Heavy metal immobilisation with microbial-induced carbonate precipitation: A review

Armstrong Ighodalo Omoregie[a], Tariq Ouahbi[b]*, Hazlami Fikri Basri[c], Dominic Ek Leong Ong[d], Khalida Muda[e], Oluwapelumi Olumide Ojuri[f], Diana Jumbo Flores[g], and Mohamed Tahar Ammami[h]

[a]Post Doctoral Researcher, Centre for Borneo Regionalism and Conservation, University of Technology Sarawak, No. 1 Jalan University, 96000 Sibu, Sarawak, Malaysia. Email: armstrong@uts.edu.my; ORCID: 0000-0002-6356-9638

[b]Professor, LOMC, UMR CNRS 6294, Université Le Havre Normandie, Normandie Université, 53 rue de Prony, 76058 Le Havre, France. Email: tariq.ouahbi@univ-lehavre.fr; ORCID: 0000-0002-2573-3230

[c]Senior Lecturer, Department of Water and Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia. Email: hazlami@utm.my; ORCID: 0000-0002-3398-1832

[d]Associate Professor, School of Engineering and Built Environment, Griffith University, 170 Kessels Rd Nathan, Queensland, 4111, Australia. Email: d.ong@griffith.edu.au; ORCID: 0000-0001-8604-8176

[e]Professor, Department of Water and Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia. Email: khalida@utm.my; ORCID: 0000-0001-7285-7044

[f]Senior Lecturer, Built Environment and Sustainable Technologies Research Institute, Liverpool John Moores University, Liverpool L3 3AF, United Kingdom. Email: O.O.Ojuri@ljmu.ac.uk; ORCID: 0000-0003-2543-2304

[g]Lecturer, Department of Chemistry, Faculty of Natural and Exact Sciences, Universidad Técnica Particular de Loja, Paris Street, San Cayetano Bajo, 110107, Loja, Ecuador. Email: dcjumbo07@utpl.edu.ec; ORCID: 0009-0009-0242-3473

[h]Associate Professor, Université Le Havre Normandie, Normandie Université, LOMC, UMR 6294 CNRS, 53 rue de Prony, 76058 Le Havre Cedex, France. Email: ammamim@univ-lehavre.fr; ORCID: 0000-0002-2198-0816

[*]**Corresponding Authors:**

Tariq Ouahbi, Professor, LOMC, UMR CNRS 6294, Université Le Havre Normandie, Normandie Université, 53 rue de Prony, 76058 Le Havre, France. Email: tariq.ouahbi@univ-lehavre.fr; ORCID: 0000-0002-2573-3230

ABSTRACT

Microbial-induced carbonate precipitation (MICP) is a promising bioremediation technology for heavy metal immobilisation. This review explores the applications and efficacy of MICP in environmental challenges. It provides a comprehensive overview of the mechanism, primarily through ureolysis, detailing the process from urea hydrolysis to heavy metal precipitation as carbonate minerals. Alternative pathways like photosynthesis and nitrate reduction are also discussed, highlighting the broad applicability of MICP. The review covers the historical evolution and advancements of MICP as a sustainable solution for heavy metal contamination. Recent studies demonstrate the efficiency of MICP in achieving high removal rates in diverse environments. The sustainable operation, precise targeting of heavy metal species, and versatility of MICP are examined. Challenges such as high copper concentrations, acidic conditions, and cost considerations are addressed. The article provides future directions and solutions to these challenges, including leveraging machine learning for optimal performance and enhancing cost considerations through detailed analyses. This review improves understanding of MICP's potential, provides a valuable resource for researchers in environmental engineering and the built environment, and encourages innovative approaches within these fields.

***Keywords*:**

Biomineralisation; Geochemical interaction; Heavy metal remediation; Microbial-induced carbonate precipitation; Cost-effective remediation; UN SDG 6: Clean Water and Sanitation

1. Introduction

The world faces an escalating challenge from environmental pollutants, including heavy metals contaminating soil, water, and ecosystems. Rapid industrialisation, human activities, and climate change have exacerbated this issue, resulting in significant health effects (Wang *et al.*, 2021). The consequences of environmental pollution are profound and extensive (Zhou *et al.*, 2022). Heavy metal contamination is a significant and pervasive environmental issue, posing a severe threat to environmental safety. These pollutants accumulate in soil, water, and air, entering the food chain and becoming more concentrated through biomagnification (Cui *et al.*, 2023), leading to severe health risks, including cancer, neurological disorders, and reproductive problems (Goswami and Neog, 2023). Additionally, heavy metal pollution degrades agricultural soils, affecting food safety and quality.

The proportion of heavy metal pollution varies by industry, with mining contributing approximately 20-40%, manufacturing 30-50%, and agriculture 10-20% (Su *et al.*, 2023). These estimates depend on industry type, location, and regulatory frameworks. For example, mining in developing nations may have higher pollution levels due to less stringent regulations, while agricultural pollution can vary with pesticide and fertiliser use (Mostafa *et al.*, 2023; Vácha, 2021). Specific pollution sources include ore extraction and waste management in mining, smelting and electroplating in manufacturing, and pesticides, fertilisers, sewage sludge, and livestock manure in agriculture (Vácha, 2021; Wang *et al.*, 2021; Zhou *et al.*, 2022). While industrial and natural activities contribute significantly to heavy metal pollution, it is critical to evaluate the effectiveness of current regulatory frameworks and identify areas needing stricter enforcement or updated policies.

Mercury (Hg), arsenic (As), lead (Pb), and chromium (Cr) pollution are primarily from industrial and natural sources, accounting for 71.99%, 51.57%, 67.39%, and 68.36% respectively (Cui *et al.*, 2023). Cadmium (Cd) pollution is predominantly linked to agriculture, representing 84.12%. Reducing heavy metal pollution is essential to protect the environment and human health. Besides commercial sources and urban runoff, natural occurrences like volcanic eruptions, floods, and landslides can disperse heavy metals, contaminating the environment and posing risks to human health (Yaashikaa and Kumar, 2022; Zhang *et al.*, 2021). In urban areas, sources include lead paint, lead pipes, industrial emissions, landfills, and sewage sludge. Improper management of wastewater effluent from industrial or municipal sources can exacerbate this issue (**Figure 1**).

[INSERT FIGURE HERE]

Figure 1: Improper drainage blockage issue in a commercial area, highlighting the presence of potential unwanted pollutants if not properly treated.

The cleanup and remediation of heavy metal pollution are costly. For instance, the estimated cost of addressing Pb contamination in Flint, Michigan, was US$2.1 billion (Mohammed *et al.*, 2011). Healthcare costs for individuals exposed to heavy metals can be substantial, with the expense of treating a child with lead poisoning estimated at US$17,000 (Herath *et al.*, 2022). Moreover, heavy metal pollution can result in lost productivity due to illness or disability, with annual costs reaching US$1.2 trillion (Wang *et al.*, 2022a). Environmental damage from heavy metal pollution, impacting crop cultivation, livestock rearing, and fishing, is projected to cost approximately US$3.4 trillion annually. These figures underscore the need for cost-effective and efficient remediation methods to mitigate heavy metal pollution and its associated economic and health burdens.

Several techniques have been developed to address heavy metal pollution, including physicochemical adsorption using biochar and natural zeolite ion exchangers (Bai *et al.*, 2023; Widiastuti *et al.*, 2011), and the decomposition of heavy metal complexes through advanced oxidation processes and biogranulation (Basri *et al.*, 2023; Nidheesh *et al.*, 2022). However, these methods have significant limitations. Physicochemical adsorption may be constrained by the low availability of functional groups in biochar, reducing ion exchange (Hama Aziz *et al.*, 2023). Advanced oxidation processes are costly and generate hazardous byproducts, requiring proper treatment and disposal (Panwar and Pawar, 2022). Biogranulation is limited by the extended setup time and is susceptible to environmental variations like temperature and pH (Omar *et al.*, 2023) The limitations of these methods highlight the need for innovative approaches that enhance remediation efficiency while minimising secondary environmental impacts.

Microbial-induced carbonate precipitation (MICP) is a biomineralisation process where microorganisms facilitate the formation of calcium carbonate ($CaCO_3$) deposits. MICP holds significant promise in bioremediation due to its ability to immobilise heavy metals and contaminants. The $CaCO_3$ crystals generated through MICP can encase contaminants, reducing their bioavailability and leaching into the environment (Yang *et al.*, 2023). MICP is effective for remediating soil and water contaminated by heavy metals (i.e., Pb, As, and Cd). Despite its potential, the scalability and consistency of MICP applications in diverse environmental conditions require further research. Researchers have explored the use of MICP for restoring concrete structures affected by corrosion and chemical degradation (Achal *et al.*, 2011a; Joshi *et al.*, 2019). The potential of creating sustainable construction materials, such as self-healing concrete and bio-bricks, is also under investigation (Farajnia *et al.*, 2022; Liu *et al.*, 2021). applications in soil biocementation, slope stabilisation, soil liquefaction, erosion control, and dust mitigation offer eco-friendly alternatives to conventional methods, which often involve high-energy inputs and synthetic chemicals (Gowthaman *et al.*, 2022; Mwandira *et al.*, 2019; Omoregie *et al.*, 2023; Sun *et al.*, 2021;

Wang *et al.*, 2022b). Compared to conventional grouting methods, microbial grouting using MICP techniques offers advantages like reduced calcium consumption while maintaining the same compressive strength (Naeimi and Haddad, 2020). These findings underscore the potential of eco-friendly alternatives in soil improvement.

MICP has wide-ranging applications in bioremediation and construction, making substantial contributions to environmental and construction sustainability. Its efficacy has garnered significant attention, leading to a surge in research and recognition as shown in **Table 1**. The number of publications on MICP increased from 2 in 1990 to 210 in 2023, with citations rising to 9,513 (see **Figure S1**). This growth reflects MICP's expanding scope, potential to address environmental and construction challenges and significance in shaping innovative solutions. Researchers and professionals increasingly recognise the value of MICP for heavy metal removal, a trend expected to continue as MICP advances and proves its effectiveness in practical applications. MICP is particularly relevant for heavy metal contamination.

This review provides a comprehensive overview of the mechanisms of MICP and factors influencing heavy metal removal. It investigates the conceptual evolution of MICP, covering historical aspects, advancements, and research hotspots. Additionally, the review addresses safety practices and sustainable approaches, such as environmental safety, optimising remediation performance, and sustainable soil improvement. Challenges in MICP efficiency, including high copper (Cu) concentration, acidic conditions, environmental impact assessment, and cost considerations are discussed. Furthermore, the review offers potential future directions for MICP research, including reducing Cu toxicity, utilising acid-tolerant microbes, ensuring long-term stability, enhancing cost considerations, and leveraging machine learning.

[INSERT TABLE HERE]

Table 1: list of various heavy metals immobilised using MICP techniques.

2. MICP Mechanism for Heavy Metal Removal

2.1. Overview of MICP

MICP is a biogeochemical process where microorganisms produce minerals at low energy costs, offering innovative possibilities in engineering applications (Murugan *et al.*, 2021). Among various types of biomineralisation, MICP is classified as biologically induced mineralisation, where microorganisms alter the pH of their surroundings, leading to carbonate precipitates (Bisht *et al.*, 2020; Power *et al.*, 2007; Zhi *et al.*, 2014). While microorganisms do not directly control mineral deposit formation, they influence the process indirectly

through environmental pH changes. Understanding the interplay of physicochemical and biological factors is crucial for optimising MICP efficiency, with bacterial cell concentration being a key factor (Murugan *et al.*, 2021).

In the MICP endeavours for heavy metal removal, the typical procedure encompasses several key steps. It commences with the preparation of ureolytic bacterial cultures and the necessary sterilisation of reagents, chemicals, and media. While conventional factors like biomass concentration/viability, pH, and urease activity are monitored, precipitation tests are routinely executed to gauge the formation of carbonate precipitates and appraise the resilience of bacterial cells against heavy metal ions present in the solution or medium (Xiao *et al.*, 2021). To showcase the transformative potential of soil biocementation, the MICP process is applied, occasionally even in a liquid solution. Advanced analytical techniques are employed to scrutinise the MICP process and its impact on the treated materials. Furthermore, the structural integrity and durability of materials treated through MICP are evaluated using an unconfined compressive strength machine. Understanding MICP mechanisms is essential for leveraging its potential in heavy metal immobilisation (**Figure 2**). This includes exploring the preferred ureolysis pathway and alternative MICP pathways, highlighting their significant potential for heavy metal remediation.

[INSERT FIGURE HERE]

Figure 2: MICP treatment for heavy metal sequestration. (a-d) MICP setup and preparation of ureolytic bacterial cultures; (e-g) precipitation tests, including the quantification of carbonate precipitates and bacterial cells undergoing tolerance tests in the presence of heavy metals; (h-i) process of soil biocementation via MICP, both before and after curing; (j-m) various analytical methods for material characterisation; and (n) the strength testing procedure using an unconfined compressive strength machine.

2.2. Ureolysis pathway for MICP

Ureolysis, or urea hydrolysis, is the most common pathway for MICP, primarily facilitated by urease-producing bacteria such as *Sporosarcina pasteurii* and *Lysinibacillus sphaericus*. These bacteria hydrolyse urea using the extracellular urease enzyme (Meier *et al.*, 2017). The hydrolysis process elevates the pH, promoting $CaCO_3$ precipitation from calcium and bicarbonate ions in solution. This pH elevation results from the consumption of organic compounds, producing carbonate ions (CO_3^{2-}) and hydroxide ions (OH^-) as byproducts (Omoregie *et al.*, 2022). The resulting alkaline environment is essential for the subsequent precipitation of $CaCO_3$.

Microorganisms play a dual role in biomineralisation. First, they create an environment conducive to carbonate mineral formation by elevating the local pH through their metabolic processes (Xiao *et al.*, 2021).

Secondly, they produce extracellular polymeric substances (EPS), complex molecules serving as a matrix for Ca^{2+} and CO_3^{2-} ions to aggregate, forming initial mineral nuclei (Li *et al.*, 2017). EPS not only initiate mineral formation but also acts as an effective immobilising agent for heavy metals. Heavy metal ions bind to the EPS and integrate into the $CaCO_3$ structure, significantly reducing their mobility and bioavailability (Huang *et al.*, 2018).

The chemical reactions involved in heavy metal removal through MICP include actions by urease and carbonic anhydrase enzymes. The process starts with urea ($CO(NH_2)_2$) reacting with water (H_2O) in the presence of urease, producing ammonia (NH_3) and carbamic acid (NH_2COOH) (Jing *et al.*, 2023; Qiao *et al.*, 2021). Urease catalyses this hydrolysis, breaking down urea (Eqn. 1). The produced NH_2COOH further reacts with H_2O to form carbonic acid (H_2CO_3) and additional NH_3 (Eqn. 2). H_2CO_3 then dissociates into (H^+) and bicarbonate ion (HCO_3^-), facilitated by carbonic anhydrase, increasing bicarbonate ion concentration (Eqn. 3).

Next, NH_3 reacts with H_2O to generate OH^- and ammonium ions (NH_4^+) (Eqn. 4), contributing to the pH increase around the microbial cells. The HCO_3^-, generated in Eqn. 3 interacts with H^+ and additional OH^- to produce CO_3^{2-} (Eqn. 5). These carbonate ions precipitate from the solution when exposed to divalent cations. Calcium ions (Ca^{2+}) in the microbial environment can react with CO_3^{2-} to form solid $CaCO_3$ precipitates (Eqn. 6). Similarly, heavy metal ions (HM^{2+}), present in the solution can react with CO_3^{2-} to produce solid heavy metal carbonates ($HMCO_3$) (Eqn. 7). In certain scenarios, $HMCO_3$ co-precipitates with $CaCO_3$ to form mixed carbonate minerals, where "x" represents the proportion of heavy metal ions in the precipitate (Eqn. 8). **Figure 3** provides a schematic representation of MICP, leading to the removal of heavy metals and the simultaneous co-precipitation of $CaCO_3$. The corresponding reaction equations are presented below:

$$CO(NH_2)_2 + H_2O \rightarrow NH_3 + NH_2COOH \quad (1)$$

$$NH_2COOH + H_2O \rightarrow H_2CO_3 + NH_3 \quad (2)$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad (3)$$

$$2NH_3 + 2H_2O \leftrightarrow 2OH^- + 2NH_4^+ \quad (4)$$

$$HCO_3^- + H^+ + 2OH^- \rightarrow CO_3^{2-} + 2H_2O \quad (5)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3(g)} \quad (6)$$

$$HM^{2+} + CO_3^{2-} \rightarrow HMCO_{3(g)} \quad (7)$$

$$xHM^{2+} + (1-x)Ca^{2+} + CO_3^{2-} \rightarrow Ca_{(1-x)}M_x\,CO_{3(g)} \quad (8)$$

[INSERT FIGURE HERE]

Figure 3: Schematic illustration showing the MICP mechanism for heavy metal immobilisation and co-precipitation of $CaCO_3$.

Urease, a large enzyme complex with a molecular mass exceeding 500 kDa, contains two nickel (Ni) ions vital for its catalytic function (Zhu *et al.*, 2021). This enzyme is essential for breaking down urea into carbonate ions, which then react with calcium ions to form $CaCO_3$ precipitates, effectively trapping and immobilising heavy metals. The Ni ions within the enzyme's active site are indispensable for catalytic activity, a prerequisite for carbonate ion production. Carbonate ions subsequently react with calcium ions to generate $CaCO_3$ precipitates, effectively trapping and immobilising heavy metals as demonstrated in **Figure 3**. The intricate molecular mechanism governing urease catalysis is yet to be fully elucidated, but it has played a fundamental inspiration in heavy metal immobilisation.

Ureolysis is preferred in MICP due to its simplicity, the abundance of urease-producing bacteria, and the rapid pH elevation from liberated ammonia (Lauchnor *et al.*, 2015). These bacteria, such as *Sporosarcina aquimarina, Sporosarcina pasteurii, and Exiguobacterium undae*, adapt well to various environmental conditions, including alkaline pH and high calcium concentrations (Keykha *et al.*, 2019; Kumari *et al.*, 2014). This knowledge forms a solid foundation for enhanced control and predictability within MICP processes. The accessibility and affordability of urea also make MICP economically viable and scalable (Chen *et al.*, 2019, 2018; Omoregie *et al.*, 2019a). The extensive knowledge of urea hydrolysis and $CaCO_3$ precipitation by these bacteria provides valuable insights for optimising the MICP process

2.3. Other MICP pathways

MICP can occur through various metabolic pathways (apart from ureolysis) through microorganisms, each contributing to mineral precipitation. These distinct mechanisms include (i) photosynthesis, (ii) ammonification, (iii) nitrate reduction (denitrification), (iv) sulfate reduction, and (v) iron reduction. Each of these pathways contributes to mineral precipitation through different mechanisms.

Firstly, oxygenic photosynthesis unfolds as a captivating process. Specific microorganisms, exemplified by cyanobacteria (i.e., *Synechococcus elongatus*), and algae (i.e., *Dinoflagellates*) harness the radiant energy of sunlight to orchestrate a transformation (Bundeleva *et al.*, 2014; Frommlet *et al.*, 2015). This transformation sees carbon dioxide (CO_2) and water metamorphose into organic matter while simultaneously liberating oxygen as a noteworthy byproduct (Eqn. 9). The exchange of HCO_3^- or OH^- ions lead to an elevation in alkalinity across microbial cells (Lamérand *et al.*, 2022). What makes this process especially intriguing is the ability of these

microorganisms to influence their immediate surroundings. Through the consumption of CO_2, they manipulate pH levels, setting the stage for the precipitation of $CaCO_3$ (Kawaguchi and Decho, 2002). This biomineralisation process is set into motion as conditions shift to favour $CaCO_3$ formation. As long there is increased alkalinity from the photosynthesis process facilitates the reaction between Ca^{2+} and HCO_3^- , $CaCO_3$ minerals will form (Eqn. 10).

$$CO_2 + H_2O \rightarrow Organic\ matter + O_2 \quad (9)$$

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + O_2 \quad (10)$$

During ammonification microorganisms convert organic nitrogen-containing compounds, such as proteins and amino acids, into NH_3 (Eqn. 11). The generated NH_3 elevates the pH levels in the vicinity. The generated NH_3 exhibits the remarkable capability to elevate the pH levels in the vicinity. Then, NH_3 react with HCO_3^- to form NH_4^+ and CO_2 (Eqn. 12). The subsequent reactions with calcium ions lead to the precipitation of $CaCO_3$ (Eqn. 13), a key development in the MICP journey. While some bacteria, like *Virgibacillus marismortui*, acidify their environment (Zhao Z. et al., 2020), others, like *Brevibacillus laterosporus*, raise the pH through ammonification (Gunes and Balci, 2021). This increase in pH, observed in various species (i.e., *Rheinheimera texasensis, Paeniglutamicibacter kerguelensis, Ensifer adhaerens, Microbacterium testaceum,* and *Pseudomonas protegens*) (Hatayama and Saito, 2019) promotes the precipitation of $CaCO_3$, a key step in MICP.

$$Protein\ or\ amino\ acid \rightarrow NH_3 \quad (11)$$

$$NH_3 + HCO_3^- \rightarrow NH_4^+ + CO_2 \quad (12)$$

$$NH_4^+ + Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + 2H_2O + NH_3 \quad (13)$$

Denitrifying bacteria contribute to MICP through a distinctive pathway. These bacteria use nitrate (NO_3^-) as a terminal electron acceptor, and in the process, they generate nitric oxide (NO) (Eqn. 14). NO, in turn, can react with calcium ions, forming calcium nitrate ($Ca(NO_3)_2$) (Liu *et al.*, 2022a). This metabolic feat leads to an intriguing pH elevation outcome. As the pH undergoes this shift, it lays the foundation for the precipitation of $CaCO_3$, an essential aspect of MICP. For instance, calcium nitrate is hydrolysed, leading to the precipitation of $CaCO_3$ and the release of nitric acid (Eqn. 15-16).

$$NO_3^- \rightarrow NO \quad (14)$$

$$Ca^{2+} + 2NO_3 \rightarrow Ca(NO_3)_2 \quad (15)$$

$$Ca(NO_3)_2 + 2H_2O \rightarrow CaCO_3 + 2NO_3^- + H_2O_2 \quad (16)$$

Halomonas sp and *Thauera* sp are reported microbial species known for their versatile metabolism and ability to form biofilms (Chetty *et al.*, 2022). This process is not well understood, especially at alkaline pH levels. Researchers observed a decrease in nitrate reduction rates from 0.72 mM/h at pH 9.5 to 0.17 mM/h at pH exceeding 11, while the concentration of nitrite increased (Chetty *et al.*, 2022). The pH shift sets the stage for the precipitation of $CaCO_3$, which plays a key role in MICP. The denitrification-driven pathway demonstrates the adaptability of the process (Pham *et al.*, 2018).

Sulfate reduction is a pivotal process contributing to sulfide generation in environments with high sulfate concentrations and low oxygen levels, both in natural and industrial contexts (Ren *et al.*, 2022). Certain sulfate-reducing microorganisms (i.e., *Desulfovibrio* sp) induce MICP by producing sulfide ions (S^{2-}). In this metabolic pathway, microorganisms pivot towards sulfate (SO_4^{2-}) as a terminal electron acceptor during anaerobic respiration (Karnachuk *et al.*, 2021). Then, sulfate later converts into S^{2-} via a transformational phase (Eqn. 17). These sulfide ions then react with Ca^{2+} in the environment, resulting in the formation of calcium sulfide (CaS) (Chetty *et al.*, 2022; Gao *et al.*, 2023). Subsequently, this calcium sulfide can be oxidised, typically by atmospheric oxygen or other oxidants, leading to the conversion of CaS into $CaCO_3$ and elemental sulfur (S) (Eqn. 18-19).

$$SO_4^{2-} \rightarrow S^{2-} \quad (17)$$

$$Ca^{2+} + S^{2-} \rightarrow CaS \quad (18)$$

$$CaS + O_2 \rightarrow CaCO_3 + S \quad (19)$$

Iron reduction unfolds as a fascinating metabolic pathway where microorganisms channel the potential of ferric iron (Fe^{3+}) as an electron acceptor during anaerobic respiration. Iron-oxidising bacteria such as *Sideroxydans* sp, *Gallionella* sp, and *Azoarcus* sp play a role in MICP by reducing (Fe^{3+}) to ferric iron (Fe^{2+}) (Eqn. 20) (Levett *et al.*, 2020). The produced ferric iron interacts with HCO_3^- in the environment, forming ferric hydroxide ($Fe(OH)_3$) and CO_2 (Eqn. 21) (Yang *et al.*, 2022). This ferric hydroxide subsequent transformation leads to the precipitation of $FeCO_3$ and H_2O (Eqn. 22). The iron-mediated pathway adds another layer of complexity to the MICP process (Ning *et al.*, 2022). Meanwhile, the release of CO_2 occurs during the initial reaction. The precipitation of $CaCO_3$ is not explicitly shown in this pathway, as $FeCO_3$ is the primary product in this case. Microbial iron reduction influences pH by balancing proton (H^+) consumption during iron reduction and (H^+) generation from organic substrate oxidation (Li *et al.*, 2022a). In Fe^{3+} rich conditions, it increases pH, converting dissolved CO_2 into bicarbonate. Beyond urea hydrolysis, MICP pathways can immobilise heavy metals

like Pb, Cd, and Cu by forming less soluble compounds. This adds complexity to MICP, which influences the pH and contributes to $FeCO_3$ formation.

$$Fe^{3+} + e^- \rightarrow Fe^{2+} \quad (20)$$

$$Fe^{2+} + HCO_3^- \rightarrow Fe(OH)_3 \quad (21)$$

$$Fe(OH)_3 \rightarrow FeCO_3 + H_2O \quad (22)$$

3. Factors Influencing MICP Effectiveness

The effectiveness of heavy metal immobilisation through MICP is governed by a multitude of factors. Understanding these factors is essential for optimising this bioremediation strategy. By critically analysing these elements, the application of MICP can be enhanced in diverse contaminated environments, ensuring effective and sustainable remediation.

3.1. Formation of Metal Carbonates

The integration of heavy metal ions into the evolving $CaCO_3$ structure is pivotal to the effectiveness of MICP. Heavy metal stabilisation is linked to the formation of metal carbonates, which render the metals less soluble and more stable. This process involves mechanisms such as isomorphic substitution of Ca^{2+} or incorporation into the crystal lattice interstices or defects (Tamayo-Figueroa *et al.*, 2019). The efficiency of this incorporation depends on the ionic radius and charge of the heavy metal ions, which influence their ability to substitute for Ca^{2+} in the lattice. Additionally, the presence of other ions can affect the formation and stability of metal carbonates, thereby influencing the overall stabilisation process. The saturation state of $CaCO_3$ in the environment also plays a role. High saturation levels promote nucleation and growth of $CaCO_3$ crystals, enhancing the entrapment of heavy metals. Conversely, low saturation levels may inhibit these processes, reducing immobilisation efficiency. The role of isomorphic substitution and incorporation into lattice defects is crucial but often complicated by the specific characteristics of each heavy metal ion (Eltarahony *et al.*, 2021). For instance, the substitution of Ca^{2+} by comparable ionic radii such as Pb^{2+}, Cd^{2+}, or Zn^{2+} tends to be more efficient compared to metals with significantly different ionic radii or charges (e.g., Cr^{3+}, Cr^{6+}) (Mitra *et al.*, 2022). Additionally, the presence of competing ions such as Mg^{2+} and SO_4^{2-} can interfere with the formation of $CaCO_3$, necessitating a careful balance of ion concentrations in the treatment environment.

3.2. Microbial Activity and Metabolic Processes

Microbial activity is a cornerstone of MICP, as the metabolic processes of microorganisms drive the precipitation of $CaCO_3$. Under adverse conditions, such as high heavy metal concentrations, microorganisms employ survival strategies like the buildup and expulsion of calcium ions and the maintenance of a conducive microenvironment. The metabolic activities that lead to the release of carbonate ions and subsequent $CaCO_3$ precipitation are influenced by factors such as exopolymers, biofilms, and dormant spores (Kim *et al.*, 2021; Zhang *et al.*, 2020). EPS produced by microbes bind heavy metals and serve as nucleation sites for $CaCO_3$ precipitation, enhancing the immobilisation process. Biofilms, which are complex microbial communities embedded in EPS, provide a protective environment for microbes and facilitate sustained metabolic activity and $CaCO_3$ production, even in the presence of toxic heavy metals (Crane *et al.*, 2022; Zhao *et al.*, 2020a). The protective nature of biofilms allows MICP microorganisms to survive and function under suboptimal conditions, which is advantageous in harsh environments. However, the heterogeneity of biofilms can result in uneven $CaCO_3$ precipitation and potential weak spots in the immobilisation matrix. Dormant spores add resilience to the microbial community, but their germination and subsequent metabolic activity are highly dependent on environmental triggers, which may not always be predictable or controllable. The complexity and variability of EPS composition can lead to inconsistent results, posing a challenge to the uniformity of $CaCO_3$ precipitation and the stability of the immobilisation matrix (Dong *et al.*, 2023).

3.3. pH Alterations and Adenosine triphosphate (ATP) Production

The interplay between ATP production and pH changes is critical in MICP. Proton flow through ATP synthase during cellular respiration causes pH shifts within the microenvironment, which are necessary for carbonate ion formation and $CaCO_3$ precipitation. These pH changes also significantly impact heavy metal stabilisation, as heavy metal ions co-precipitate with $CaCO_3$, rendering them insoluble (Zhang *et al.*, 2022c). The production of ATP during cellular respiration is closely linked to pH modulation. Protons are shuttled during ATP synthesis, leading to pH changes that influence the solubility and speciation of heavy metals and carbonate ions (Jing *et al.*, 2023; Qiao *et al.*, 2021). These pH changes create a favourable environment for $CaCO_3$ precipitation and heavy metal stabilisation. Furthermore, the efficiency of ATP production and pH regulation is influenced by environmental factors such as temperature, oxygen availability, and nutrient concentration processes (Zhang *et al.*, 2022a). Optimal conditions for microbial metabolism and ATP synthesis can enhance MICP processes, while suboptimal conditions can hinder these processes and reduce stabilisation efficiency. The correlation between ATP production and pH modulation is highly sensitive to environmental fluctuations. Temperature variations can

significantly impact microbial respiration rates and, consequently, ATP production and pH changes. Oxygen availability is another critical factor; anaerobic conditions can limit the efficiency of aerobic microbes, leading to reduced ATP production and less effective pH modulation (Kang *et al.*, 2022; Sharma *et al.*, 2022b). Nutrient limitations can also hamper microbial growth and metabolic activity, necessitating the provision of a balanced nutrient supply to sustain effective MICP.

4. Conceptual Evolution of the Research Field

Researchers can be enlightened about the historical perspective and the remarkable developmental milestones that have intricately shaped the trajectory of this field. Visual representation depicting the chronological evolution of MICP strategies for heavy metal removal, spanning from the 1970s to the 2020s is shown in **Figure 4**. Understanding the historical perspective, key research milestones and hotspots of research themes and areas is vital for scholars in the field as it provides essential context, and a roadmap of progress, and identifies current areas of significance, enabling them to make informed contributions and advancements in their research

[INSERT FIGURE HERE]

Figure 4: Chronological evolution of MICP strategies for heavy metal removal (the 1970s-2020s).

4.1. Early Research (1975-1998) on MICP for Heavy Metal Removal

Early research (1975-1998) laid the groundwork for understanding MICP's potential in heavy metal removal. Brown *et al.*, (1975) introduced ureolysis, a key process in MICP, while Nannipieri *et al.*, (1983, 1990) demonstrated ureolysis-driven ammonium release in soils. Bihari and Basu (1984) highlighted the industrial applications of immobilised urease, and Perucci (1990) and García *et al.*, (1994) emphasised microbial influences on soil conditions and enzymatic activities. Goldstein (1994) extended the potential of MICP by uncovering microbial roles in marine carbon cycling. Benini *et al.*, (1996) advanced the understanding of urease structure in *Sporosarcina pasteurii*, crucial for ureolysis in MICP. Xu and Johnson (1997) accentuated the importance of microbial processes in soil nitrogen cycling in hydrocarbon-contaminated soils. Nielsen *et al.*, (1998) revealed rapid soil urea turnover's importance in nitrogen cycling. Ejechi and Akpomedaye (1998) showed how ureolytic microorganisms limited wood-rot fungi growth, indicating their ecological significance. Early studies provided foundational insights into the mechanisms of MICP, particularly ureolysis. However, the focus was predominantly on understanding basic microbial processes rather than direct applications for heavy metal removal. This period

was crucial for setting the stage for future applied research but lacked targeted strategies for environmental remediation.

4.2. Advancements (1999-2008) in MICP for Environmental Remediation

Advancements (1999-2008) showcased MICP's efficacy in environmental remediation. Stocks-Fischer *et al.,* (1999) and Fujita *et al.*, (Fujita *et al.*, 2000) placed the foundation for bacterial mineral precipitation and the ability to capture inorganic contaminants. Other important early studies underscored MICP's potential for environmental remediation, particularly in capturing inorganic contaminants (Bachmeier *et al.*, 2002; Stuczynski *et al.*, 2003; Warren *et al.*, 2001). Hammes *et al.*, (2003), explored industrial wastewater treatment through MICP, while Amos *et al.*, (2004) and Rekha *et al.*, (2005) demonstrated MICP's applicability in acid mine drainage and lake sediment remediation, respectively. Mitchell and Ferris (2006) studied *Sporosarcina pasteurii'*s impact on metal immobilisation, and Garau *et al.*, (2007) investigated metal solubility reduction through amendments. Lee *et al.,* (2008) studied metal removal in acid mine drainage, focusing on adsorption and showing sustained capacity of MICP over time. This period marked significant progress in applying MICP for environmental remediation. The research expanded beyond basic mechanisms to practical applications, demonstrating MICP's potential in diverse environmental contexts. However, these studies are still largely experimental and face challenges in scalability and field application.

4.3. Progress (2009-2018) in MICP for Heavy Metal Immobilisation

Between 2009 and 2018, significant progress was made in the field. Researchers like Sarda *et al.*, (2009) showed MICP's potential in reducing water absorption in bricks, extending its use to heavy metal immobilisation. Li *et al.*, (2010) demonstrated that ureolytic bacteria could immobilise Cd in contaminated soil with a 92% removal rate. Achal *et al.*, (2011; 2012b; 2012c; 2012a) successfully removed Cu from contaminated soil and extended the method to remediate Pb, Sr, and As-contaminated soil with up to 95% immobilisation efficiency. Li *et al.,* (2013) explored biomineralisation of heavy metals (Ni, Cu, Pb, Co, Zn, Cd) by metal-resistant bacterial strains, achieving high removal rates (88% to 99%). Achal *et al.*, (2013) demonstrated the use of *Bacillus* sp. strain CS8 for the bioremediation of chromate (Cr (VI)) from chromium slag. Lauchnor *et al.*, (2013) addressed Sr-contamination via ureolysis, suggesting a viable strategy for field-scale applications. Kang *et al.*, (2014) investigated the biomineralisation of Cd, achieving a 99.95% removal rate. Kumari *et al.*, (2014) explored MICP at low temperatures for Cd immobilisation in soil, showing a 90% removal rate. Kang *et al.*, (2015) tackled Pb contamination, successfully immobilised Pb ions and achieved a 60% removal rate after 48 hours of incubation. Kang *et al.*, (2016) isolated bacteria from abandoned mines and used them for MICP to sequestrate Cu^{2+}, resulting

in a 61.8% Cu immobilisation rate. Mwandira *et al.*, (2017) addressed Pb-contaminated mine waste bioremediation using MICP, offering an eco-friendly method. Gui *et al.,* (2018) reinforced fine-grained uranium tailings effectively through MICP, indicating its potential for tailings dam reinforcement. This period saw substantial advancements in applying MICP for heavy metal immobilisation. Studies demonstrated high removal rates and expanded the range of heavy metals addressed. However, while lab-scale experiments were successful, there were still significant challenges in translating these results to field-scale applications. Issues such as microbial survival in different environments, the consistency of ureolysis, and cost-effectiveness remained barriers.

4.4. Recent Advances (2019-Present) in MICP for Heavy Metal Remediation

From 2019 onwards, MICP research for heavy metal removal has advanced significantly, demonstrating its potential in various environmental contexts. Zhang *et al.,* (2019) introduced biochar to remediate Ni via MICP, finding that it inhibited calcite formation by *Bacillus cereus*, impacting Ni remediation. Khadim *et al.,* (2019) used ureolytic bacteria from barn horse soil for Ni and Cd remediation, achieving up to 96% removal for Cd and 89% for Ni. Wang *et al.,* (2020) isolated urease-producing bacteria from lettuce rhizosphere soil, effectively reducing Cd and Pb accumulation in lettuce. Peng *et al.,* (2020) used a Cd-resistant ureolytic bacterium for MICP, achieving 99.50% Cd removal in solution and 56.10% in soil. Qiao *et al.,* (2021) demonstrated that *Sporosarcina* sp. could remove multiple heavy metals, with removal rates of 75-98% within two hours. Bai *et al.,* (2021) employed a halophilic ureolytic bacterium to remediate heavy metal-contaminated saline environments, achieving around 89% Pb removal under high salinity. He *et al.,* (2022) used *Lysinibacillus fusiformis* for in-situ biomineralisation of Cu-Ni-tailings, significantly reducing heavy metal leaching. Disi *et al.,* (2022) achieved 100% removal of Cr and zinc (Zn) using hydrocarbon-degrading ureolytic bacteria. Li *et al.,* (2022) reported high removal rates for Cd, Cu, and Pb with *Sporosarcina pasteurii*. He *et al.,* (2023) enhanced Pb immobilisation using ureolytic *Staphylococcus epidermidis* with poly-Lysine, achieving a 92% immobilisation rate. Zeng *et al.,* (2023) demonstrated 98.46% Cd immobilisation in sludge, with significant increases in urease metabolism genes. He *et al.,* (2023) reported that adding calcium oxide (CaO) to MICP improved passivation rates for Cu, Ni, Pb, and Cr. Zhang *et al.,* (2023) showed the potential of ureolytic microorganisms in detoxifying heavy metals from intensive Cu production, identifying mechanisms in areas with varying heavy metal content. Recent advancements in MICP research have shown its potential in various environmental contexts and achieved high removal rates for multiple heavy metals. Innovations such as the use of biochar, halophilic bacteria, and poly-lysine have enhanced the efficiency and applicability of MICP. However, challenges remain in scaling up these methods for practical, field-

scale applications. Variability in microbial activity, environmental conditions, and cost-effectiveness are critical issues that need to be addressed to fully harness MICP's potential for heavy metal remediation.

4.5. Hotspots of Research Themes and Areas

VOSviewer is an invaluable tool for identifying research hotspots and trends, helping researchers understand current dynamics and emerging areas of interest. Leading keywords based on frequency offer valuable insights into prominent research areas. The density visualisation of the author keyword using VOSviewer software displays the hotspot of the field as shown in **Figure 5**. "MICP" underscores its central role, followed closely by "urease" and "heavy metals", highlighting the significance of this enzyme in the MICP process for heavy metal removal. Other dominant keywords include "soil enzyme activities", "bio-mineralisation", "microbial communities", "bacterial community", "cadmium", "*Sporosarcina pasteurii*", and "calcium carbonate", signifying specific elements and compounds that researchers are actively investigating. Keywords such as "bio-cementation", "enzymatic activities", "rhizosphere microenvironment", "microorganisms", "constructed wetlands", and "bio-remediation" emphasise the importance of these areas in current research. These keywords represent the focal points of extensive academic literature and are instrumental in understanding the research landscape. Additionally, less common but noteworthy keywords such as "coal combustion fly ashes", "environmental scanning electron microscope", "ecophysiological index", and "sustainable technology" offer a glimpse into the diverse and evolving research areas that researchers are exploring.

[INSERT FIGURE HERE]

Figure 5: Density visualisation of author keyword hotspots using VOSviewer software.

Data from the VOSviewer co-occurrence analysis of author keywords, illustrated in Figure S2, revealed key trends and focal points within the MICP field for heavy metal removal. The analysis shows "Cd" as the most researched heavy metal, followed by "Pb" and "Cu", highlighting their significance as environmental pollutants and targets for MICP research. There is strong interest in terms like "biochar" and "carbon", which enhance microbial activity and facilitate $CaCO_3$ precipitation. Enzymatic activities (e.g., "catalase", "glucosidase", "acid phosphatase") and techniques (e.g., "scanning electron microscopy", "X-ray diffraction") are crucial in optimising MICP. The central role of microorganisms is emphasised with terms like "dehydrogenase", "microbial community structure", and "*Sporosarcina pasteurii*". Key terms such as "absorption", "accumulation", "bioavailability", "contaminated soil", and "toxicity" underline the focus on heavy metal absorption and immobilisation. References

476 to “bioremediation”, “surface treatment”, and “cementitious material” highlight their importance, while terms like
477 “biocementation”, “stabilisation”, and “carbon sequestration” suggest an emerging interest in broader
478 environmental applications, such as soil strengthening and carbon capture. Different subgroups within these
479 research themes are detailed in **Figure S2**.
480
481
482 **5. Safety Practices and Sustainable Approaches**
483 MICP offers a promising and sustainable approach for heavy metal immobilisation, provided that safety practices
484 are rigorously followed and continuously improved. To ensure the long-term safety and efficacy of MICP, further
485 research is needed in several areas. Developing standardised protocols for monitoring and evaluating MICP
486 performance in different contexts is essential. Additionally, understanding the long-term durability of MICP-based
487 structures and materials is crucial. While biomineralisation offers advantages, comprehending how these
488 structures weather and degrade over time is vital for ensuring safety and sustainability. Understanding microbial
489 processes, utilising waste materials, and incorporating machine learning are all crucial for enhancing the safety,
490 efficiency, and environmental benefits of MICP. By focusing on these themes, MICP can be developed into a
491 reliable and eco-friendly technique for environmental remediation.

492 5.1. Environmental Safety
493 MICP holds the potential for reduced environmental impact compared to conventional techniques. Studies by
494 Ivanov *et al.*, (2019) and El Enshasy *et al.*, (2020) highlight the importance of environmentally safe construction
495 practices, noting that MICP avoids the release of harmful substances like ammonia associated with traditional
496 methods. This is critical, as ammonia can contribute to groundwater contamination and air pollution. Additionally,
497 Ivanov and Stabnikov (2020) demonstrate how MICP aligns with sustainable practices by promoting
498 biomineralisation, which enhances the durability of structures while reducing the environmental footprint
499 compared to traditional cement production. This biomineralisation process not only sequesters carbon dioxide but
500 also produces less waste and consumes fewer natural resources.

501 5.2. Optimising Safety and Remediation Performance
502 Safety practices can be improved by understanding the metabolic pathways of microorganisms used in MICP
503 (Porter *et al.*, 2021). This understanding is vital for controlling the process and preventing unintended
504 environmental consequences. Ensuring the purity of input chemicals and byproducts is also crucial, as
505 contaminants could undermine the safety and effectiveness of MICP. Furthermore, scholars have showcased how

machine learning can predict alternative stabilising materials that minimise environmental impact (Liu *et al.*, 2022b; Raza and Khushnood, 2022; Zhang *et al.*, 2022b). Machine learning can optimise the selection and combination of materials to enhance the efficacy and safety of MICP processes, thus making the approach more reliable and environmentally friendly. Studies have shown that MICP is a cleaner production approach for remediating contaminated soil and industrial materials, offering a sustainable alternative for construction materials (Mokhtar *et al.*, 2021; Yu *et al.*, 2021). This is particularly relevant for heavy metal immobilisation, as MICP can stabilise heavy metals in soils, preventing their leaching and reducing their bioavailability. Additionally, researchers have investigated using waste materials like kitchen waste in bioremediation processes (Sharma *et al.*, 2022a). This approach not only provides a sustainable method for waste disposal but also adds value to waste materials, transforming them into useful inputs for MICP. Such practices highlight MICP's potential for sustainable building material production while addressing waste disposal concerns.

5.3. Sustainable Soil Improvement

Suriya and Sangeetha, (2023) demonstrated how MICP can improve the erosive resistance of dispersive soil through the incorporation of jute fibres. This aligns with sustainable practices in geotechnical engineering by enhancing soil strength while mitigating erosion. The use of natural fibres like jute not only reinforces soil but also promotes biodegradability and reduces reliance on synthetic materials. This approach exemplifies how MICP can be integrated with other sustainable practices to achieve multiple environmental benefits. Studies exploring industrial waste materials represent a breakthrough in heavy metal remediation methodologies Bioaugmentation and biostimulation approaches utilise unconventional yet abundant resources like waste materials (such as food scraps, agricultural residues, construction debris or mining waste) to cultivate bacteria essential for MICP processes (Gomez *et al.*, 2017; Raveh-Amit and Tsesarsky, 2020; Wang *et al.*, 2014). This highlights the potential for safe and sustainable MICP implementation. This not only reduces the need for expensive commercial bacterial cultures but also promotes sustainability by diverting waste materials from landfills and potentially lowering the environmental impact of MICP. Moreover, these waste-derived microbial communities may be more adaptable to various environmental conditions, harbouring a wider diversity of metal-resistant bacteria that can enhance heavy metal immobilisation through carbonate precipitation.

6. Challenges in MICP Efficiency

6.1. High Copper Concentrations and Acidic Conditions

Cu is a crucial but toxic heavy metal, with soil levels often exceeding safety thresholds globally. This has led to bans in many countries due to heightened health and environmental risks. While MICP shows promise in controlled laboratory settings, its application in the field is challenging due to the need for controlled conditions (Chen and Achal, 2019). In addition, MICP is effective on numerous heavy metals including Cu. However, high Cu concentrations can inactivate the ureolytic bacteria crucial for the process (Xue *et al.*, 2022). More so, social acceptance of using bacteria for bioremediation also varies by region. The United States Environmental Protection Agency sets an action level of 1.3 mg/L for Cu in drinking water, while the World Health Organisation suggests a median value of 1.5 mg/L (Taylor *et al.*, 2020; WHO, 2018).

Chen & Achal (2019) explored biostimulation to enhance MICP for Cu immobilisation in soil by spiking it with 100 mg/kg of Cu. Despite promising results, the study's short one-month duration and controlled lab setting raise questions about long-term effectiveness and field applicability. The impact of biostimulation on Cu-resistant bacteria versus the general ureolytic population remains unclear, and the long-term effects on soil chemistry need further investigation. Sepúlveda *et al.*, (2021) investigated *Staphylococcus equorum* and *Sporosarcina pasteurii* for Cu removal using MICP, finding low removal rates (around 10%) insufficient for practical use. The formation of Cu-NH_3 complexes could prevent $CuCO_3$ precipitation, requiring additional measures to optimise Ca precipitation.

Heavy metal contamination from mine tailings poses serious environmental problems. Current treatment methods are often costly and ineffective. Yang *et al.*, (2016) proposed using *Bacillus firmus* to remediate acidic Cu mine tailing soils, demonstrating that MICP could reduce heavy metal mobility. Oliveira *et al.*, (2021) examined MICP for treating Cu mine tailings, finding that *Sporosarcina pasteurii*'s sensitivity to Cu (inhibited growth at 0.2-1 mM) limits its suitability. Anaerobic ureolytic bacteria may address oxygen transfer issues. L Wang *et al.*, (2023) studied purified urease enzyme from Jack bean seeds for Cu removal (5 to 50 mM). They found chitosan protects urease from Cu toxicity but increases NH_4^+ concentration, creating an alkaline environment where Cu forms complexes with NH_3, hindering immobilisation. Further research should focus on reducing Cu-ammonia complex formation and understanding carbonate-type effects on Cu immobilisation efficiency. The authors later compared urease from *S. pasteurii* and *Canavalia ensiformis* for Cu and Pb removal in water, achieving near 100% Pb removal but lower Cu removal (Wang *et al.*, 2023a). They identified less stable carbonate precipitates (cotunnite and atacamite) under extreme conditions, potentially reducing remediation

efficiency. High NH_4^+ concentrations in MICP can raise pH, promoting Cu-NH_3 complex formation that hinders Cu removal. Hu *et al.*, (2024) reported that *Brucella intermedia* effectively removes heavy metals, including Cu, from water. This bacterium has a complete urease gene cluster and efficiently uptakes urea, but the study's low Cu concentration (1 mmol/L) limits its generalisability. Further research with a broader range of Cu concentrations is needed. X Hu *et al.*, (2024) also found *B. intermedia* highly resistant to Cu, with an IC50 value of 1.901 mmol/L. The bacteria effectively remove Cu through MICP, enhanced by Ca^{2+} co-precipitation with vaterite, facilitating Cu compound adhesion and precipitation. This study used a higher Cu concentration (1.6 mmol/L) compared to natural water levels (0.1 ppb to 30 ppb), relevant for studying bioremediation in contaminated environments. Further research should focus on efficiency at varying contamination levels to develop practical strategies.

Heavy metal contamination in soil poses significant ecological and environmental threats, particularly in acidic soils prevalent in certain regions. These acidic conditions present unique challenges for remediation because they increase the mobility and bioavailability of heavy metals, making them more toxic (Yang *et al.*, 2016). Additionally, they limit the effectiveness of existing bioremediation methods that rely on carbonate-producing bacteria, as these bacteria often struggle in acidic environments (Saad *et al.*, 2021). Therefore, novel bioremediation solutions are critically needed to effectively address heavy metal contamination in acidic soils. Hu, *et al.*, (2024) explored the potential of *Lysinibacillus capsica* for bioremediating Cu in acidic soil (initial pH 5.16). The bacteria significantly increased the carbonate-bound state of the soil after 30 days, reducing metal mobility and bioavailability. Additionally, *L. capsica* raised the soil pH during remediation, further reducing acidity and stabilising the heavy metals. However, large-scale field application effectiveness remains untested, requiring further research to evaluate long-term survival and effectiveness in acidic soils. Huang *et al.*, (2024) studied a two-step MICP method for remediating high Cd concentration solutions. Direct exposure of *Sporosarcina pasteurii* to Cd (10-40 mM) decreased urease activity, lowering Cd immobilisation efficiency. Simulations suggested nearly complete Cd removal when the carbonate to Cd concentration ratio was greater than 1:1. However, higher Cd concentrations limited carbonate production, resulting in incomplete Cd precipitation and decreased pH solution. Wang *et al.*, (2023) investigated a novel EK-PRB (Electrokinetic-Permeable Reactive Barrier) technology for removing Cu and Pb from soil. The bio-PRB (containing urease enzyme) in the EK reactor enhanced Cu and Pb removal. Acidic conditions near the anode promoted Cu and Pb desorption from the soil, allowing them to migrate towards the bio-PRB. There, they combined with CO_3^{2-} ions produced by urease to form precipitates like malachite (for Cu) and cerussite (for Pb), effectively removing them from the soil. However,

595 acidic conditions could lead to competition, as some Cu and Pb might combine with CO_3^{2-} ions migrating towards
596 the anode, reducing their removal by the bio-PRB itself.

597 Hu *et al.*, (2023) addressed the challenge of acidic environments releasing Pb captured by biochar. They
598 proposed using MICP to create a $CaCO_3$-surface barrier around the biochar after Pb capture. This barrier
599 physically blocks contact between acids and Pb and chemically buffers against acidic attacks. The study
600 demonstrated that MICP treatment significantly increased the stable fraction of Pb immobilised by biochar, with
601 optimised conditions raising the stable Pb fraction from 4.8% to 92.5% compared to biochar alone. Further
602 investigation is needed to validate its effectiveness in real-world soil settings. Xue *et al.*, (2022) proposed a method
603 to improve Cu immobilisation using MICP in acidic environments (pH < 4). They cultivated ureolytic microbes
604 separately (without Cu) to produce NH_4^+ and OH^- ions, then added the culture solution to Cu-rich water. The OH-
605 ions reacted with CO_2 to form CO_3^{2-} for Cu immobilisation (as azurite or malachite, depending on final pH). This
606 approach avoided exposing bacteria to high Cu concentrations, protecting their activity and promoting efficient
607 Cu immobilisation even in Cu-rich environments. However, very high Cu concentrations (above 50 mM) could
608 still affect the bacteria. Further research is needed to determine the ideal ratio of bacteria to Cu solution to avoid
609 overly alkaline environments that hinder Cu immobilisation. Additionally, the long-term stability of immobilised
610 Cu and the potential for Cu release over time require further investigation.

611 6.2. Environmental Impact

612 Despite the eco-friendliness of MICP as a bio-mediated, nature-based approach, certain environmental concerns
613 necessitate further research and development to optimise its benefits. Key areas for optimisation include materials,
614 processes, and performance of MICP applications. Jiang *et al.*, (2022) highlighted that bio-stimulation could
615 address the drawbacks of bio-augmentation, such as higher costs, unpredictable environmental risks, and labour-
616 intensive procedures. Additionally, MICP's engineering performance can be compromised by environmental
617 factors like wet-dry cycles, freeze-thaw cycles, and acid rain infiltration, which necessitates robust experimental
618 approaches to characterise the durability of MICP-treated soils. Porter *et al.*, (2021) reported that the ureolytic
619 pathway, the most commonly used metabolic route for engineered MICP, has poor sustainability due to the high
620 carbon footprint and energy demand of supplied urea, as well as the eutrophication potential of ammonium waste.
621 They noted that MICP using ureolytic bacteria has the highest embodied energy (28.4 MJ), while MICP with
622 carbonic anhydrase-producing bacteria has the lowest (12.9 MJ). The high embodied energy is predominantly due
623 to laboratory-grade calcium chloride, which accounts for 44-98% of the total energy. Wang *et al.*, (2024) observed
624 that the ammonia/ammonium by-products of ureolysis-driven MICP/EICP processes pose environmental risks

such as eutrophication, oxygen depletion, and increased toxicity when released in excess. They emphasised optimising MICP/EICP solution dosages to avoid adverse effects on local flora and fauna, prevent root penetration issues, and manage residual chemicals like unreacted $CaCl_2$ and urea that can alter soil salinity and affect plant growth.

Sun *et al.*, (2024) evaluated the concentration of heavy metals and other pollutants in the waste slurry supernatant, comparing them to national standards to identify potential environmental hazards. They investigated the impact of waste slurry on soil chemistry and plant growth, finding that while MICP is effective for some heavy metals, it has limitations for others, such as arsenic. However, the study lacked a comprehensive analysis of the broader environmental impact of the entire MICP process, including air pollution, energy consumption, and mitigation strategies beyond MICP optimisation. Justo-Reinoso *et al.*, (2023) conducted a Life Cycle Assessment (LCA) of bacteria-based self-healing concretes (BBSHC), offering insights relevant to an Environmental Impact Assessment (EIA). The LCA compared the environmental impact of producing 1 cubic meter of BBSHC with conventional concrete of similar strength and assessed the potential reduction in steel reinforcement needs. The study provided a basis for understanding BBSHC's environmental footprint by analysing factors like energy consumption and material requirements. However, it did not explicitly state the environmental benefits or drawbacks compared to conventional concrete, nor did it provide a complete EIA. Future research should aim to bridge these gaps by developing more sustainable MICP methods, thoroughly evaluating long-term environmental impacts, and expanding the scope of EIAs to encompass the full lifecycle and broader ecological consequences of MICP applications.

6.3. Cost Considerations

Among the numerous studies on MICP for heavy metal abatement, only a few have explicitly projected MICP as a low-cost and eco-friendly method. However, the application of MICP in other fields, such as soil stabilisation, has a wealth of well-documented reports on the cost-effectiveness of the technique (Gowthaman *et al.*, 2023; Omoregie *et al.*, 2019b). This discrepancy highlights the need for more research focusing on the economic aspects of MICP for heavy metal immobilisation. For instance, Huang *et al.*, (2024) proposed a two-step MICP method as a more cost-effective alternative. While the authors suggest a potentially more cost-effective method for Cd remediation, a comprehensive cost analysis is necessary to determine its true feasibility and widespread applicability. Xing *et al.*, (2023) demonstrated the potential of MICP for Zn-contaminated soil remediation, but a crucial aspect, cost analysis, is missing. Without a comprehensive cost analysis considering scale-up, it is

challenging to assess MICP's economic viability for extensive remediation projects. Furthermore, a comparison of MICP's costs with established Zn remediation techniques is lacking, which is essential to demonstrate its economic advantage.

Zeng *et al.*, (2021) investigated MICP for remediating toxic metals in landfill leachate, mentioning its cost-effectiveness without providing a detailed cost breakdown. The economic viability for large-scale applications remains unclear without a thorough cost analysis considering the material, labour, equipment costs, and scalability challenges. Furthermore, the study does not account for all potential expenses, such as optimising urea dosage and recovering ammonium, which could impact its cost-effectiveness. Hu *et al.*, (2021) explored MICP for removing calcium and contaminants from hypersaline-produced water, highlighting its potential for low cost due to the efficient use of urea and the possibility of ammonium recovery. However, a complete cost breakdown and comparison with other treatment methods are needed to assess MICP's relative cost-effectiveness accurately. Mwandira *et al.*, (2017) investigated the use of *Pararhodobacter* sp. for Pb removal from contaminated sites, noting its effectiveness in lab studies. However, further investigation is needed for real-world applications, including a cost-effectiveness assessment.

7. Potential Future Directions for MICP to Address Challenges

7.1. Reducing Copper Toxicity

To improve MICP's effectiveness, scholars can explore genetic modification to develop bacteria with higher Cu tolerance. Utilising CRISPR-Cas9 or other gene-editing technologies (Hu *et al.*, 2024a), researchers can insert/modify Cu-resistance genes in ureolytic bacteria. Alternatively, exposing bacteria to gradually increasing Cu concentrations can help select naturally occurring Cu-resistant strains. Investigating culture conditions that enhance ureolytic activity and CO_3 precipitation in the presence of Cu is crucial. Scholars can experiment with growth media formulations in MICP studies, such as adding chelating agents like EDTA or specific amino acids, and phosphate that bind Cu ions. Screening urease from extremophiles or Cu-tolerant plants can identify enzymes with high activity and stability in the presence of Cu ions. Investigating methods to immobilise urease on various substrates, like silica gel, alginate beads, or polyurethane foams, can enhance their stability and reusability in MICP processes.

7.2. Acid-Tolerant Ureolytic Bacteria

To enhance MICP in acidic soils, the identification or engineering of acid-tolerant ureolytic bacteria which can thrive in low-pH environments should be explored. Researchers in this area could also focus more on isolating new novel bacteria from underexplored acidic environments. Subsequent lab and field trials can assess the survival and efficacy of these engineered bacteria in acidic soils. Another approach to enhance MICP in acidic soils is soil pre-conditioning, which involves modifying soil properties before MICP application to create a more favourable environment for ureolytic bacteria and CO_3 precipitation. This could include the addition of buffering agents such as lime to raise soil pH to a level conducive to bacterial activity. Testing different application methods and monitoring soil pH changes over time can help optimise this pre-conditioning process. Comparing the effectiveness of two-stage approaches with traditional single-stage methods can provide insights into the optimal treatment strategy for acidic soils in terms of heavy metal immobilisation and soil pH stabilisation.

7.3. Long-term Stability and Monitoring

Investigating the long-term stability of MICP is crucial for assessing its effectiveness in immobilising heavy metals and preventing their release over time. Conducting field trials over several years can provide insights into the durability of the CO_3 precipitates formed and their resistance to environmental changes. Establishing methods to monitor changes in metal mobility, soil chemistry, and microbial communities over time can help identify potential issues early and guide adjustments to the treatment process. Continuous monitoring of soil parameters can provide valuable data on the long-term impact of MICP on the environment and help researchers refine their approach for optimal remediation outcomes. Field trials and environmental monitoring can provide valuable insights into the long-term effectiveness and environmental impact of MICP, ultimately enhancing its applicability as a sustainable remediation technique.

7.4. Minimising Ammonia Production

Mitigating the effects of NH_4^+ production in MICP is crucial for improving the efficiency and sustainability of the process. Future scholars can minimise ammonia production by focusing on manipulating bacterial urease genes to reduce the enzyme's activity without affecting its ureolytic function. Another avenue is metabolic engineering, which involves modifying bacterial metabolic pathways to divert the carbon and nitrogen fluxes towards carbonate precipitation instead of ammonia formation. This can be achieved by enhancing the activity of enzymes involved in CO_3 precipitation pathways while reducing those involved in ammonia production. Enhancing Cu-CO_3 precipitation is another key area for future research such as using additives (i.e., organic ligands or polymers).

This can also prevent their dissolution in the presence of ammonia. Additionally, optimising the concentrations of reactants involved in carbonate precipitation can promote the formation of stable Cu-CO_3 precipitates.

7.5. Enhancing Cost Consideration in MICP for Heavy Metal Immobilisation

Addressing the limitation of cost consideration in MICP for heavy metal immobilisation is crucial for several reasons. Firstly, understanding the economic feasibility of MICP is essential for its widespread adoption and application in remediation projects. Without a comprehensive cost analysis, decision-makers may be hesitant to invest in MICP, opting for more traditional but potentially less sustainable remediation methods. Secondly, cost consideration is vital for optimising MICP processes and making them more efficient and affordable. By identifying cost-effective strategies and materials, researchers can enhance the viability and scalability of MICP for heavy metal immobilisation. Future research should focus on conducting detailed cost analyses that include all relevant expenses, such as material costs, labour costs, equipment costs, and waste management costs. Additionally, comparisons with other remediation techniques should be made to demonstrate the economic advantages of MICP. Moreover, studies should explore innovative approaches to reduce costs, such as using alternative materials, optimising process parameters, and integrating MICP with other remediation technologies. By addressing these aspects, future research can provide valuable insights into the cost-effectiveness of MICP for heavy metal immobilisation and pave the way for its wider application in environmental remediation.

7.6. Leveraging Machine Learning for Optimal Performance

Future research should increasingly leverage machine learning to improve MICP processes for cost-effective heavy metal remediation. By analysing data from experiments and field trials, machine learning algorithms can identify patterns and relationships to optimise various aspects of MICP, including culture conditions, additive formulations, and long-term stability predictions. For example, machine learning can predict optimal culture conditions for ureolytic bacteria and identify bacteria with high heavy metal resistance. Additionally, it can enhance additive usage to reduce heavy metal toxicity and enhance co-precipitation. Furthermore, machine learning can model the effects of different interventions, aiding in the design of efficient and sustainable remediation strategies. By optimising reagent usage, improving microbial scalability, and assessing environmental impacts, machine learning enhances the viability and affordability of MICP as a remediation method. Future research should prioritise the integration of machine learning techniques to advance the field of MICP and its applications in heavy metal remediation.

7.7. Incorporating Comprehensive Environmental Impact Assessment

To advance the field of MICP for heavy metal removal, it is crucial to incorporate comprehensive EIA. Thorough environmental risk assessments for bacterial strains used in MICP are vital, including their potential to disrupt native microbial communities, become invasive, or introduce antibiotic resistance. Enhancing bacterial specificity and developing control mechanisms to prevent accidental release or uncontrolled growth will mitigate risks. Implementing life cycle monitoring programmes to track the long-term effects of bacterial processes on soil and concrete is necessary. This includes monitoring potential degradation, chemical leaching, and impacts on structural integrity and soil health. Exploring novel or engineered bacterial strains that produce less harmful metabolites can improve both environmental and material outcomes. Developing sustainable methods for large-scale production of bacterial spores used in MICP is important. This could involve exploring alternative growth substrates, optimising culturing processes to reduce waste, and investigating renewable energy sources. Expanding LCA studies to cover the entire MICP process, including resource extraction, spore production, transportation, and waste disposal, will provide a comprehensive understanding of the environmental footprint and identify areas for improvement. Investigating potential air quality impacts, including emissions from bacterial growth processes or dust generation, is essential. Developing mitigation strategies to minimise negative effects on air quality and optimising MICP processes to reduce energy consumption is crucial. Future research should focus on understanding the speciation and bioavailability of heavy metals immobilised by MICP and their long-term stability and mobility under different environmental conditions. **Figure 6** provides a concise visual summary of the diverse and promising future directions, and opinions, reflecting the collective efforts aimed at promoting MICP as a sustainable and efficient solution for mitigating heavy metal contamination across various industries and disciplines.

[INSERT FIGURE HERE]

Figure 6: Pie chart representing the future directions of MICP applications for heavy metal removal.

8. Conclusion

This review highlights the substantial potential of MICP as a versatile bioremediation technology, extending beyond heavy metal removal to contribute to sustainable construction practices. The growing body of research underscores its effectiveness and adaptability. MICP's biogeochemical prowess, particularly through ureolysis,

offers a scalable solution for the remediation of heavy metals, including Cu, Pb, Cd, Ni, and Zn. Additionally, alternative pathways like photosynthesis and nitrate reduction demonstrate its broad applicability in environmental cleanup. Looking ahead, continuous exploration and interdisciplinary collaboration are crucial to unlock MICP's full potential. Future advancements in nanomaterials and genetic engineering hold significant promise for further optimisation. A key area of focus is overcoming challenges associated with high Cu concentrations and highly acidic soils or tailings, which can inhibit the urease enzyme critical to MICP processes. Addressing these limitations and prioritising safety practices are essential for MICP to become a cornerstone of sustainable solutions for heavy metal contamination. Furthermore, enhancing cost considerations through detailed analyses and innovative approaches will be vital for the practical application and scalability of MICP. Leveraging machine learning to optimise MICP processes can also play a significant role in improving efficiency and cost-effectiveness. This review paves the way for researchers and industry experts to shape the future of MICP. Embracing collaboration and cutting-edge technologies can ensure MICP plays a critical role in achieving a cleaner and healthier environment, cementing its place as a key tool in environmental remediation and sustainable construction.

References

Achal, V., Mukherjee, A. and Reddy, M. S. (2011a) Effect of calcifying bacteria on permeation properties of concrete structures, *Journal of Industrial Microbiology and Biotechnology,* **38** (9): pp. 1229–1234. DOI:10.1007/s10295-010-0901-8.

Achal, V., Pan, X., Fu, Q. and Zhang, D. (2012a) Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli, Journal of Hazardous Materials*, 201–202, pp. 178–184. DOI: 10.1016/j.jhazmat.2011.11.067.

Achal, V., Pan, X., Lee, D.-J., Kumari, D. and Zhang, D. (2013) Remediation of Cr(VI) from chromium slag by biocementation, *Chemosphere*, **93** (7), pp. 1352–1358. DOI: 10.1016/j.chemosphere.2013.08.008.

Achal, V., Pan, X. and Zhang, D. (2012b) Bioremediation of strontium (Sr) contaminated aquifer quartz sand based on carbonate precipitation induced by Sr resistant Halomonas sp., *Chemosphere*, **89** (6), pp. 764–768. DOI: 10.1016/j.chemosphere.2012.06.064.

Achal, V., Pan, X., Zhang, D. and Fu, Q. (2012c) Bioremediation of Pb-contaminated soil based on microbially induced calcite precipitation, *J Microbiol Biotechnol*, **22** (2), pp. 244–247. DOI: 10.4014/jmb.1108.08033.

Achal, Varenyam., Pan, Xiangliang. and Zhang, Daoyong. (2011b) Remediation of copper-contaminated soil by *Kocuria flava* CR1, based on microbially induced calcite precipitation, *Ecological Engineering*, **37** (10), pp. 1601–1605. DOI: 10.1016/j.ecoleng.2011.06.008.

Amos, R. T., Mayer, K. U., Blowes, D. W. and Ptacek, C. J. (2004) Reactive transport modeling of column experiments for the remediation of acid mine drainage, *Environmental Science and Technology*, **38** (11), pp. 3131–3138. DOI:10.1021/es0349608.

Bachmeier, K. L., Williams, A. E., Warmington, J. R. and Bang, S. S. (2002) Urease activity in microbiologically-induced calcite precipitation, *Journal of Biotechnology*, **93** (2), pp. 171–181. DOI: 10.1016/S0168-1656(01)00393-5.

Bai, H., Liu, D., Zheng, W., Ma, L., Yang, S., Cao, J., Lu, X., Wang, H. and Mehta, N. (2021) Microbially-induced calcium carbonate precipitation by a halophilic ureolytic bacterium and its potential for remediation of heavy metal-contaminated saline environments, *International Biodeterioration and Biodegradation*, **165**, article 105311. DOI: 10.1016/j.ibiod.2021.105311.

Bai, H., Zhang, Q., Zhou, X., Chen, J., Chen, Z., Liu, Z., Yan, J. and Wang, J. (2023) Removal of fluoroquinolone antibiotics by adsorption of dopamine-modified biochar aerogel, *Korean Journal of Chemical Engineering*, **40** (1), pp. 215–222. DOI: 10.1007/s11814-022-1263-4.

Basri, H. F., Anuar, A. N., Halim, M. H. A., Yuzir, M. A., Muda, K., Omoregie, A. I. and Najib, M. Z. M. (2023) Aerobic granular sludge development using diatomite for low-strength wastewater treatment, *Environmental Monitoring and Assessment*, **195** (3), pp. 420. DOI: 10.1007/s10661-023-11028-9.

Benini, S., Ciurli, S., Nolting, H. F. and Mangani, S. (1996) X-ray absorption spectroscopy study of native and phenylphosphorodiamidate-inhibited *Bacillus pasteurii* urease, *European Journal of Biochemistry*, **239** (1), pp. 61–66. DOI: 10.1111/j.1432-1033.1996.0061u.x.

Bhattacharya, A., Naik, S. N. and Khare, S. K. (2018) Harnessing the bio-mineralization ability of urease producing Serratia marcescens and *Enterobacter cloacae* EMB19 for remediation of heavy metal cadmium (II), *Journal of Environmental Management*, **215**, pp. 143–152. DOI: 10.1016/j.jenvman.2018.03.055.

826 Bihari, V. and Basu, S. K. (1984) Immobilized Microbial Cells - General and Process Engineering Evaluation,
827 *Journal of Scientific and Industrial Research*, **43** (12), pp. 679–687.

828 Bisht, V., Chaurasia, L. and Singh, L. P. (2020) Studies on corrosion and carbonation resistance by bacteria-
829 mediated mineralization in concrete, *ACI Materials Journal*, **117** (4), pp. 13–26. DOI: 10.14359/51724610.

830 Brown, R. L., Gibson, J. A., Fenton, J. C., Snedden, W., Clark, M. L. and Sladen, G. E. (1975) Ammonia and urea
831 transport by the excluded human colon, *Clinical Science and Molecular Medicine*, **48** (4), pp. 279–287.
832 DOI: 10.1042/cs0480279.

833 Bundeleva, I. A., Ménez, B., Augé, T., Bodénan, F., Recham, N. and Guyot, F. (2014) Effect of cyanobacteria
834 *Synechococcus* PCC 7942 on carbonation kinetics of olivine at 20 °c, *Minerals Engineering*, **59**, pp. 2–11.
835 DOI: 10.1016/j.mineng.2014.01.019.

836 Chen, H.J., Huang, Y.H., Chen, C.C., Maity, J. P. and Chen, C.Y. (2019) Microbial Induced Calcium Carbonate
837 Precipitation (MICP) Using Pig Urine as an Alternative to Industrial Urea, *Waste and Biomass Valorization*,
838 **10** (10), pp. 2887–2895. DOI: 10.1007/s12649-018-0324-8.

839 Chen, H.J., Huang, Y.H., Chen, C.C., Maity, J. P. and Chen, C.Y. (2018) Microbial Induced Calcium Carbonate
840 Precipitation (MICP) Using Pig Urine as an Alternative to Industrial Urea, *Waste and Biomass Valorization*,
841 **10**, pp. 2887–2895. DOI: 10.1007/s12649-018-0324-8.

842 Chen, X. and Achal, V. (2019) Biostimulation of carbonate precipitation process in soil for copper immobilization,
843 *Journal of Hazardous Materials*, **368**, pp. 705–713. DOI: 10.1016/j.jhazmat.2019.01.108.

844 Chetty, K., Garbe, U., Wang, Z., Zhang, S., McCarthy, T., Hai, F. and Jiang, G. (2022) Bioconcrete based on
845 sulfate-reducing bacteria granules: cultivation, mechanical properties, and self-healing performance,
846 *Journal of Sustainable Cement-Based Materials*. DOI: 10.1080/21650373.2022.2153389.

847 Crane, L., Ray, H., Hamdan, N. and Boyer, T. H. (2022) Enzyme-induced carbonate precipitation utilizing fresh
848 urine and calcium-rich zeolites, *Journal of Environmental Chemical Engineering*, **10** (2). DOI:
849 10.1016/j.jece.2022.107238.

850 Cuaxinque-Flores, G., Aguirre-Noyola, J. L., Hernández-Flores, G., Martínez-Romero, E., Romero-Ramírez, Y.
851 and Talavera-Mendoza, O. (2020) Bioimmobilization of toxic metals by precipitation of carbonates using

Sporosarcina luteola: An in vitro study and application to sulfide-bearing tailings, *Science of the Total Environment*, **724**, article 138124. DOI: 10.1016/j.scitotenv.2020.138124.

Cui, G. W., Mei, Y., L, Hua. S. and Zhang, D. X. (2023) Health risk assessment of heavy metal pollution and its sources in agricultural soils near Hongfeng Lake in the mining area of Guizhou Province, China, *Frontiers in Public Health*, **11**, article 1276925. DOI: 10.3389/fpubh.2023.1276925.

de Oliveira, D., Horn, E. J. and Randall, D. G. (2021) Copper mine tailings valorization using microbial induced calcium carbonate precipitation, *Journal of Environmental Management*, **298**, article 112440. DOI: 10.1016/j.jenvman.2021.113440.

Disi, Z. Al, Attia, E., Ahmad, M. I. and Zouari, N. (2022) Immobilization of heavy metals by microbially induced carbonate precipitation using hydrocarbon-degrading ureolytic bacteria, *Biotechnology Reports*, **35,** article e00747. DOI: 10.1016/j.btre.2022.e00747.

Dong, Y., Gao, Z., Di, J., Wang, D., Yang, Z., Wang, Y., Guo, X. and Li, K. (2023) Experimental study on solidification and remediation of lead–zinc tailings based on microbially induced calcium carbonate precipitation (MICP), *Construction and Building Materials*, **369**, article 130611. DOI: 10.1016/j.conbuildmat.2023.130611.

Ejechi, B. O. and Akpomedaye, D. E. (1998) The hurdle effect of ureolytic *Proteus* sp. activity and *Trichoderma Viride* culture filtrate on growth and wood deteriorating activities of four fungi, *International Biodeterioration and Biodegradation*, **41** (2), pp. 153–155. DOI: 10.1016/S0964-8305(97)00083-8.

El Enshasy, H., Dailin, D. J., Malek, R. A., Nordin, N. Z., Keat, H. C., Eyahmalay, J., *et al.* (2020) Biocement: A Novel Approach in the Restoration of Construction Materials BT - Microbial Biotechnology Approaches to Monuments of Cultural Heritage, in: Yadav, A. N., Rastegari, A. A., Gupta, V. K., and Yadav, N. (eds.) *Microbial Biotechnology Approaches to Monuments of Cultural Heritage*. Singapore: Springer Singapore, pp. 177–198.

Eltarahony, M., Kamal, A., Zaki, S. and Abd-El-Haleem, D. (2021) Heavy metals bioremediation and water softening using ureolytic strains *Metschnikowia pulcherrima* and *Raoultella planticola*, *Journal of Chemical Technology and Biotechnology*, **96** (11), pp. 3152–3165. DOI:10.1002/jctb.6868.

878 Farajnia, A., Shafaat, A., Farajnia, S., Sartipipour, M. and Khodadadi Tirkolaei, H. (2022) The efficiency of
879 ureolytic bacteria isolated from historical adobe structures in the production of bio-bricks, *Construction*
880 *and Building Materials*, **317**, pp. 125868. DOI: 10.1016/j.conbuildmat.2021.125868.

881 Frommlet, J. C., Sousa, M. L., Alves, A., Vieira, S. I., Suggett, D. J. and Serôdio, J. (2015) Coral symbiotic algae
882 calcify ex hospite in partnership with bacteria, *Proceedings of the National Academy of Sciences of the*
883 *United States of America*, **112** (19), pp. 6158–6163. DOI: 10.1073/pnas.1420991112.

884 Fujita, Y., Grant Ferris, F., Daniel Lawson, R., Colwell, F. S. and Smith, R. W. (2000) Calcium carbonate
885 precipitation by ureolytic subsurface bacteria, *Geomicrobiology Journal*, **17** (4), pp. 305–318. DOI:
886 10.1080/782198884.

887 Gao, K., Zhu, H., Zhou, W., Hu, S., Zhang, B., Dang, Z. and Liu, C. (2023) Effect of phosphate on ferrihydrite
888 transformation and the associated arsenic behavior mediated by sulfate-reducing bacterium, *Journal of*
889 *Hazardous Materials*, **448**, article 130863. DOI: 10.1016/j.jhazmat.2023.130863.

890 Garau, G., Castaldi, P., Santona, L., Deiana, P. and Melis, P. (2007) Influence of red mud, zeolite and lime on
891 heavy metal immobilization, culturable heterotrophic microbial populations and enzyme activities in a
892 contaminated soil, *Geoderma*, **142** (1–2), pp. 47–57. DOI: 10.1016/j.geoderma.2007.07.011.

893 García, C., Hernández, T., Costa, F. and Ceccanti, B. (1994) Biochemical Parameters In Soils Regenerated By The
894 Addition Of Organic Wastes, *Waste Management and Research*, **12** (6), pp. 457–466. DOI:
895 10.1006/wmre.1994.1035.

896 Goldstein, R. A. (1994) The role of whitings in CO_2 circulation and sequestration, *Journal of the Air and Waste*
897 *Management Association*, **44** (1), pp. 53. DOI: 10.1080/1073161x.1994.10467238.

898 Gomez, M. G., Anderson, C. M., Graddy, C. M. R., DeJong, J. T., Nelson, D. C. and Ginn, T. R. (2017) Large-
899 scale comparison of bioaugmentation and biostimulation approaches for biocementation of sands, *Journal*
900 *of Geotechnical and Geoenvironmental Engineering*, **143** (5), pp. 4016124–4016136. DOI:
901 10.1061/(ASCE)GT.1943-5606.0001640.

902 Goswami, R. and Neog, N. (2023) Heavy Metal Pollution in the Environment: Impact on Air Quality and Human
903 Health Implications BT- Heavy Metal Toxicity: Environmental Concerns, Remediation and Opportunities,
904 in: Singh, R. P., Singh, P., and Srivastava, A. (eds.) Singapore: Springer Nature Singapore, pp. 75–103.

905 Gowthaman, S., Iki, T., Ichinohe, A., Nakashima, K. and Kawasaki, S. (2022) Feasibility of Bacterial-Enzyme
906 Induced Carbonate Precipitation Technology for Stabilizing Fine-grained Slope Soils, *Frontiers in Built*
907 *Environment*, pp. 1–15. DOI: 10.3389/fbuil.2022.1044598.

908 Gowthaman, S., Koizumi, H., Nakashima, K. and Kawasaki, S. (2023) Field experimentation of bio-cementation
909 using low-cost cementation media for preservation of slope surface, *Case Studies in Construction*
910 *Materials*, **18**, article e02086. DOI: 10.1016/j.cscm.2023.e02086.

911 Gui, R., Pan, Y.X., Ding, D.X., Liu, Y. and Zhang, Z.J. (2018) Experimental study on the fine-grained uranium
912 tailings reinforced by MICP, *Advances in Civil Engineering*, article 2928985. DOI:10.1155/2018/2928985.

913 Gunes, Y. and Balci, N. (2021) The Catalytic Effect of the Heterotrophic Bacterium *Virgibacillus marismortui* on
914 Basaltic Rock Dissolution Under Excess Nutrient Conditions, *Geomicrobiology Journal*, **38** (4), pp. 315–
915 328. DOI: 10.1080/01490451.2020.1852453.

916 Hama Aziz, K. H., Mustafa, F. S., Omer, K. M., Hama, S., Hamarawf, R. F. and Rahman, K. O. (2023) Heavy
917 metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their
918 toxicity: a review, *RSC Adv.*, **13** (26), pp. 17595–17610. DOI: 10.1039/D3RA00723E.

919 Hammes, F., Seka, A., De Knijf, S. and Verstraete, W. (2003) A novel approach to calcium removal from calcium-
920 rich industrial wastewater, *Water Research*, **37**, pp. 699–704. DOI: 10.1016/S0043-1354(02)00308-1.

921 Hatayama, K. and Saito, K. (2019) Calcite formation induced by *Ensifer adhaerens, Microbacterium testaceum,*
922 *Paeniglutamicibacter kerguelensis, Pseudomonas protegens* and *Rheinheimera texasensis, Antonie van*
923 *Leeuwenhoek, International Journal of General and Molecular Microbiology*, **112** (5), pp. 711–721. DOI:
924 10.1007/s10482-018-1204-8.

925 He, Z., Xu, Y., Wang, W., Yang, X., Jin, Z., Zhang, D. and Pan, X. (2023) Synergistic mechanism and application
926 of microbially induced carbonate precipitation (MICP) and inorganic additives for passivation of heavy
927 metals in copper-nickel tailings, *Chemosphere*, **311**, article 136981. DOI:
928 10.1016/j.chemosphere.2022.136981.

929 He, Z., Xu, Y., Yang, X., Shi, J., Wang, X., Jin, Z., Zhang, D. and Pan, X. (2022) Passivation of heavy metals in
930 copper–nickel tailings by in-situ bio-mineralization: A pilot trial and mechanistic analysis, *Science of The*
931 *Total Environment*, **838**, article 156504. DOI: 10.1016/j.scitotenv.2022.156504.

Herath, I. K., Wu, S., Ma, M. and Ping, H. (2022) Heavy metal toxicity, ecological risk assessment, and pollution sources in a hydropower reservoir, *Environmental Science and Pollution Research*, **29** (22), pp. 32929–32946. DOI: 10.1007/s11356-022-18525-3.

Hu, H., Tang, C.-S., Shen, Z., Pan, X., Gu, K., Fan, X., Lv, C., Mu, W. and Shi, B. (2023) Enhancing lead immobilization by biochar: Creation of "surface barrier" via bio-treatment, *Chemosphere*, **327**, article 138477. DOI: 10.1016/j.chemosphere.2023.138477.

Hu, L., Wang, H., Xu, P. and Zhang, Y. (2021) Biomineralization of hypersaline produced water using microbially induced calcite precipitation, *Water Research*, **190**, article 116753. DOI: 10.1016/j.watres.2020.116753.

Hu, X., He, B., Liu, Y., Ma, S. and Yu, C. (2024a) Genomic characterization of a novel ureolytic bacteria, *Lysinibacillus capsici* TSBLM, and its application to the remediation of acidic heavy metal-contaminated soil, *Science of The Total Environment*, **927**, article 172170. DOI: 10.1016/j.scitotenv.2024.172170.

Hu, X., Yu, C., Li, X., Zou, J., Du, Y. and Paterson, D. M. (2024b) Biomineralization of heavy metals based on urea transport and hydrolysis within a new bacterial isolate, *B. intermedia* TSBOI, *Journal of Hazardous Materials*, **469**, article 134049. DOI: 10.1016/j.jhazmat.2024.134049.

Hu, X., Yu, C., Shi, J., He, B., Wang, X. and Ma, Z. (2024c) Biomineralization mechanism and remediation of Cu, Pb and Zn by indigenous ureolytic bacteria *B. intermedia* TSBOI, *Journal of Cleaner Production*, **436**, article 140508. DOI: 10.1016/j.jclepro.2023.140508.

Huang, L., Li, M., Si, G., Wei, J., Ngo, H. H., Guo, W., *et al.* (2018) Assessment of microbial products in the biosorption process of Cu(II) onto aerobic granular sludge: Extracellular polymeric substances contribution and soluble microbial products release, *Journal of Colloid and Interface Science*, **527**, pp. 87–94. DOI: 10.1016/j.jcis.2018.05.032.

Huang, X., Zhang, R., Xu, Y. and Zheng, J. (2024) Immobilization of Cd^{2+} in an aqueous environment using a two-step microbial-induced carbonate precipitation method, *Journal of Environmental Management*, **351**, article 119868. DOI: 10.1016/j.jenvman.2023.119868.

Ivanov, V. and Stabnikov, V. (2020) Environmental safety of biotechnological materials and processes, in: *Bio-based Materials and Biotechnologies for Eco-efficient Construction*. Advanced Research Laboratory and Department of Biotechnology and Microbiology, National University of Food Technologies, Kyiv, Ukraine: Elsevier, pp. 359–375.

960 Ivanov, V., Stabnikov, V., Stabnikova, O. and Kawasaki, S. (2019) Environmental safety and biosafety in
961 construction biotechnology, *World Journal of Microbiology and Biotechnology*, **35** (2), pp. 26.
962 DOI:10.1007/s11274-019-2598-9.

963 Jiang, N.J., Wang, Y.J., Chu, J., Kawasaki, S., Tang, C.S., Cheng, L., *et al.* (2022) Bio-mediated soil improvement:
964 An introspection into processes, materials, characterization and applications, *Soil Use and Management*,
965 **38** (1), pp. 68–93. DOI: 10.1111/sum.12736.

966 Jing, L., Kiewhuo, P., Ao, B. and Kakati, L. N. (2023) Nutrient stabilization and heavy metal reduction in organic
967 wastes using *Eisenia fetida* (Savigny) and *Perionyx excavatus* (Perrier), *Environment, Development and*
968 *Sustainability,* pp. 9165–9184. DOI: 10.1007/s10668-023-03088-1.

969 Joshi, S., Goyal, S., Mukherjee, A. and Reddy, M. S. (2019) Protection of concrete structures under sulfate
970 environments by using calcifying bacteria, *Construction and Building Materials*, **209**, pp. 156–166. DOI:
971 10.1016/j.conbuildmat.2019.03.079.

972 Justo-Reinoso, I., Arena, N., Reeksting, B. J., Gebhard, S. and Paine, K. (2023) Bacteria-based self-healing
973 concrete− A life cycle assessment perspective, *Developments in the Built Environment*, **16**, pp. 100244.
974 DOI: 10.1016/j.dibe.2023.100244.

975 Kang, B., Zha, F., Li, H., Xu, L., Sun, X. and Lu, Z. (2022) Bio-Mediated Method for Immobilizing Copper
976 Tailings Sand Contaminated with Multiple Heavy Metals, *Crystals*, **12** (4), article 522. DOI:
977 10.3390/cryst12040522.

978 Kang, C.H., Han, S.H., Shin, Y., Oh, S. J. and So, J.S. (2014) Bioremediation of Cd by Microbially Induced Calcite
979 Precipitation, *Applied Biochemistry and Biotechnology*, **172** (6), pp. 2907–2915. DOI: 10.1007/s12010-
980 014-0737-1.

981 Kang, C.-H., Oh, S. J., Shin, Y., Han, S.-H., Nam, I.-H. and So, J.-S. (2015) Bioremediation of lead by ureolytic
982 bacteria isolated from soil at abandoned metal mines in South Korea, *Ecological Engineering*, **74**, pp. 402–
983 407. DOI: 10.1016/j.ecoleng.2014.10.009.

984 Kang, C.-H., Shin, Y. J., Anbu, P., Nam, I.-H. and So, J.-S. (2016) Biosequestration of copper by bacteria isolated
985 from an abandoned mine by using microbially induced calcite precipitation, *Journal of General and*
986 *Applied Microbiology*, **62** (4), pp. 206–212. DOI:10.2323/jgam.2016.03.001.

Karnachuk, O. V, Rusanov, I. I., Panova, I. A., Grigoriev, M. A., Zyusman, V. S., Latygolets, E. A., *et al.* (2021) Microbial sulfate reduction by *Desulfovibrio* is an important source of hydrogen sulfide from a large swine finishing facility, *Scientific Reports*, **11** (1). DOI: 10.1038/s41598-021-90256-w.

Kawaguchi, T. and Decho, A. W. (2002) A laboratory investigation of cyanobacterial extracellular polymeric secretions (EPS) in influencing $CaCO_3$ polymorphism, *Journal of Crystal Growth*, **240** (1–2), pp. 230–250. DOI: 10.1016/S0022-0248(02)00918-1.

Keykha, H. A., Asadi, A., Huat, B. B. K. and Kawasaki, S. (2019) Microbial induced calcite precipitation by *Sporosarcina pasteurii* and *Sporosarcina aquimarina*, *Environmental Geotechnics*, **6** (8), pp. 562–566. DOI: 10.1680/jenge.16.00009.

Khadim, H. J., Ammar, S. H. and Ebrahim, S. E. (2019) Biomineralization based remediation of cadmium and nickel contaminated wastewater by ureolytic bacteria isolated from barn horses soil, *Environmental Technology and Innovation*, **14**, article 100315. DOI: 10.1016/j.eti.2019.100315.

Kim, Y., Kwon, S. and Roh, Y. (2021) Effect of Divalent Cations (Cu, Zn, Pb, Cd, and Sr) on Microbially Induced Calcium Carbonate Precipitation and Mineralogical Properties, *Frontiers in Microbiology*, **12**, article 721478. DOI: 10.3389/fmicb.2021.721478.

Kumari, D., Pan, X., Lee, D.-J. and Achal, V. (2014) Immobilization of cadmium in soil by microbially induced carbonate precipitation with *Exiguobacterium undae* at low temperature, *International Biodeterioration & Biodegradation*, 94, pp. 98–102. DOI: 10.1016/j.ibiod.2014.07.007.

Lamérand, C., Shirokova, L. S., Petit, M., Bénézeth, P., Rols, J.-L. and Pokrovsky, O. S. (2022) Kinetics and mechanisms of cyanobacterially induced precipitation of magnesium silicate, *Geobiology*, 20 (4), pp. 560–574. DOI: 10.1111/gbi.12503.

Lauchnor, E. G., Schultz, L. N., Bugni, S., Mitchell, A. C., Cunningham, A. B. and Gerlach, R. (2013) Bacterially induced calcium carbonate precipitation and strontium coprecipitation in a porous media flow system, *Environmental Science and Technology*, **47** (3), pp. 1557–1564. DOI: 10.1021/es304240y.

Lauchnor, E. G., Topp, D. M., Parker, A. E. and Gerlach, R. (2015) Whole cell kinetics of ureolysis by *Sporosarcina pasteurii, Journal of Applied Microbiology*, **118** (6), pp. 1321–1332. DOI: 10.1111/jam.12804.

1014 Lee, S. H., Oh, B. Il and Kim, J. gyu (2008) Effect of various amendments on heavy mineral oil bioremediation
1015 and soil microbial activity, *Bioresource Technology*, **99** (7), pp. 2578–2587. DOI:
1016 10.1016/j.biortech.2007.04.039.

1017 Levett, A., Gagen, E. J., Vasconcelos, P. M., Zhao, Y., Paz, A. and Southam, G. (2020) Biogeochemical cycling of
1018 iron: Implications for biocementation and slope stabilisation, *Science of the Total Environment*, **707**, article
1019 136128. DOI: 10.1016/j.scitotenv.2019.136128.

1020 Li, L., Qian, C., Cheng, L. and Wang, R. (2010) A laboratory investigation of microbe-inducing CdCO3 precipitate
1021 treatment in Cd^{2+} contaminated soil, *Journal of Soils and Sediments*, 10 (2), pp. 248–254.
1022 DOI:10.1007/s11368-009-0089-6.

1023 Li, Meng., Cheng, Xiaohui. and Guo, Hongxian. (2013) Heavy metal removal by biomineralization of urease
1024 producing bacteria isolated from soil, *International Biodeterioration & Biodegradation*, **76**, pp. 81–85.
1025 DOI: 10.1016/j.ibiod.2012.06.016.

1026 Li, S., Feng, Q., Liu, J., He, Y., Shi, L., Boyanov, M. I., *et al.* (2022a) Carbonate Minerals and Dissimilatory Iron-
1027 Reducing Organisms Trigger Synergistic Abiotic and Biotic Chain Reactions under Elevated
1028 CO2Concentration, *Environmental Science and Technology*, **56** (22), pp. 16428–16440. DOI:
1029 10.1021/acs.est.2c03843.

1030 Li, X., Luo, K., Ren, J., Wang, X., Mu, Q. and Fan, W. (2017) Characterisation of extracellular polymeric
1031 substances from different cyanobacterial species and their influence on biocalcification processes,
1032 *Environmental Chemistry*, **14** (4), pp. 254–265. DOI: 10.1071/EN17068.

1033 Li, X., Wang, Y., Tang, J. and Li, K. (2022b) Removal Behavior of Heavy Metals from Aqueous Solutions via
1034 Microbially Induced Carbonate Precipitation Driven by Acclimatized *Sporosarcina pasteurii, Applied*
1035 *Sciences (Switzerland)*, **12** (19), article 9958. DOI:10.3390/app12199958.

1036 Liu, J., Su, J., Ali, A., Wang, Z. and Zhang, R. (2022a) Potential of a novel facultative anaerobic denitrifying
1037 *Cupriavidus* sp. W12 to remove fluoride and calcium through calcium bioprecipitation, *Journal of*
1038 *Hazardous Materials*, **423**, article 126976. DOI: 10.1016/j.jhazmat.2021.126976.

1039 Liu, M., Kwon, B. and Kang, P. K. (2022b) Machine learning to predict effective reaction rates in 3D porous
1040 media from pore structural features, *Scientific Reports*, **12** (1), article 5486. DOI: 10.1038/s41598-022-
1041 09495-0.

1042 Liu, S., Du, K., Huang, W., Wen, K., Amini, F. and Li, L. (2021) Improvement of erosion-resistance of bio-bricks
1043 through fiber and multiple MICP treatments, *Construction and Building Materials*, **271**, article 121573.
1044 DOI: 10.1016/j.conbuildmat.2020.121573.

1045 Mao, Q., Xie, X., Pinzon-Nuñez, D. A., Xie, Z., Liu, T. and Irshad, S. (2023) Native microalgae and *Bacillus*
1046 XZM remediate arsenic-contaminated soil by forming biological soil crusts, *Journal of Environmental*
1047 *Management*, **345**, article 118858. DOI: 10.1016/j.jenvman.2023.118858.

1048 Meier, A., Kastner, A., Harries, D., Wierzbicka-Wieczorek, M., Majzlan, J., Büchel, G. and Kothe, E. (2017)
1049 Calcium carbonates: Induced biomineralization with controlled macromorphology, *Biogeosciences*, **14**
1050 (21), pp. 4867–4878. DOI: 10.5194/bg-14-4867-2017.

1051 Mitchell, A. C. and Grant Ferris, F. (2006) The influence of *Bacillus* pasteurii on the nucleation and growth of
1052 calcium carbonate, *Geomicrobiology Journal*, **23** (3–4), pp. 213–226. DOI: 10.1080/01490450600724233.

1053 Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. Bin, Nainu, F., Khusro, A., *et al.* (2022) Impact of heavy
1054 metals on the environment and human health: Novel therapeutic insights to counter the toxicity, *Journal of*
1055 *King Saud University - Science*, **34** (3), pp. 101865. DOI: 10.1016/j.jksus.2022.101865.

1056 Mohammed, A. S., Kapri, A. and Goel, R. (2011) Heavy Metal Pollution: Source, Impact, and Remedies, in: Khan,
1057 M. S., Zaidi, A., Goel, R., and Musarrat, J. (eds.) *Biomanagement of Metal-Contaminated Soils*. Dordrecht:
1058 Springer Netherlands, pp. 1–28.

1059 Mokhtar, N., Megat Johari, M. A., Tajarudin, H. A., Al-Gheethi, A. A. and Algaifi, H. A. (2021) A sustainable
1060 enhancement of bio-cement using immobilised *Bacillus sphaericus*: Optimization, microstructural
1061 properties, and techno-economic analysis for a cleaner production of bio-cementitious mortars, *Journal of*
1062 *Cleaner Production*, **318**, article 128470. DOI: 10.1016/j.jclepro.2021.128470.

1063 Mostafa, H., Alireza, B., Hamid, H., Raouf, H. M., Hobbenaghi, M., Baghbanan, A., Hashemolhosseini, H. and
1064 Hosseini, M. R. (2023) Biomediated Conservation of Unwelded Ignimbrites in Kandovan, Iran, *Journal of*
1065 *Materials in Civil Engineering*, **35** (1), article 4022393. DOI: 10.1061/(ASCE)MT.1943-5533.0004550.

1066 Murugan, R., Suraishkumar, G. K., Mukherjee, A. and Dhami, N. K. (2021) Insights into the influence of cell
1067 concentration in design and development of microbially induced calcium carbonate precipitation (MICP)
1068 process, *PLoS ONE*, **16**, article 0254536. DOI: 10.1371/journal.pone.0254536.

Mwandira, W., Nakashima, K. and Kawasaki, S. (2017) Bioremediation of lead-contaminated mine waste by *Pararhodobacter* sp. based on the microbially induced calcium carbonate precipitation technique and its effects on strength of coarse and fine grained sand, *Ecological Engineering*, **109**, pp. 57–64. DOI: 10.1016/j.ecoleng.2017.09.011.

Mwandira, W., Nakashima, K., Kawasaki, S., Ito, M., Sato, T., Igarashi, T., *et al.* (2019) Solidification of sand by Pb(II)-tolerant bacteria for capping mine waste to control metallic dust: Case of the abandoned Kabwe Mine, Zambia, *Chemosphere*, **228**, pp. 17–25. DOI: 10.1016/j.chemosphere.2019.04.107.

Naeimi, M. and Haddad, A. (2020) Environmental impacts of chemical and microbial grouting, *Environmental Science and Pollution Research*, **27** (2), pp. 2264–2272. DOI: 10.1007/s11356-019-06614-9.

Nannipieri, P., Ciardi, C., Palazzi, T. and Badalucco, L. (1990) Short-term nitrogen reactions following the addition of urea to a grass-legume association, *Soil Biology and Biochemistry*, **22** (4), pp. 549–553. DOI: 10.1016/0038-0717(90)90192-3.

Nannipieri, P., Muccini, L. and Ciardi, C. (1983) Microbial biomass and enzyme activities: Production and persistence, *Soil Biology and Biochemistry*, **15** (6), pp. 679–685. DOI: 10.1016/0038-0717(83)90032-9.

Nidheesh, P. V, Divyapriya, G., Ezzahra Titchou, F. and Hamdani, M. (2022) Treatment of textile wastewater by sulfate radical based advanced oxidation processes, *Separation and Purification Technology*, **293**, pp. 121115. DOI: 10.1016/j.seppur.2022.121115.

Nielsen, T. H., Bonde, T. A. and Sørensen, J. (1998) Significance of microbial urea turnover in N cycling of three Danish agricultural soils, *FEMS Microbiology Ecology*, **25** (2), pp. 147–157. DOI: 10.1016/S0168-6496(97)00091-3.

Ning, X., Wang, S., Zhao, B., Long, S., Wang, Y. and Nan, Z. (2022) Arsenic and nitrate remediation by isolated FeOB strains coupled with additional ferrous iron in the iron-deficient arid soils, *Science of the Total Environment*, **825**, 154057. DOI: 10.1016/j.scitotenv.2022.154057.

Omar, A. H., Muda, K., Omoregie, A. I., Majid, Z. A., Ali, N. S. B. A. and Pauzi, F. M. (2023) Enhancement of biogranules development using magnetized powder activated carbon, *Biodegradation*, **34**, pp. 235–252. DOI: 10.1007/s10532-023-10016-7.

1095 Omoregie, A. I., Ngu, L. H., Ong, D. E. L. and Nissom, P. M. (2019a) Low-cost cultivation of *Sporosarcina*
1096 *pasteurii* strain in food-grade yeast extract medium for microbially induced carbonate precipitation (MICP)
1097 application, *Biocatalysis and Agricultural Biotechnology*, **17**, pp. 247–255. DOI:
1098 10.1016/j.bcab.2018.11.030.

1099 Omoregie, A. I., Ong, D. E. L., Li, P. Y., Senian, N., Hei, N. L., Esnault-Filet, A., Muda, K. and Nissom, P. M.
1100 (2023) Effects of push–pull injection–suction spacing on sand biocementation treatment, *Geotechnical*
1101 *Research*, **11** (1), pp. 28–142. DOI: 10.1680/jgere.22.00053.

1102 Omoregie, A. I., Palombo, E. A., Ong, D. E. L. and Nissom, P. M. (2019b) Biocementation of sand by
1103 *Sporosarcina pasteurii* strain and technical-grade cementation reagents through surface percolation
1104 treatment method, *Construction and Building Materials*, **228**, article 116828. DOI:
1105 10.1016/j.conbuildmat.2019.116828.

1106 Omoregie, A.I., Muda, K. and Ngu, L. H. (2022) Dairy manure pellets and palm oil mill effluent as alternative
1107 nutrient sources in cultivating *Sporosarcina pasteurii* for calcium carbonate bioprecipitation, *Letters in*
1108 *Applied Microbiology*, **74**, pp. 671–683. DOI: 10.1111/lam.13652.

1109 Panwar, N. L. and Pawar, A. (2022) Influence of activation conditions on the physicochemical properties of
1110 activated biochar: a review, *Biomass Conversion and Biorefinery*, **12** (3), pp. 925–947. DOI:1
1111 0.1007/s13399-020-00870-3.

1112 Peng, D., Qiao, S., Luo, Y., Ma, H., Zhang, L., Hou, S., Wu, B. and Xu, H. (2020) Performance of microbial
1113 induced carbonate precipitation for immobilizing Cd in water and soil, *Journal of Hazardous Materials*,
1114 **400**, article 123116. DOI: 10.1016/j.jhazmat.2020.123116.

1115 Perucci, P. (1990) Effect of the addition of municipal solid-waste compost on microbial biomass and enzyme
1116 activities in soil, *Biology and Fertility of Soils*, **10** (3), pp. 221–226. DOI: 10.1007/BF00336141.

1117 Pham, V. P., van Paassen, L. A., van der Star, W. R. L. and Heimovaara, T. J. (2018) Evaluating strategies to
1118 improve process efficiency of denitrification-based MICP, *Journal of Geotechnical and Geoenvironmental*
1119 *Engineering*, **144** (8). DOI: 10.1061/(ASCE)GT.1943-5606.0001909.

1120 Porter, H., Mukherjee, A., Tuladhar, R. and Dhami, N. K. (2021) Life Cycle Assessment of Biocement: An
1121 Emerging Sustainable Solution?, *Sustainability,* **13** (4), article 13878. DOI: 10.3390/su132413878.

Power, I. M., Wilson, S. A., Thom, J. M., Dipple, G. M. and Southam, G. (2007) Biologically induced mineralization of dypingite by cyanobacteria from an alkaline wetland near Atlin, British Columbia, Canada, *Geochemical Transactions*, **8** (13). DOI: 10.1186/1467-4866-8-13.

Qiao, S., Zeng, G., Wang, X., Dai, C., Sheng, M., Chen, Q., Xu, F. and Xu, H. (2021) Multiple heavy metals immobilization based on microbially induced carbonate precipitation by ureolytic bacteria and the precipitation patterns exploration, *Chemosphere*, **274**, article 129661. DOI: 10.1016/j.chemosphere.2021.129661.

Qiu, J., Xiang, J., Zhang, W., Zhao, Y., Sun, X. and Gu, X. (2022) Effect of microbial-cemented on mechanical properties of iron tailings backfill and its mechanism analysis, *Construction and Building Materials*, **318**, article 126001. DOI:10.1016/j.conbuildmat.2021.126001.

Raveh-Amit, H. and Tsesarsky, M. (2020) Biostimulation in desert soils for microbial-induced calcite precipitation, *Applied Sciences (Switzerland)*, **10** (8). DOI:10.3390/APP10082905.

Raza, A. and Khushnood, R. A. (2022) Repair of mortar cracks using *Bacillus pumilus* based bio-suspension assessed by machine learning algorithm for image processing, *Journal of Building Engineering*, **61** (8), article 2905. DOI: 10.1016/j.jobe.2022.105267.

Rekha, P., Suman Raj, D. S., Aparna, C., Hima Bindu, V. and Anjaneyulu, Y. (2005) Bioremediation of contaminated lake sediments and evaluation of maturity indicies as indicators of compost stability, *International Journal of Environmental Research and Public Health*, **2** (2), pp. 251–262. DOI: 10.3390/ijerph2005020008.

Ren, X., Yan, N., Chen, S., Yao, J. and Liu, J. (2022) Remediation of arsenic-containing ferrihydrite in soil using iron- and sulfate-reducing bacteria: Implications for microbially-assisted clean technology, *Journal of Environmental Chemical Engineering*, **10** (6), article 108876. DOI: 10.1016/j.jece.2022.108876.

Saad, A. H., Nahazanan, H., Yusoff, Z. B. M., Mustafa, M., Elseknidy, M. H. and Mohammed, A. A. (2021) Evaluating biosedimentation for strength improvement in acidic soil, *Applied Sciences (Switzerland)*, **11** (22), article 10817. DOI: 10.3390/app112210817.

Sarda, D., Choonia, H. S., Sarode, D. D. and Lele, S. S. (2009) Biocalcification by *Bacillus pasteurii* urease: A novel application, *Journal of Industrial Microbiology and Biotechnology*, **36** (1), pp. 1111–1115, DOI:10.1007/s10295-009-0581-4.

Sepúlveda, S., Duarte-Nass, C., Rivas, M., Azócar, L., Ramírez, A., Toledo-Alarcón, J., Gutiérrez, L., Jeison, D. and Torres-Aravena, Á. (2021) Testing the capacity of *Staphylococcus equorum* for calcium and copper removal through MICP process, *Minerals*, **11** (8), article 905. DOI:10.3390/min11080905.

Sharma, A., Kuthiala, T., Thakur, K., Thatai, K. S., Singh, G., Kumar, P. and Arya, S. K. (2022a) Kitchen waste: sustainable bioconversion to value-added product and economic challenges, *Biomass Conversion and Biorefinery*. DOI:10.1007/s13399-022-02473-6.

Sharma, M., Satyam, N., Reddy, K. R. and Chrysochoou, M. (2022b) Multiple heavy metal immobilization and strength improvement of contaminated soil using bio-mediated calcite precipitation technique, *Environmental Science and Pollution Research*, **29** (34), pp. 51827–51846. DOI:10.1007/s11356-022-19551-x.

Stocks-Fischer, S., Galinat, J. K. and Bang, S. S. (1999) Microbiological precipitation of $CaCO_3$, *Soil Biology and Biochemistry*, **31** (11), pp. 1563–1571. DOI:10.1016/S0038-0717(99)00082-6.

Stuczynski, T. I., McCarty, G. W. and Siebielec, G. (2003) Response of Soil Microbiological Activities to Cadmium, Lead, and Zinc Salt Amendments, *Journal of Environmental Quality*, **32** (4), pp. 1346–1355. DOI:10.2134/jeq2003.1346.

Su, Q., Zhang, X., Zhang, Y., Sun, G., Li, Z., Xiang, L. and Cai, J. (2023) Risk assessment of heavy metal pollution in agricultural soil surrounding a typical pharmaceutical manufacturing complex, *Frontiers in Environmental Science*, **10**, article 1105910. DOI: 10.3389/fenvs.2022.1105910.

Sun, P., He, Y., Zhou, S., Erneste, H., Gao, Q., Zou, Z. and Zhu, J. (2024) Experimental study on environmental chemical effect and purification treatment of waste slurry in horizontal directional drilling, *Tunnelling and Underground Space Technology*, **145**, article 105548. DOI: 10.1016/j.tust.2023.105548.

Sun, X., Miao, L., Chen, R., Wang, H., Wu, L. and Xia, J. (2021) Liquefaction resistance of biocemented loess soil, *Journal of Geotechnical and Geoenvironmental Engineering*, **147** (11), article 0002638. DOI: 10.1061/(ASCE)GT.1943-5606.0002638.

Suriya, P. and Sangeetha, S. P. (2023) Enhancing the Strength Parameters of Dispersive Soil with Microbes and Jute Fibres as Sustainable Alternative, *Ecological Engineering and Environmental Technology*, **24** (1), pp. 154–164. DOI: 10.12912/27197050/154907.

1177 Tamayo-Figueroa, D. P., Castillo, E. and Brandão, P. F. B. (2019) Metal and metalloid immobilization by
1178 microbiologically induced carbonates precipitation, *World Journal of Microbiology and Biotechnology*,
1179 **35**, pp. 1–10. DOI: 10.1007/s11274-019-2626-9.

1180 Taylor, A. A., Tsuji, J. S., Garry, M. R., McArdle, M. E., Goodfellow, W. L., Adams, W. J. and Menzie, C. A.
1181 (2020) Critical Review of Exposure and Effects: Implications for Setting Regulatory Health Criteria for
1182 Ingested Copper, *Environmental Management*, **65** (1), pp. 131–159. DOI: 10.1007/s00267-019-01234-y.

1183 Vácha, R. (2021) Heavy metal pollution and its effects on agriculture, *Agronomy*, **11** (9), article 1719. DOI:
1184 10.3390/agronomy11091719.

1185 Wang, J., Yu, D., Wang, Y., Du, X., Li, G., Li, B., Zhao, Y., Wei, Y. and Xu, S. (2021) Source analysis of heavy
1186 metal pollution in agricultural soil irrigated with sewage in Wuqing, Tianjin, *Scientific Reports*, **11** (1), pp.
1187 17816. DOI: 10.1038/s41598-021-96367-8.

1188 Wang, L., Cheng, W.C., Xue, Z.F., Rahman, M. M., Xie, Y.X. and Hu, W. (2023a) Immobilizing lead and copper
1189 in aqueous solution using microbial- and enzyme-induced carbonate precipitation, *Frontiers in*
1190 *Bioengineering and Biotechnology*, **11**, article 1146858. DOI: 10.3389/fbioe.2023.1146858.

1191 Wang, L., Cheng, W.C., Xue, Z.F., Xie, Y.X. and Lv, X.J. (2023b) Study on Cu- and Pb-contaminated loess
1192 remediation using electrokinetic technology coupled with biological permeable reactive barrier, *Journal of*
1193 *Environmental Management*, **348**, article 119348. DOI: 10.1016/j.jenvman.2023.119348.

1194 Wang, L., Cheng, W.C., Xue, Z.F., Zhang, B. and Lv, X.J. (2023c) Immobilizing of lead and copper using chitosan-
1195 assisted enzyme-induced carbonate precipitation, *Environmental Pollution*, **319**, article 120947. DOI:
1196 10.1016/j.envpol.2022.120947.

1197 Wang, T., Sun, H., Mao, H., Zhang, Y., Wang, C., Zhang, Z., Wang, B. and Sun, L. (2014) The immobilization of
1198 heavy metals in soil by bioaugmentation of a UV-mutant bacillus subtilis 38 assisted by novoGro
1199 biostimulation and changes of soil microbial community, *Journal of Hazardous Materials*, **65**, pp. 62–69.
1200 DOI: 10.1016/j.jhazmat.2014.06.028.

1201 Wang, T., Wang, S., Tang, X., Fan, X., Yang, S., Yao, L., Li, Y. and Han, H. (2020) Isolation of urease-producing
1202 bacteria and their effects on reducing Cd and Pb accumulation in lettuce (Lactuca sativa L.), *Environmental*
1203 *Science and Pollution Research*, **27**, pp/ 8707–8718. DOI: 10.1007/s11356-019-06957-3.

1204 Wang, W., Lu, N., Pan, H., Wang, Z., Han, X., Zhu, Z. and Guan, J. (2022a) Heavy Metal Pollution and Its Prior
1205 Pollution Source Identification in Agricultural Soil: A Case Study in the Qianguo Irrigation District,
1206 Northeast China, *Sustainability*, **14** (8). DOI: 10.3390/su14084494.

1207 Wang, Y., Sun, X., Miao, L., Wang, H., Wu, L., Shi, W. and Kawasaki, S. (2024) State-of-the-art review of soil
1208 erosion control by MICP and EICP techniques: Problems, applications, and prospects, *Science of The Total*
1209 *Environment*, 912, pp. 169016. DOI: 1016/j.scitotenv.2023.169016.

1210 Wang, Y.J., Jiang, N.J., Han, X.L., Liu, K. and Du, Y.J. (2022b) Biochemical, Strength and Erosional
1211 Characteristics of Coral Sand Treated by Bio-Stimulated Microbial Induced Calcite Precipitation, *Acta*
1212 *Geotechnica*, **17** (9), pp. 4217–4229. DOI: 10.1007/s11440-022-01491-y.

1213 Warren, L. A., Maurice, P. A., Parmar, N. and Ferris, F. G. (2001) Microbially mediated calcium carbonate
1214 precipitation: Implications for Interpreting calcite precipitation and for solid-phase capture of inorganic
1215 contaminants, *Geomicrobiology Journal*, **18** (1), pp. 93–115. DOI: 10.1080/01490450151079833.

1216 WHO (2018) A global overview of national regulations and standards for drinking-water quality, *Water,*
1217 *Sanitation, Hygiene and Health (WSH)*, pp. 1–44. Available from:
1218 https://www.who.int/publications/i/item/9789241513760 [Accessed at 05/05/2024].

1219 Widiastuti, N., Wu, H., Ang, H. M. and Zhang, D. (2011) Removal of ammonium from greywater using natural
1220 zeolite, *Desalination*, **277** (1), pp. 15–23. DOI: 1016/j.desal.2011.03.030.

1221 Xiao, Y., He, X., Wu, W., Stuedlein, A. W., Evans, T. M., Chu, J., Liu, H., van Paassen, L. A. and Wu, H. (2021)
1222 Kinetic biomineralization through microfluidic chip tests, *Acta Geotechnica*, **16**, 3229–3237. DOI:
1223 10.1007/s11440-021-01205-w.

1224 Xing, W., Zhou, F., Zhu, R., Wang, X. and Chen, T. (2023) Performance and Mechanism of Zn-Contaminated Soil
1225 through Microbe-Induced Calcium Carbonate Precipitation, *Buildings*, **13** (8), article 1974. DOI:
1226 10.3390/buildings13081974.

1227 Xu, J. G. and Johnson, R. L. (1997) Nitrogen dynamics in soils with different hydrocarbon contents planted to
1228 barley and field pea, *Canadian Journal of Soil Science*, **77** (3), pp. 453–458. DOI: 10.4141/S96-046.

1229 Xue, Z.-F., Cheng, W.-C., Wang, L. and Xie, Y.-X. (2022) Catalyzing urea hydrolysis using two-step microbial-
1230 induced carbonate precipitation for copper immobilization: Perspective of pH regulation, *Frontiers in*
1231 *Microbiology*, **13**, article 1001464. DOI: 10.3389/fmicb.2022.1001464.

1232 Yaashikaa, P. R. and Kumar, P. S. (2022) Bioremediation of hazardous pollutants from agricultural soils: A
1233 sustainable approach for waste management towards urban sustainability, *Environmental Pollution*, **312**,
1234 article 120031. DOI: 10.1016/j.envpol.2022.120031.

1235 Yang, J., Pan, X., Zhao, C., Mou, S., Achal, V., Al-Misned, F. A., Mortuza, M. G. and Gadd, G. M. (2016)
1236 Bioimmobilization of heavy metals in acidic copper mine tailings soil, *Geomicrobiology Journal*, **33** (3–
1237 4), pp. 261–266. DOI: 10.1080/01490451.2015.1068889.

1238 Yang, M., Wang, S., Liu, M., Ning, X., Wu, Y. and Nan, Z. (2023) Dose relationships and interactions of four
1239 materials and MICP technology in simultaneously reducing the exchangeable parts of As, Pb, and Cd in
1240 multiple contaminated soils, *Journal of Soils and Sediments*, **23** (11), pp. 3903–3916. DOI:
1241 10.1007/s11368-023-03574-z.

1242 Yang, Y., Ali, A., Su, J., Xu, L., Wang, X. and Liang, E. (2022) Simultaneous removal of nitrate, tetracycline, and
1243 Pb(II) by iron oxidizing strain Zoogloea sp. FY6: Performance and mechanism, *Bioresource Technology*,
1244 **360**, article 127569. DOI:10.1016/j.biortech.2022.127569.

1245 Yu, X., Chu, J., Yang, Y. and Qian, C. (2021) Reduction of ammonia production in the biocementation process for
1246 sand using a new biocement, *Journal of Cleaner Production*, **286**, article 124928. DOI:
1247 10.1016/j.jclepro.2020.124928.

1248 Zakrzewska, M., Rzepa, G., Musialowski, M., Goszcz, A., Stasiuk, R. and Debiec-Andrzejewska, K. (2023)
1249 Reduction of bioavailability and phytotoxicity effect of cadmium in soil by microbial-induced carbonate
1250 precipitation using metabolites of ureolytic bacterium *Ochrobactrum* sp. POC9, *Frontiers in Plant Science*,
1251 **14**, article 1109467. DOI: 10.3389/fpls.2023.1109467.

1252 Zeng, Y., Chen, Z., Du, Y., Lyu, Q., Yang, Z., Liu, Y. and Yan, Z. (2021) Microbiologically induced calcite
1253 precipitation technology for mineralizing lead and cadmium in landfill leachate, *Journal of Environmental*
1254 *Management*, **296**, article 113199. DOI: 10.1016/j.jenvman.2021.113199.

1255 Zeng, Y., Chen, Z., Lyu, Q., Cheng, Y., Huan, C., Jiang, X., Yan, Z. and Tan, Z. (2023) Microbiologically induced
1256 calcite precipitation for in situ stabilization of heavy metals contributes to land application of sewage
1257 sludge, *Journal of Hazardous Materials*, **441**, article 129866. DOI: 10.1016/j.jhazmat.2022.129866.

1258 Zhang, J., Kumari, D., Fang, C. and Achal, V. (2019) Combining the microbial calcite precipitation process with
1259 biochar in order to improve nickel remediation, *Applied Geochemistry*, **103**, pp. 68–71. DOI:
1260 10.1016/j.apgeochem.2019.02.011.

1261 Zhang, J., Su, P., Li, Y. and Li, L. (2021) Environmental investigation of bio-modification of steel slag through
1262 microbially induced carbonate precipitation, *Journal of Environmental Sciences (China)*, **101**, pp. 282–
1263 292. DOI: 10.1016/j.jes.2020.08.023.

1264 Zhang, J., Wang, S., Wang, X., Zhang, M. and Fan, S. (2023) Detoxification pathways of multiple metals from
1265 intensive copper production by indigenous ureolytic microbes coupled with soil nitrogen transformation,
1266 *Journal of Cleaner Production*, **384**, article 135643. DOI: 10.1016/j.jclepro.2022.135643.

1267 Zhang, P., Liu, X.-Q., Yang, L.-Y., Sheng, H.-Z.-Y., Qian, A.-Q. and Fan, T. (2022a) Immobilization of Cd^{2+} and
1268 Pb^{2+} by biomineralization of the carbonate mineralized bacterial consortium JZ1, *Environmental Science*
1269 *and Pollution Research*. DOI: 10.1007/s11356-022-23587-4.

1270 Zhang, L. V, Marani, A. and Nehdi, M. L. (2022b) Chemistry-informed machine learning prediction of
1271 compressive strength for alkali-activated materials, *Construction and Building Materials*, **316**, article
1272 126103. DOI: 10.1016/j.conbuildmat.2021.126103.

1273 Zhang, X., Guo, J., Wu, S., Chen, F. and Yang, Y. (2020) Divalent heavy metals and uranyl cations incorporated
1274 in calcite change its dissolution process, *Scientific Reports*, **10** (1). DOI: 10.1038/s41598-020-73555-6.

1275 Zhang, X., Yang, H., Sun, R., Cui, M., Sun, N. and Zhang, S. (2022c) Evaluation and analysis of heavy metals in
1276 iron and steel industrial area, *Environment, Development and Sustainability*, **24** (9), pp. 10997–11010.
1277 DOI: 10.1007/s10668-021-01893-0.

1278 Zhao, Y., Fan, C., Ge, F., Cheng, X. and Liu, P. (2020a) Enhancing Strength of MICP-Treated Sand with Scrap of
1279 Activated Carbon-Fiber Felt, *Journal of Materials in Civil Engineering*, **32** (4), article 003136.
1280 DOI:10.1061/(ASCE)MT.1943-5533.0003136.

Zhao, Z., Zhao, C., Do, H., Li, M., Wu, D., Chen, Y. and Zhang, F. (2020b) *Brevibacillus laterosporus* ZN5 Induces Different Carbonate Precipitations of Lead in Ammonification and Nitrate Assimilation Processes, *Geomicrobiology Journal*, **37** (8), pp. 764–773. DOI:10.1080/01490451.2020.1774687.

Zhi, S.-H., Wan, L.-S. and Xu, Z.-K. (2014) Poly(vinylidene fluoride)/poly(acrylic acid)/calcium carbonate composite membranes via mineralization, *Journal of Membrane Science*, **454**, pp. 144–154. DOI: 10.1016/j.memsci.2013.12.011.

Zhou, H., Chen, Y., Liu, Y., Wang, Q. and Liang, Y. (2022) Farmers' adaptation to heavy metal pollution in farmland in mining areas: The effects of farmers' perceptions, knowledge and characteristics, *Journal of Cleaner Production*, **365**, pp. 132678. DOI: 10.1016/j.jclepro.2022.132678.

Zhu, J., Shen, D., Xie, J., Tang, C., Jin, B. and Wu, S. (2021) Mechanism of urea decomposition catalyzed by *Sporosarcina pasteurii* urease based on quantum chemical calculations, *Molecular Simulation*, **47** (16), pp. 1335–1348. DOI:10.1080/08927022.2021.1970156.

List of Chemical Notations

1. $CO(NH_2)_2$ - Urea
2. H_2O - Water
3. NH_3 - Ammonia
4. NH_2COOH - Carbamic acid
5. H_2CO_3 - Carbonic acid
6. H^+ - Hydrogen ion
7. HCO_3^- - Bicarbonate ion
8. OH^- - Hydroxide ion
9. NH_4^+ - Ammonium ion
10. CO_3^{2-} - Carbonate ion
11. Ca^{2+} - Calcium ion
12. $CaCO_3$ - Calcium carbonate
13. HM^{2+} - Heavy metal ion (general term for divalent heavy metal ions)
14. $HMCO_3$- Heavy metal carbonate

15. $Ca_{(1-X)}M_x\,CO_3$ - Mixed calcium-heavy metal carbonate (where X is the fraction of heavy metal substitution)
16. CO_2 - Carbon dioxide
17. O_2 - Oxygen
18. NO_3^- - Nitrate ion
19. NO - Nitric oxide
20. $Ca(NO_3)_2$ - Calcium nitrate
21. H_2O_2 - Hydrogen peroxide
22. SO_4^{2-} - Sulfate ion
23. S^{2-} - Sulfide ion
24. CaS - Calcium sulfide
25. Fe^{3+} - Ferric ion
26. e^- - Electron
27. Fe^{2+} - Ferrous ion
28. $Fe(OH)_3$ - Ferric hydroxide
29. $FeCO_3$ - Ferrous carbonate
30. CaO - Calcium Oxide

List of Equations

1. $CO(NH_2)_2 + H_2O \rightarrow NH_3 + NH_2COOH$
2. $NH_2COOH + H_2O \rightarrow H_2CO_3 + NH_3$
3. $H_2CO_3 \leftrightarrow H^+ + HCO_3^-$
4. $2NH_3 + 2H_2O \leftrightarrow 2OH^- + 2NH_4^+$
5. $HCO_3^- + H^+ + 2OH^- \rightarrow CO_3^{2-} + 2H_2O$
6. $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_{3(g)}$
7. $HM^{2+} + CO_3^{2-} \rightarrow HMCO_{3(g)}$
8. $xHM^{2+} + (1-x)Ca^{2+} + CO_3^{2-} \rightarrow Ca_{(1-X)}M_x\,CO_{3(g)}$
9. $CO_2 + H_2O \rightarrow Organic\ matter +$

10. $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + O_2$

11. $Protein\ or\ amino\ acid \rightarrow NH_3$

12. $NH_3 + HCO_3^- \rightarrow NH_4^+ + CO_2$

13. $NH_4^+ + Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + 2H_2O + NH_3$

14. $NO_3^- \rightarrow NO$

15. $Ca^{2+} + 2NO_3 \rightarrow Ca(NO_3)_2$

16. $Ca(NO_3)_2 + 2H_2O \rightarrow CaCO_3 + 2NO_3^- + H_2O_2$

17. $SO_4^{2-} \rightarrow S^{2-}$

18. $Ca^{2+} + S^{2-} \rightarrow CaS$

19. $CaS + O_2 \rightarrow CaCO_3 + S$

20. $Fe^{3+} + e^- \rightarrow Fe^{2+}$

21. $Fe^{2+} + HCO_3^- \rightarrow Fe(OH)_3$

22. $Fe(OH)_3 \rightarrow FeCO_3 + H_2O$

List of Abbreviations

1. MICP: Microbial-Induced Carbonate Precipitation
2. Hg: Mercury
3. As: Arsenic
4. Pb: Lead
5. Cr: Chromium
6. Cd: Cadmium
7. Cu: Copper
8. Ni: Nickel
9. EPS: Extracellular Polymeric Substances
10. ATP: Adenosine Triphosphate
11. ATPase: Adenosine Triphosphatase
12. S. pasteurii: Sporosarcina pasteurii
13. SEM: Scanning Electron Microscopy
14. XRD: X-ray Diffraction

15. EK-PRB: Electrokinetic-Permeable Reactive Barrier
16. BBSHC: Bacteria-Based Self-Healing Concretes
17. EIA: Environmental Impact Assessment
18. LCA: Life Cycle Assessment
19. IC50: Half Maximal Inhibitory Concentration
20. WHO: World Health Organization
21. CRISPR: Clustered Regularly Interspaced Short Palindromic Repeats
22. EDTA: Ethylenediaminetetraacetic Acid
23. kDa: Kilodalton

Acknowledgement

The authors appreciate the University Technology of Sarawak and Universiti Teknologi Malaysia for facilitating access to essential databases and resources for obtaining bibliometric data.

Authors Contribution

A.I.O.: Conceptualised and designed the review, conducted the literature review, and wrote and critically revised the manuscript. T.O. and D.E.L.O.: Supervised the project, provided critical revisions, and ensured the overall integrity and accuracy of the review. H.F.B., K.M., O.O.O., D.J.F., and T.A.: Assisted with the literature search, contributed to writing the discussion, and provided revisions based on peer review feedback. All authors read and commented on previous versions of the manuscript, and they collectively approved the final version.

Funding Statement

This research was made possible through the generous support of the Normandy region in France, with funding provided under grant number R2020-RIN-0043.

Conflict of Interest

The authors declare no competing financial interests or personal relationships that could influence this study.

Data Availability

The data supporting the findings of this study are available upon reasonable request. Interested parties may contact the corresponding author (TO) or the first author (AIO) for access.