ma et al. 2021). It is to be noted that both of the above-mentioned studies have proposed injecting clay suspension along with bacterial and cementation solutions to enhance MICP; however, that will reduce the soil hydraulic conductivity continuously with treatment, leading to clogging in the upper layers. Moreover, it is to be noted that soil is heterogeneous in nature, containing different proportions of sand, clay, and gravel. Therefore, further studies on potential strategies of MICP on fine-grained soils are necessitated.

Extensive reviews capturing the key findings and processes involved in biocementation for engineering applications such as soil strength improvement, antidesertification, liquefaction control, recycling construction and demolition wastes aggregates, mine tailing stabilisation, and metal inhibition are available in the literature (Mitchell and Santamarina 2005; De Muynck et al. 2010; DeJong et al. 2010; Barkouki et al. 2011; Phillips et al. 2013; Dhami et al. 2013a; Anbu et al. 2016; Shashank et al. 2016; Mujah et al. 2017; Tamayo-Figueroa et al. 2019; Terzis and Laloui 2019a; Castro-Alonso et al. 2019; Mistri et al. 2020; Patil et al. 2021, 2023; Sharma et al. 2021a; Jain et al. 2021; Jha 2022; Jimenez-Martinez et al. 2022; Zúñiga-Barra et al. 2022; Xiao et al. 2022; Mahabub et al. 2023; Omoregie et al. 2023; Fu et al. 2023; Harran et al. 2023; Carter et al. 2023). These review papers are brilliant in capturing up-to-date information in the field of biocementation. However, a comprehensive review specifically focussing on soil erosion control is largely unexplored. In this paper, the key findings from recent studies on soil erosion control via biocementation techniques are discussed.

3.1 Influence of MICP on wind erosion resistance of soil

In the past few years, several studies have investigated the potential of biocementation to control aeolian erosion in the laboratory-scale wind tunnel (Maleki et al. 2016; Duo et al. 2018; Tian et al. 2018; Zomorodian et al. 2019; Devrani et al. 2021; Dubey et al. 2021a; Dagliya et al. 2022). One certain advantage of MICP over conventional cementation practices is easy permeation through soil media due to the water-like viscosity of the cementation solution (DeJong et al. 2010; Dhami et al. 2013a; Ivanov and Stabnikov 2017). The key findings on aeolian erosion mitigation with MICP in literature are summarised in Table 3.

The erosive stresses (τ) on the soil due to wind action can be calculated in Eq. (5) (Bagnold 1984)-

$$\tau = \rho_a \left(v_D\right)^2 \tag{5}$$

Here, ρ_a is the density of air, and v_D is the drag velocity. The critical wind velocity (v_c), often termed threshold wind velocity (in m/s), that induces stresses equivalent to Critical stresses (τ_c) can be estimated for cohesionless soils from Eq. (6) (Bagnold 1984; Ravi et al. 2006; Hamdan and Kavazanjian 2016).

$$v_C = A\sqrt{\frac{(\rho_s - \rho_a)}{\rho_a} gd} \tag{6}$$

For cohesive soil, the critical wind velocity (Ravi et al. 2006) is proposed as follows-

Table 3 Key findings in the literature on aeolian erosion control with MICP treatment

Reference & area of Study	Micro-organism	Urease activity & (O.D.$_{600}$)	Urea & CaCl$_2$ (Number of cycles)	CaCO$_3$ content (in %)	Type of soil (D$_{50}$ in mm)	Major findings
Maleki et al., (2016) -Yazd Desert, Iran	SP PTCC 1645	2.2 mM/Litre/Minute (1.5 g /l dry)	0.1–1 M Urea and CaCl$_2$ (1)	NA	Desert sand (NA)	More than 95% of soil erosion is controlled against wind velocity of 55 km with a developed crust having a penetration resistance ≥ 50 kPa
Duo et al. (2018) & Tian et al. (2018) -Tengger Desert, China	SP ATCC 11859	8.62 mM/Litre/Minute (≈1.9)	0.5–2.5 M Urea and CaCl$_2$ (8)	10–19.5	Fine sand (0.15)	No erosion was observed for samples treated with three cycles of 0.5 M cementation solution against a wind velocity of 16 m/s. (Tian et al. 2018) A high UCS value of 18 MPa is obtained with 19.5% CaCO$_3$ content (Duo et al. 2018)
Li et al. (2018) -Kubuqi Desert, China	SP ATCC 11859	NA (0.5–0.8)	0.5 M Urea and CaCl$_2$ (NA)	NA	Mixture of desert and silica sand (0.17–0.90)	Samples were treated continuously in a batch reactor for seven days The maximum UCS (780 kPa) was observed with a 0.5 O.D.$_{600}$ of bacterial density For a well-graded mixture of aeolian sand and silica sand, maximum friction angle (ϕ) was observed around 44° at bacterial O.D.$_{600}$ = 0.5

Table 3 (continued)

Reference & area of Study	Micro-organism	Urease activity & (O.D.$_{600}$)	Urea & $CaCl_2$ (Number of cycles)	$CaCO_3$ content (in %)	Type of soil (D_{50} in mm)	Major findings
Zomorodian et al. (2019) -Khormoj, Iran)	SP PTCC 1645	NA (1–2.5)	0.5 M Urea and $CaCl_2$ (1)	NA	Three types of sand (0.20 to 0.28)	Soil erosion ceased against wind velocity of 20 m/s with 0.5 M cementation solution, O.D. $_{600}$ = 1.5, and 28 days curing at 28℃ The strength of the crust was reported 39 kPa for silica sand and 69 kPa for silty carbonate sand
Devrani et al. (2021)-Thar Desert, India	*B. megaterium* NCIM 5472	250 U/ml (≈0.8)	0.25 to 1 M Urea and $CaCl_2$ (1)	1.94 to 4.1	Fine sand (0.15)	Wind erosion ceased for soil specimens with 2.97% calcium carbonate or with 0.25% Biopolymer treatment against 45 km/h wind velocity
Dubey et al. (2021c) - Thar Desert, India	*P. auburnensis* (Isolated from Vegetation rich soil)	2.45 mM urea hydrolysed/minute pe/OD_{600}	0.25–1 M Urea and $CaCl_2$ (1)	0.5–2.1	Fine sand (0.16)	Erosion nearly ceased at a $CaCO_3$ content of 1.1% with a 0.5 M cementation media against a wind velocity of 55 km/h

$$v_C = A\sqrt{\frac{(\rho_s - \rho_a)}{\rho_a} gd} \cdot \sqrt{1 + \frac{F_c.B}{(\rho_s - \rho_a)gd^3}} \quad (7)$$

Here, ρ_s and ρ_a denote the density of sand particles and air (in kg/m^3), g is the gravitational acceleration (9.81 m/s^2), and "*d*" stands for the diameter of the particles in Eq. (7). A is a dimensionless parameter that depends on the shape factor, drag coefficient and ratio of the moment arm lengths to the soil grain diameter. F_c stands for interparticle cohesive forces, and B is a parameter depending on the shape factor of the particles. These equations can be useful to simulate the aeolian erosion in a wind tunnel and comprehend the mechanics of erosion control. With biocementation, the soil grains are bridged together, as illustrated in Figs. 5 and 6b. Therefore, the effective diameter of the soil grains enlarges, and the threshold detachment velocity improves. Apart from this, MICP treatment also imparts interparticle binding forces.

The threshold frictional velocity for fine desert sandy soil is reported to be around 20 km/h (Dubey et al. 2021a), which matches the theoretical value estimated from Eq. 5. Chen et al. (2016) reported that the desert soil from North Xinjiang, China, was able to withstand wind erosion even after 12-day exposure to freeze–thaw cycles. The existing studies have suggested that a low $CaCO_3$ content of up to 4% can cease erosion against wind velocity of up to 45–55 km/h (Zomorodian et al. 2019; Dubey et al. 2021a). However, the threshold frictional velocity is difficult to determine for heavily biocemented soil due to the instrumental limitation of the generation of higher wind velocities (Dubey et al. 2021a). Nonetheless, there are several challenges associated with the filed-scale implementation and durability of MICP treatment for aeolian erosion mitigation.

With a large-scale experiment, Gomez et al. (2015) reported no deterioration after 44 days and moderate degradation after 298 days, withstanding a harsh winter season in the biocemented crust containing 2.1% $CaCO_3$ content formed with low-concentration cementation solution (10^8 cells/litre SP, 15 g/l urea and 13.875 g/l $CaCl_2$) in a mine site in dryland of the province of Saskatchewan, Canada. In other field-scale trials conducted in the Ulan Buh Desert of China, Meng et al. (2021a, b) reported that a soil crust of 1.25 cm and $CaCO_3$ content of 0.57% withstood a wind velocity of 30 m/s and the depth of erosion was almost zero even after 30 days of exposure to the harsh local desert environment. They reported a 0.2 M equimolar urea and $CaCl_2$ treatment with an application rate of 4 L/m^2 for optimum plant growth. A deteriorating influence of higher concentration cementation media is observed, and therefore, plant-growth-promoting rhizobacteria (PGPR) must be investigated (Coban et al. 2022) for biocementation applications. However, it is to be noted that the water requirement for biocementation in deserts and drylands is a formidable concern apart from the harsh weather.

It is worth noting that the total water requirement for one cycle of 1 M biocementation treatment can be as high as 48 L/m^2, resulting in 1.75% $CaCO_3$ content and a 3.5 cm crust depth (Dubey et al. 2021a). The formed crust could withstand a wind velocity of up to 55 km/h without any detachment. Extensive future research is required to standardise the treatment procedures for design purposes considering these factors.

The key learning from the literature on aeolian erosion control with biocementation is as follows-

- A biocemented soil crust of 2 to 3 cm containing $CaCO_3$ content in the range of 2% to 4% is capable of controlling soil erosion against wind velocity up to 55 km/h.
- A major challenge in the desert environment for biocementation treatment is the harsh environment for microbes and water scarcity. Therefore, the local microbial community's adaptability to desert environments and protocols with low-water demands must be investigated.
- The studies have not considered the disastrous case of dust storms where wind velocities can rise up to 150 km/h due to instrumental limitations of the wind tunnel. These events must be investigated in future studies in the field via pilot-scale investigations.

3.2 Influence of MICP on hydraulic-erosion resistance of soil

Similar to aeolian erosion, the detachment of soil particles with water occurs when the applied erosive stress exceeds the critical stress of the soil. Briaud (2008) proposed that the critical velocity of cohesionless soil is dependent on particle diameter and can be estimated from Eq. (8).

$$v_C = 0.35(D_{50})^{0.45} \quad (8)$$

v_c (m/s) stands for critical flow velocity, and D_{50} is the mean diameter of cohesionless soils (in mm). In the case of the cohesive soils of particle size lesser than 100 microns, the following Eqs. (9 and 10) are proposed by Briaud (2008) as lower and upper bounds-

$$v_C = 0.1(D_{50})^{-0.2} \quad (9)$$

$$v_C = 0.03(D_{50})^{-1} \quad (10)$$

The erosive stresses (τ) on the wall of an open channel, such as a flume, can be calculated from Eq. (11) (Briaud 2013; Clarà Saracho et al. 2021a).

$$\tau = \frac{1}{8}\varphi.\rho_w v^2 \quad (11)$$

Here, φ (friction factor) is a function of the flow regime and can be estimated with the help of pipe roughness, and Reynolds number and v is the velocity of the hydraulic flume. These equations can be used in designing the experimental flow velocity to simulate natural conditions in the hydraulic flume. Biocementation improves interparticle locking, and the effective particle diameter enlarges with bridging. Therefore, erosion can be controlled with biocementation. The key findings from the literature on hydraulic erosion mitigation via biocementation have been summarised in Table 4.

The soil erosion for riverlike tangential flow-induced erosion is usually investigated in an erosion function apparatus (EFA) or hydraulic flume. Amin et al. (2017) demonstrated the different injection strategies with and without aeration to ensure uniformity in calcium carbonate precipitation and reported that the critical shear stress increased five-fold upon MICP treatment with aeration in an EFA. Wang et al. (2018a, b) have investigated the efficiency of polyvinyl alcohol-modified MICP treatment and reported that the synthetic polymer is useful in anchoring the $CaCO_3$ crystals and, thus, provides better control over erosion. Clarà Saracho et al. (2021a) reported that although biocementation can cease soil erosion against the tangential flow with ten cycles of 0.08 M cementation solution, the treated specimen cracks along with the tangential flow due to brittleness.

The above-discussed studies have considered the bio-augmentation approach for soil treatment. Transporting the microbes to the site following the proposed strategies might be a challenge. On the other hand, the bio-stimulation-based approach employing indigenous soil microbes can tackle the challenge of bacteria transport; however, this domain is relatively underexplored in the context of mitigating riverbank/coastal erosion. Behzadipour and Sadrekarimi (2021) have investigated the direct shear strength characteristics of the sand from the Karoon riverbank of southwest Iran upon biochar-assisted MICP via native strains without identification of the microbial diversity. In another study, six biocementation potent strains were isolated from the banks of the Brahmaputra River of Assam Valley of India (Dubey et al. 2021c, b). The strains shared significant genomics similar to the conventionally used microbe SP. The studies concluded that soil erosion could be reduced significantly with a biostimulation approach. The stimulation approach minimises the risk of biodiversity contamination with external microbes and can be helpful in reducing the transportation cost of microbes.

The coastal erosion scenario is often investigated in a hydraulic flume. The biocemented soil specimens are tested against hydraulic waves of a specific frequency and amplitude. Shahin et al. (2020) observed that less than 5% erosion occurs for a sample containing 1.52% $CaCO_3$ content withstanding erosional waves of height 6.9 cm and wavelength 23 cm for two hours. Contrastingly, Kou et al. (2020) demonstrated erosion ceases for a soil specimen having 30.1% $CaCO_3$ content against the waves of 4 cm amplitude and frequency of 1 cycle per minute for a 30-min test. Interestingly, Liu et al. (2021) reported that two cycles of MICP treatment were inefficient in preventing erosion for a 2-h test duration without quantifying the precipitated calcite content. Behzadipour and Sadrekarimi (2021) reported that negligible erosion occurred in a physical riverbank model treated with 20 cycles of biochar-assisted biocementation treatment against 600 strong waves. It is evident from these studies that the number of cycles of biocementation treatment, i.e., the quantity of $CaCO_3$ precipitates, is one of the deciding factors in controlling erosion. Moreover, these studies have reported

Table 4 Key findings in the literature on hydraulic erosion mitigation with MICP

Reference & subject of study	Urea & $CaCl_2$ (no. of cycles)	$CaCO_3$ content (w/w %)	Type of Soil (D_{50} in mm)	Major findings
Salifu et al. (2016) Tidal flow-induced erosion	0.7 M urea and $CaCl_2$ (18)	≈10%	Fine sand (0.33)	The MICP-treated soil (9.9% pore volume filled with $CaCO_3$) exhibited almost no erosion for a slope of 35° and 53° against 30 tidal cycles
Jiang and Soga (2017) Internal erosion	0.2–2 M of Urea and $CaCl_2$ (1)	0–0.95	Gravel-sand blend (1)	At least 0.28% $CaCO_3$ was suggested for erosion control against a water pressure up to 50 kPa
Amin et al. (2017) Surficial- erosion	0.5 & 0.75 M of Urea and $CaCl_2$ (1–2)	2.7–8	Fine sand(0.28)	The soil treated with two cycles of 0.5 M cementation solution with aeration with 6-day drainage resulted in 6.1% $CaCO_3$ and 95% reduction in erodibility coefficient
Wang et al. (2018a, b) Tangential flow-induced erosion	0.5–1.5 M of Urea and $CaCl_2$ (1)	1.3–2	Fine sand (0.33)	PVA polymer-modified 1 M cementation solution was suggested for erosion control
Jiang et al. (2019) Rainfall-induced erosion	0.2 M,1 M and 2 M of Urea and $CaCl_2$ (4)	NA	Fine sand (0.23)	2 M cementation solution was found to be not effective against erosion Maximum erosion resistance was observed with a 1 M cementation solution
Chung et al. (2021) Rainfall-induced erosion	0.45 M Urea and $CaCl_2$ (1–13)	0–12%	Sand and sandy loam (multiple)	Soil erosion rate (g/m^2-minute) almost ceases for MICP stabilised slope up to 15° against rainfall intensity up to 75 mm/hour with more than three cycles of treatment on the sand and more than five treatment cycles for the sandy loam
Shahin et al. (2020) Coastal erosion	1 M Urea and $CaCl_2$ (1–2)	0–1.52%	Medium sand (0.4)	1.52% $CaCO_3$ with 2 treatment cycles of 1 M cementation solution can cease the wave-induced erosion for a 2-h test duration
Kou et al. (2020) Coastal erosion	1 M Urea and $CaCl_2$ (1 to 4)	0–30%(residual)	Qingdao Sea sand (0.75)	With 2 to 4 cycles of MICP treatment, soil erosion reduced to less than 50%
Clarà Saracho et al. (2021a, b) Tangential flow-induced erosion	0.02–0.1 M Urea and $CaCl_2$ (10)	0.4–2%	Fine and Coarse sand (0.21& 1.61)	A treatment with 0.8 M cementation solution brings down the soil erosion to a legible level for surficial flow ranging from 0·033–0·18 m/s

Table 4 (continued)

Reference & subject of study	Urea & $CaCl_2$ (no. of cycles)	$CaCO_3$ content (w/w %)	Type of Soil (D_{50} in mm)	Major findings
Liu et al. (2021) Coastal erosion	0.5 M urea and 0.25 M $CaCl_2$ (1–2)	NA	Calcareous sand (≈0.7)	Both MICP and EICP (Enzyme-induced carbonate precipitation) were observed to be not effective for long-term (2 h) big wave (0.8 cm) attacks

the erosion characteristics against the wave features such as dimension, frequency and test duration. In a recent study by Dubey et al. (2022a), it was determined that the tangential and perpendicular waves to the shoreline have different responses in terms of erosion. While a $CaCO_3$ content of 98 mg/g-sand was sufficient to cease erosion against the wave energy density of 6 J/cm^2, in the case of tangential waves, an equivalent biocemented sand eroded more than 40% at the wave energy density of 5.3 J/cm^2. For upscaling the laboratory results to the field, further studies considering natural wave energy at coasts, temperatures and saline environement are needed.

Biocemented soil slopes have also been investigated in the case of rainfall-induced soil erosion (Jiang et al. 2019; Sun et al. 2022a; Chung et al. 2021; Wang et al. 2023). A rainfall simulator is used to investigate the resiliency of biocemented soil against erosion. Jiang et al. (2019) reported that a high concentration of cementation solution (2 M) could be detrimental to the $CaCO_3$ precipitation. At the same time, Chung et al. (2021) demonstrated that in the presence of high organic content in soils, the MICP treatment for erosion mitigation is less effective compared to sandy soil with lower organic content. Although several attempts have been made to investigate the efficiency of biocementation in the mitigation of hydraulic-induced erosion, there is a large gap to fill to come up with datasets that can be useful for standardising the treatment process similar to concrete design standards.

The key learning from the literature on hydraulic-erosion control studies with biocementation can be encapsulated as follows-

- The erosion tests on biocemented soils reveal notable improvements in the erodibility parameters (erosion rate and critical stress) with the biocementation treatment. A $CaCO_3$ content in the range of 2–12% in the shallow depth of soils around 10 to 20 cm is suggested in the above-discussed studies to mitigate the hydraulic-induced erosion by different environmental events such as rain, tangential flow (rivers) and coastal waves.
- However, the studies in the literature are broad and fundamental quantification and mechanism of erosion parameters for different types of soils, different erosive forces and different levels of biocementation are still obscure.

- Application of biopolymer to assist biocementation is recommended to tackle the challenge of non-uniform $CaCO_3$ precipitation in heterogeneous soil matrix to the desired depth. Moreover, the application of biocementation is only possible in dry conditions in the wetlands to avoid the dilution of bacteria and cementation media that could result in insufficient precipitation.

3.3 Influence of MICP on permeability and strength of soil

Although a direct relationship between the strength of soils and erosion resistance is not established, the erosion resistance of the soil is assumed to be improving with an increase in the strength of the soil, primarily because both the parameters improve with soil binding. Nevertheless, it is critical to assess the behaviour of soils upon biocementation in terms of the fundamental parameters such as permeability and strength for their geotechnical applications. The key findings from the literature have been summarised in Table 5.

It is to be noted that a one to two-order decrease in hydraulic conductivity of soil (specifically fine sand) has been reported in literature upon MICP treatment (Al Qabany and Soga 2013; Chu et al. 2014; Cheng and Shahin 2016; Ma et al. 2021). With a high calcite content of 14% and unconfined compressive strength of around 1000 kPa, the maximum reduction reported in the literature is less than one order (Cheng et al. 2013; Jain and Das 2023), indicating that biocementation treatment is capable of retaining the high permeability of granular material while imparting strength. It is an obvious advantage over the traditional soil stabilisation methods such as lime or cement-based soil improvement, which clog the pores, resulting in a minimum reduction of 2–3 orders of permeability (Karol 2003; Cheng et al. 2013). Enhancement in soil strength without clogging the soil pores is one of the desirous as allowing drainage of pore liquid (Mujah et al. 2017) limits the generation of excess pore water pressure and risks of soil and foundation failure.

Several studies have reported substantial improvement in soil strength via MICP, as mentioned in Table 5. Most of these studies have utilised injection strategy for treatment and evaluated soil strength via UCS and triaxial tests. An unconfined compressive strength in the range of 1 to 5 MPa is reported in the literature, with $CaCO_3$ content in the range of 5–10%, with a few exceptions (Al Qabany and Soga 2013; Terzis and Laloui 2019a; Mori and Venkata Uday 2022). The disparity in the UCS findings is attributed to the location of $CaCO_3$ precipitates, mineralogy of soils and precipitates, degree of saturation and the density of the soils. The maximum UCS strength is around 12 MPa with 27% $CaCO_3$ content in fine sands of a mean diameter of 0.17 mm (van Paassen et al. 2010b). On the other hand, Terzis and Laloui (2018) reported a UCS strength of up to 11.3 MPa for fine sands of a mean diameter of 0.3 mm. Primarily, it was assumed that the strength of MICP-treated soil is dependent on the quantity and mineralogy of precipitates. However, Cheng and Shahin 2016 reported that the location of precipitate in the soil matrix plays a vital role in the development of strength. They reported that treating specimens with 30% pore volumes of biocementation treatment may result in optimum strength.

Drained and undrained triaxial tests have also been conducted extensively for biocemented soils. Both friction angle and cohesion are reported to improve substantially with biocementation. In a recent study, Wu et al. (2021) proposed that the effective friction angle of the biocemented soil improves only up to 5% $CaCO_3$ precipitation. While investigating fine sand in $CaCO_3$ precipitation ranging from 0 to 14.25%, it was reported that the shear strength of biocemented sand above 5% $CaCO_3$ content rises only due to enhancement in cohesion. The study also reported an increase in the dilatancy behaviour of sand with the increase in $CaCO_3$ content. The improvement in the shear modulus of soil can also be measured non-destructively with bender elements, which could also be installed in triaxial instruments. In one of the studies, the shear wave velocity (v_s) was found to improve from 107 to 395 m/s when $CaCO_3$ content varies from 12 to 27% (van Paassen et al. 2010b). In another study, Montoya and DeJong (2015) reported that the shear wave velocity of MICP-treated fine sand improved from 190 to 1400 m/s for heavy cementation with 5.31% calcite content. The differences in their findings are influenced by the confinement conditions and type of soil. In a large-scale test on biocementation with stimulation and augmentation approaches, Gomez et al. (2017) reported that the shear wave velocity improved from 107 to 1028 m/s for MICP-treated sand and a maximum $CaCO_3$ content of 5.3%.

Table 5 Key findings in the literature on the improvement of soil strength

Reference	Micro-organism	Urease activity & (O.D.$_{600}$)	Urea & $CaCl_2$ (Number of cycles)	$CaCO_3$ content (w/w %)	Type of Soil & (D_{50} in mm)	Improvement after treatment					Remarks
						K_{sat} in 10^{-5} m/s	UCS in kPa	Shear strength parameter		V_s (m/s)	
								c’	ϕ’		
van Paassen et al. (2010b)	SP DSM 33	1.1 M urea/litre/hour (NA)	1 M Urea and $CaCl_2$ (10)	12–27	Fine sand (0.17)	NA	700 to 12,400	NA	NA	107–395	A Large-scale experiment was conducted on a 100 m^3 sample
Al Qabany and Soga (2013)	SP ATCC 11859	NA (0.8–1.2)	0.1–1 M Urea and $CaCl_2$ (multiple)	0–8	Fine sand (0.15)	15–1	0–3000	NA	NA	NA	At lower concentrations of cementation media with injection strategy, uniform precipitation was observed
Cheng et al. (2013)	*B. sphaericus* MCP-11	10 U/ml (1.5–2.0)	1 M Urea and $CaCl_2$ (multiple)	1–14	Fine & Medium sand (0.23 & 0.70)	9 to 2 (fine) 45 to 10 (medium)	150–2300	0–290 kPa	23°–40°	NA	Soil was treated at various levels of saturation Optimum strength was observed at 30% saturation
Montoya and DeJong (2015)	SP ATCC 11859	NA (0.8–1)	333 mM Urea & 50 mM $CaCl_2$ (6–16)	0–5.31	Ottawa 50–70 Sand (0.22)	NA	NA	NA	33°–44°	190–1400	Samples were treated in a triaxial apparatus with constant monitoring by bender elements

Table 5 (continued)

Reference	Micro-organism	Urease activity & (O.D.$_{600}$)	Urea & $CaCl_2$ (Number of cycles)	$CaCO_3$ content (w/w %)	Type of Soil & (D_{50} in mm)	Improvement after treatment					Remarks
						K_{sat} in 10^{-5} m/s	UCS in kPa	Shear strength parameter		V_s (m/s)	
								c'	ϕ'		
Terzis and Laloui (2018)	SP ATCC 11859 lyophilised	104 mM urea/litre/hour -Rehydrated	1 M	3–10	Fine sand (0.19 & 0.30)	NA	0–11300	NA	NA	NA	A cell-free mechanism for MICP was proposed that reduces the costs
Mujah et al. (2019)	*Bacillus sp.* (Isolated in a prior study)	8.3 to 32.1 U/ml (1.2–4.46)	0.25 to 1 M	0–8.5	Fine sand (0.23)	NA	0–4000	NA	NA	NA	32 U/ml urease and 0.25 M of cementation solution resulted in maximum UCS
Wu et al. (2021)	*Bacillus sp.* (Isolated in a prior study)	2–4 mM urea/minute (1.2)	1 M urea and 0.75 M $CaCl_2$ (10–40)	0–14.25	Ottawa 30–100 Sand (0.30)	NA	NA	0–550 kPa	33°–44°	NA	The increase in shear strength was attributed to an increase in effective cohesion as friction increased only up to 5% $CaCO_3$

Although researchers have demonstrated that the MICP treatment can be monitored through bender elements, more insights are required for predicting the relationship between shear wave velocity, $CaCO_3$ content, strength parameters and intrinsic properties of soil.

Another approach for measuring the magnitude of improvement in soil strength upon biocementation is determining the local strength at various points of the formed crust of soil is the needle penetration test (Ulusay et al. 2014; Dipova 2018; Sun et al. 2022b; Dubey et al. 2021c, 2021b, 2022b; Chung et al. 2021; Ramachandran et al. 2022). The benefit of using needle penetration tests is that they can be conducted on various points to measure the deviation in the improvement in soil properties upon biocementation, specifically in the case of spraying strategy. The existing studies established that the needle penetration index (NPI) improves to around 25 N/mm for 54.5 ± 3.6 mg $CaCO_3$ per gram of sand before plateauing for 150–500 µm sand (Chung et al. 2021). However, a linear relationship between $CaCO_3$ content and needle penetration index was observed up to 100 mg of $CaCO_3$ per gram of 75–425 µm sand (Dubey et al. 2021c, 2022b). The disparity in the findings is expected due to the different gradation of soils and treatment strategies used. Bender elements are relatively costly alternatives for non-destructively evaluating soil strength. The needle penetrometer can provide a cheaper, non-destructive alternative for monitoring the soil strength of the developed crust. Therefore, further research to establish a correlation between needle penetration index and $CaCO_3$ content is necessary.

The key findings from the literature on the permeability and strength of biocemented soils are as follows-

- Biocementation treatment is capable of retaining the high permeability of granular materials while improving the strength substantially. This is a clear advantage as it minimally intervenes with the natural groundwater flow paths and allows easy release of excess pore pressure, limiting the risks of soil failure.
- The UCS of soil is reported in the range of 1–5 MPa, corresponding to $CaCO_3$ content in the range of 5–10%, with a small number of exceptions. The inconsistency in the UCS findings is attributed to the location of $CaCO_3$ precipitates, mineralogy of soils and precipitates, degree of saturation and the density of the soils.
- The cohesion and friction angle of soils improves substantially upon biocementation. Overall, the friction angle is reported to improve from 33° to 44° upon a 5% $CaCO_3$ precipitation in fine sand (Montoya and DeJong 2015; Wu et al. 2021). The increase in the strength above 5% $CaCO_3$ content is attributed to an increase in cohesion value only.
- Other tools, such as bender elements and needle penetration tests, are found to be promising for the measurement of strength improvement of biocemented soils non-destructively. The transition of soils from granular materials ($100\ m/s < v_s < 200\ m/s$ and almost no needle penetration resistance) to a soft-rock-like behaviour ($v_s > 1000$ m/s and NPI of 25 N/mm) can be captured with the real-time monitoring of biocementation treatment.

4 Challenges in upscaling and future perspective of biocementation technique

Extending laboratory knowledge of biocementation techniques to the field is the most formidable challenge. Many peers consider that biocementation can never replace the conventional grouting system (DeJong et al. 2013), which is rational as, in the current state of knowledge, there is uncertainty over its service life, monitoring tools and durability. The upscaling concerns are due to (a). The by-product ammonia/ammonium; (b). Non-uniform distribution; (c). Durability; (d). The possible interaction of biocementation media with pore fluid/organic matter; (e). Actual carbon footprint; and (f). High cost of MICP due to chemical grade pure reagents. The challenges with the upscaling of biocementation and the recent advances for tackling them are discussed in Table 6.

In summary, there is ongoing research to reduce ammonia by zeolites, struvite precipitation and urea replacement with asparaginase (Li et al. 2015; Keykha et al. 2019; Gowthaman et al. 2022). Non-uniform precipitation could be tackled with polymer composite treatment (Wang et al. 2018a; Dubey et al. 2021c, 2022b) and low-concentration cementation solutions (Al Qabany and Soga 2013; Cheng et al. 2019; Mujah et al. 2019). The existing pore liquid and organic matter present in the soil matrix can hinder the precipitation, and therefore, there might be a need to investigate and pump them out (Patil et al. 2021; Chung et al. 2021). A promising permanence of biocement treatment was reported through freeze–thaw and acid rain tests (Cheng et al. 2013; Sharma et al. 2021b); however, its service life has not been quantified yet. In addition, it is established that MICP is not a net-zero carbon footprint technique due to the inherent CO_2 associated with the chemical-grade urea and $CaCl_2$ in lab-scale investigations (Porter et al. 2021). Therefore, it is critical to investigate natural sources and waste resources as an alternative for chemical reagents that are used in MICP (Choi et al. 2016; Røyne et al. 2019; Gowthaman et al. 2021; Meng et al. 2021b).

Furthermore, the most obvious cause limiting the upscaling of MICP is the associated cost. Ivanov and Chu (2008) reported that the cost of materials for biocementation treatment could vary from 0.5 to 9 US$/$m^3$, which is competitive with the cost of existing grout material (2–72 US$/$m^3$) such as sodium silicates, polyurethane, and acrylamides. In contrast, the estimates are also reported in a wide range of 25–500 US$/$m^3$ (DeJong et al. 2013). These estimated costs are in vast range due to the uncertainty in labour, electricity and transport costs. A recent study revealed that biopolymer-biocement composite material cost could vary from US$4.6 to US$9 for a 5 cm target depth depending upon the concentration of cementation reagents and biopolymer (Dubey et al. 2022b). The material cost could be further brought down by the recommended strategy in Table 6. However, to establish a fair estimation and optimisation of cost, a collaborative interdisciplinary field-scale investigation must be conducted.

Developing an end-user standard procedure is of critical importance for the unanimous acceptance of biocementation technique by policymakers and the public. Unlike the mixed design of concrete with the standard grades of cement used in retaining walls/abutment that prevents erosion, the proposed biocementation technique has many discords in application parameters and strategies such as (a). The ratio of the volume of bacterial solution to cementation solution, (b). The optimum concentration of bacterial solution/urease and cementation media, (c). The number of treatments, (d). The retention time for each cycle, and (e). Different application strategies. It must also be noted that proper safety training must be provided to the students and researchers working in the biostimulation field, as many pathogenic ureolytic microbes, such as *Mycobacterium tuberculosis*, are abundantly available in the soil (Velayati et al. 2015). Furthermore, it is recommended that the final end-user product for employing the biocementation technique should be designed in a non-hazardous powder or liquid form with conveniently transportable packaging to the end users.

In the context of erosion control with biocementation technique, there are several practical challenges against upscaling in different terrestrial environments such as deserts, riverbanks, and seashores, as illustrated in Fig. 7. They key aspects learnt from literature review to effectively mitigate erosion has also been captured in Fig. 7 in terms of cementation media concentration (Urea/Ca^{2+}) and recommended $CaCO_3$ content. Future studies must consider these challenges to devise a strategic approach for the different terrestrial environments.

The parameters such as suitable range of cementation media concentration, target depth of treatment, target range of $CaCO_3$ content and number of treatment cycles have been summarised in Table 7. It is to be noted that the recommended range is based on previous literature, and they might be refined further based on future research. The common recommendation for all the landforms is to work with plant-promoting microbes, strategies for ammonia reduction, and cost optimisation for field application.

There is very limited literature on field-scale investigations based on biocementation. van Paassen (2011) reported the first pilot study for the stabilisation of gravel to support horizontal directional drilling for a gas pipeline in the Netherlands in collaboration with contractors Visser & Smit Hanab. Despite several flushes, the calcite precipitation was heterogeneous; however, improvement in shear strength was significant, and the horizontal drilling was successful. Fujita et al. (2010) and Smith et al. (2012) reported a successful biostimulation operation to immobilise heavy metals, strontium-90, along with calcium carbonate, in the field. In contrast, in a recent study, Zeng et al. (2021) reported no significant improvement in the cone penetration resistance upon MICP treatment of three plots, each of 125 m^3 via injection strategy and reasoned it with the heterogenous profile

Table 6 Challenges for upscaling MICP and recent advances

Challenges	Reasons/consequences	Assessment and recent advances to tackle the challenges	References
Ammonia/ammonium	The urea-hydrolysis process essentially generates ammonia Harmful to aquatic and human life if ammonia is in excess concentration (> 0.5 mg/l) in drinking water	Struvite-based precipitation Asparaginase-based MICP process Filtering through zeolite Single-phase all-in-one low-pH solution Post-treatment rinsing with high pH and ionic solution (200 mM $CaCl_2$, pH ≈10.0)	Li et al. (2015); Yu et al. (2016); Cheng et al. (2019); Keykha et al. (2019; Lee et al. (2019); Konstantinou et al. (2021)
Non-uniformity	Non-uniform bacteria distribution Geometric incompatibility of fine soils (clays) to permeate microbes due to restricted pore throat (< 0.2 μm)	Bacterial fixation solution, including polymers Low-urease activity microbes Injectable urease-active bioslurry Cell-free biocementation Hydrogel-encapsulation of microbes	Harkes et al. (2010); Cheng et al. (2019); Terzis and Laloui (2019b); Clarà Saracho et al. (2021b); Dubey et al. (2021c)
Durability/ permanence	$CaCO_3$ is soluble in an acidic environment The durability of biocementation might be influenced by rain (pH < 6) Degradation due to seasonal thermal variations	There is no evident change in strength with a five-year-equivalent rainfall (1000 mm/year) simulating acid rain (pH 3.5) Biocemented specimens (with 9–12% $CaCO_3$) retain 90% of strength after 10 freeze–thaw cycles	Cheng et al. (2013); Sharma et al. (2021b)
Interaction with existing pore fluid/ organic matter	Organic matter and pore fluid may hinder the biocementation process High concentration cementation reagent influence on soil fertility/crop-productivity	Dissolved organic matter negatively impacts bacterial growth and precipitates small $CaCO_3$ crystals Higher concentration of cementation reagents leads to inhibition of plant/vegetation growth	Patil et al. (2023); Meng et al. (2021a); Chung et al. (2021); Ghasemi and Montoya (2022a)
Actual CO_2 footprint	MICP is not a net-zero carbon emitting technique due to the use of chemical-grade pure reagents in cementation solution	Alternatives such as waste resources for nutrients, urea and calcium must be considered for biocementation, which can lead to 82% reduction in total carbon footprint	Porter et al. (2021)
Cost	Bacterial transport and maintenance cost for large quantities for field application Reagents' cost Operational cost for large-scale application Requirement of skilled labour due to biosafety concerns	Biostimulation approach to reduce transport and maintenance cost of microbes Use of abundant raw resources (such as limestones), industrial waste (slags, mine tailings) and municipal waste (kitchen waste, eggshells) for urease, calcium, and urea	Burbank et al. (2011); Choi et al. (2016); Røyne et al. (2019); Kaur et al. (2021); Meng et al. (2021b); Dubey et al. (2021b); Feng et al. (2023); Yu et al. (2023)

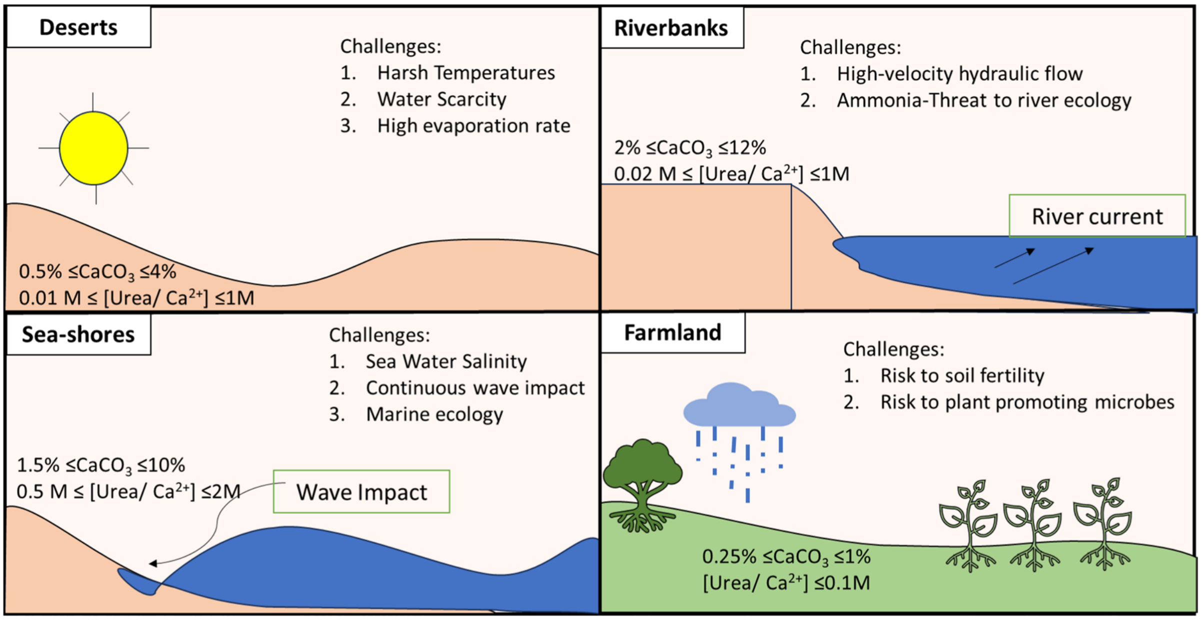


Fig. 7 Challenges associated with application of MICP in different landforms

of the soil and inhibition of urease activity due to high amount of natural calcium salts and low pH of the soil.

In a recent study, Ghasemi and Montoya (2022b) implemented MICP in the field to improve erosion resistance for shallow soil depths through three application strategies, including surface spraying, shallow trenches and prefabricated vertical drains (PVDs) employing lower-grade chemicals and pond water. They reported wider zones for treatment and maximum improvement in erosion resistance with surface spraying technique for a monitoring period of around 11 months. These studies have provided promising results but the possibility of profit-making with the MICP technique for field-scale applications is still uncertain. Currently, three business start-ups, namely, Medusoil, BioMason and Basilisk, based on biocementation techniques, are operational. Their projects could provide more insights into the commercialisation of biocementation techniques. Nonetheless, further studies are required addressing the cost–benefit, service life and durability of biocementation for field-scale applications and replacing existing erosion control and grouting techniques.

5 Concluding remarks

Soil erosion leads to the degradation of arable and habitable land around the globe. In this environmentally conscious era, it is necessary for researchers to devise sustainable alternatives to the current erosion mitigation practices that harm ecology. The current review revisits the recent studies based on laboratory and pilot-scale investigations on soil erosion control and strength improvement through biocementation, with the aim of consolidating the gained knowledge and highlighting the challenges that need to be addressed for upscaling and commercialisation of biocementation technique.

The critical evaluation of the literature outlines the general consensus that a small to moderate quantity of $CaCO_3$ (4–10% of soil weight) is satisfactory for a notable strength improvement and erosion control. However, there are disparities in the reported findings due to differences in types of soils, their gradation, density, soil mineralogy, biocementation application strategy, microbial characteristics (urease activity), loading/erosion testing strategy and environmental conditions (pH, temperature, aeration). Moreover, the obvious concerns of MICP-based biocementation

Table 7 Recommendation for future studies to tackle challenges of different terrestrial landforms

S. N	Terrestrial environment	Range of cementation solution conc. (M)	Target Depth of target crust (mm)	Target range of $CaCO_3$ content (% wt)	No. of treatment cycles	References	Recommended strategies for future research
1	Deserts	0.1–1	12.5–40	0.5–4	5–20	Zomorodian et al. (2019); Devrani et al. (2021); Dubey et al. (2021a); Meng et al. (2021a, b); Dagliya et al. (2022)	Use of superabsorbent polymer along with biocementation to retain moisture against extreme weather Strategies to minimise the water requirement Use of native microbial communities that can adapt to the harsh desert environment
2	Riverbanks and Estuaries	0.02–1	50–200	2–12	4–18	Dubey et al. (2021c, b); Behzadipour and Sadrekarimi (2021); Clarà Saracho et al. (2021a, b); Salifu et al. (2016)	Application in dry season only in the erosion-prone zones Minimising the concentration of cementation media for protecting riparian ecology Strategies for minimising the ammonia/ammonium concentration
3	Seashores	0.5–2	20–50	1.5–10	4–16	Kou et al. (2020); Shahin et al. (2020); Dubey et al. (2022a)	Application in low tide seasons to erosion-prone zones Utilising the seawater for biocementation as it is rich in calcium and magnesium Quantification of erosion rates against wave energy
4	Farmlands	≤0.1	10–30	0.25–1	1–10	Meng et al. (2021a, b); Ghasemi and Montoya (2022a)	Utilising plant-promoting microorganisms for biocementation The utilisation of slow degrading urea and finding optimum concentration for undisturbed growth of plants along with biocementation

over non-uniform precipitation, durability, cost-effectiveness, and overall environmental impact (due to generated by-product ammonia) have not been addressed for devising a viable and affordable strategy for field-scale applications. Therefore, there is an urgent need to explore the technique further to address the above-mentioned aspects in future studies. A systematic interdisciplinary approach must be channelised for standardising the biocementation procedure for upscaling. Moreover, different pathways of biocementation must be explored for erosion control applications to find their suitability. The biocementation technique is still in a nascent state despite the magnanimous efforts of researchers worldwide. This review will be helpful for the early-stage researchers of geotechnical and geoenvironmental engineering domain, who intend to work on the facilitation of biocementation technique from laboratories to the field.

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Conflict of interest The authors declare that they have no conflict of interest.

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