CO_2 sequestration derived calcium carbonate and methane formation in deep subsurface porous media: A State-of-art review to decoding microbes-minerals crosstalk and molecular bio mineralization process

Abstract

The concentration of carbon dioxide has been rising extensively due to human activities and it reached dangerous levels that had not been seen in the previous 3 million years. In 2022, carbon dioxide emissions from the transport sector increase by 250Mt CO_2 which is 3% more than in 2021(8Gt). Natural sources of carbon dioxide emissions include decomposition, forest fires, ocean release, volcanic eruption, and ocean release. Each year globally 2.6 billion tons of carbon dioxide are released from natural forest fires. Ocean absorbs 30% of carbon dioxide which is released by human activities and holds 60 times more carbon than the atmosphere. Microbial communities play a major role in carbonate rock formation through bio mineralization within subsurface porous media. Moisture content in subsurface porous media significantly impacts the carbonate bio mineralization process during CO_2 sequestration. It influences mineral dissolution, microbial activity, water transport, CO_2 solubility, and transport efficiency. Environmental factors like temperature, pH, and nutrient availability can influence urease activity. Microbial community dynamics also impact ureolysis efficiency. Understanding these aspects is essential for applications like CO_2 sequestration and environmental remediation. To stop CO_2 leakage in the context of CO_2 sequestration, the subsurface may be covered with a layer of cap rock, or impermeable rock. The formation of carbonate minerals induced by MICP can strengthen the integrity of the cap rock by sealing potential pathways for CO_2 migration and filling fractures. Maintaining sustainable CO_2 sequestration and bio-methane production requires striking a balance between the advantages of MICP and its effects on subsurface processes. This review examines how geochemical and environmental controls affect microbial activity and bio mineralization, emphasizing the importance of sustainability and long-term stability.

Keywords

CO_2 sequestration, microbial communities, subsurface porous media, bio mineralization, MICP.

Introduction

Since the Industrial Revolution, the concentration of carbon dioxide has been rising extensively due to human activities and it reached dangerous levels that had not been seen in the previous 3 million years[1]. Increased concentrations of carbon dioxide in the atmosphere are due to anthropogenic activities such as deforestation, as well as the burning of fossil fuels. Although anthropogenic sources of carbon emission are much smaller than natural emissions, they disturb the natural balance that was before human influence. Researchers estimated that the world's emission of carbon dioxide exceeded 40 billion tons in 2023 and nearly 37 billion tons of emissions are from fossil fuels[2].

Every year due to deforestation more than 1.5 billion tons of carbon dioxide are released into the atmosphere. Global carbon dioxide emissions from fossil fuel burning are about 34 billion tons (Gt) per year[3]. Industrialization and energy consumption had a positive impact on carbon emissions, a 1% increase in industrialization leads to a 0.54% rise in CO_2 emissions while a 1% rise in energy consumption produces a 0.61% increase in emissions. In 2022, carbon dioxide emissions from the transport sector increase by 250Mt CO_2 which is 3% more than in 2021(8Gt). Air travel contributed to 70% of emissions in 2019. Between 2001 and 2023 global forest fires release 35.9 tons of carbon dioxide. While agriculture contributes to 10% of global CO_2 emissions[4].

Furthermore, flavonoids and phenolic also being explored for pharmaceutical and medical applications[5].A range of natural compounds derived from plants has been explored for their potential health benefits[6]. Chlorogenic Acid from Equisetum arvense L. is a phenolic compound that possesses antioxidant properties and has been studied for its antiviral, antibacterial, and anti-inflammatory effects[7]. Methotrexate from Plantago lanceolata, on the other hand, is a versatile phenolic drug used to treat various conditions, including cancer and autoimmune diseases[8]. Among the flavonoids, Tamoxifen, Raloxifen, and Anastrazole are derived from Urtica dioica, showing promise when combined with radiotherapy and adjuvants in improving the survival rates of breast cancer patients[9]. Additionally, Genistein, being a flavonoid, is being studied in clinical trials for prostate cancer treatment. Crofelemer serve various medical purposes, including cancer and tumors[10], while Silibinin, a flavonolignan, and is used for treating toxic liver damage, cirrhosis, and hepatitis. It's crucial to consult with healthcare professionals and rely on scientific research and clinical trials when considering the use of these compounds to ensure their effectiveness and safety[11].

Natural Sources

Carbon emissions from natural sources are a vital part of Earth's carbon cycle. Natural sources of carbon dioxide emissions include decomposition, forest fires, ocean release, volcanic eruption, and ocean release. The decomposition of leaves and plants releases 60 pentagrams of carbon every year into the atmosphere[12]. Oceans release 10 billion tons of carbon every year into the atmosphere but oceans quickly absorb 3 billion tons of these emissions. Each year globally 2.6 billion tons of carbon dioxide are released from natural forest fires. Due to volcanic eruptions globally 94 million tons of carbon dioxide are released each year[13]**.**

Carbon sequestration methods

The removal, capturing, and storage of carbon dioxide from the earth's atmosphere is called carbon sequestration. Two basic forms of carbon sequestration are biological and global carbon sequestration. Three main carbon sequestration methods are described below:

1. Biological Carbon sequestration

Biology carbon is stored in the natural environment. Major carbon sinks in nature are forests, grasslands, soil, oceans, and other bodies of water. Forest plays a significant role in natural/biological carbon sequestration[14]. 25% of global carbon emissions are sequestered by forests and other vegetative forms such as rangelands or grasslands (FAO) [15]. Forest stores double carbon as they emit. In the fight against climate change, soil plays a very important role as healthy soil helps remove carbon from the atmosphere and store it in soil (IPCC)[16]. Globally 1500- 2500 billion tons of carbon can be sequestered by soil (USDA) [17]. Aquatic bodies are the greatest absorbers of CO2, as they absorb 25% of carbon dioxide emitted by the earth's atmosphere [18]. 50% of the oxygen we need is generated by the ocean while it absorbs 25% of all carbon emissions and oceans capture 90% of heat emitted by these emissions. Ocean absorbs 30% of carbon dioxide which is released by human activities and holds 60 times more carbon than the atmosphere[19].

2. Geological Carbon Sequestration

The storage of carbon in underground geological formations or rocks is called geological carbon sequestration [20]. It is an effective way of neutralizing the carbon emissions due to human activities such as construction or manufacturing[21]. Recent technological innovations show that carbon can be sequestered on a larger scale more effectively. These technological innovations include:

Graphene production

Carbon dioxide is used as a raw material in grapheme production. It is heavily utilized in certain industries for the production of tech devices such as computer processors and smartphones [22].

Engineered molecules

By capturing carbon from the air, scientists can change the shape of molecules which helps in the formation of new compounds. While reducing atmospheric carbon could be a systematic way of creating raw material[23].

3. Mechanical carbon sequestration

It is a method of capturing and storing carbon dioxide from the atmosphere by the usage of mechanical processes such as enhanced weathering or air capture. In this method, carbon dioxide is physically removed from the air and then stored in oceans, geological formations, or other long-term storage site[24]. Direct capture from the air is the best strategy in the fight against climate change and it is designed to remove 4000 tons of carbon dioxide per year. DAC is not limited to national emissions it can be done anywhere in those areas that have good wind speeds[25]. In the case of exhaust stack capture it usually be carried out closer to CO_2 burial sites. While mechanical trees absorb carbon more effectively, when planted in clusters of 12 they capture a metric ton of CO_2 per day. A large farm with 120,000 trees in the working phase, can capture 10,000 metric tons of carbon per day which would be equal to the CO_2 emissions of 800,000 cars[26].

The most stable and permanent form of CO_2 sequestration in geological formation is mineralization. Different researchers conducted experiments on this method and they revealed that the reaction takes decades to sequester CO_2. The process takes place directly or indirectly when dissolved CO_2 and brine form carbonic acid[27]. In the geologic formation, there is a reaction that takes place after a long time between carbonic acid and minerals which leads to the improvement of precipitates of carbonate minerals and after that results in solid precipitates of carbon dioxide. It is attractive because it can permanently store CO_2. It is the most secure trapping mechanism in the CO_2 sequestration process[28]. Trapping speed is slow but if certain parameters are completely understood then there is the possibility to speed up the trapping process. Some factors such as brine pH, brine composition, temperature, pressure, leakage rate, microorganism interaction, and CO_2 dissolution kinetics have a major effect on the mineral trapping of CO_2 in brines[29].

Rock formation via bio mineralization

A process by which living organisms facilitate mineral formation is called bio mineralization. During this process, microorganisms interact with injected CO_2 and the subsurface environment. High concentrations of carbon dioxide are injected underground, where they interact with minerals found in the rock formation[30]. The aim of this process is also referred to as mineralization or mineral trapping it turns gaseous CO_2 into stable mineral form to prevent its release into the atmosphere. Various factors can contribute to rock formation through bio mineralization in the context of deep industrial subsurface porous media during the injection of high concentrations of CO_2[31]. Here is a general overview of how this might happen:

Mineral Activity

Bacteria and other microorganism can be very important to bio mineralization. Certain bacteria can modify the local geochemical conditions to catalyze mineral precipitation reactions. They can produce metabolic byproducts that alter the subsurface chemical composition[32].

Ureolysis and calcium carbonate precipitation

Certain bacteria are known for their ureolytic activity, which allows them to hydrolyze urea and produce carbonate ions. PH and carbonate ion availability increase as a result of this process which encourages the precipitation of calcium carbonate. It is a mineral that can help to form a solid rock by consolidating the porous media[33].

Sulfide mineral precipitation

Sulfide ions are produced when certain microbes participate in the sulfate reduction process. Iron sulfide (pyrite, greigite) and other sulfide minerals may precipitate as a result of this process. As a result of these minerals, the properties of subsurface rocks may change[34].

Biofilm formation

On rock surfaces, microorganisms frequently form biofilms. Biofilms can precipitate minerals and serve as nucleation sites for the synthesis of new minerals. A mineralized matrix that strengthens the rock structure may result from this[35].

Nutrient availability

Carbon, nitrogen, and phosphorus availability are examples of nutrients that can affect microbial activity and in turn bio mineralization. These nutrients may be utilized by microorganisms for metabolic activities that contribute to the formation of minerals. It's important to note the details of bio mineralization in the deep industrial subsurface during CO_2 injection can differ based on the site's geological and geochemical features, the composition of CO_2 injected, as well as the microbiological community that is present[36].

Molecular mechanism of carbonate rock formation

As discussed, earlier rock formation takes place by the process of bio mineralization when a high concentration of CO_2 is injected into subsurface porous media. Although the specific microbiological species and reactions may differ, the general procedure usually entails the following steps[37].

Injection of CO_2

Subsurface porous media that contains minerals and water is injected with CO_2[38]. A favorable atmosphere for bio mineralization is created by the high concentration of carbon dioxide[39].

Microbial Activity

Some bacteria can catalyze bio mineralization; these bacteria are commonly found in genera like Bacillus and Sporosarcina[40]. Through metabolic processes, these bacteria help in the formation of carbonate minerals[41].

Uptake of CO_2 by microorganisms

CO2 serves as a source of carbon for the metabolism of microorganism. The CO_2 is transformed into bicarbonate ions (HCO_3^-) through enzymatic processes such as carbonic anhydrase activity[42].

Production of carbonate ion

The calcium ions (Ca_2^+) in the subsurface porous media react with the bicarbonate ions produced by microbial activity. As a result, calcium carbonate ($CaCO_3$) is produced[43]

Biochemical reaction

The bio mineralization process involves many biochemical reactions. One simplified example of a reaction is:

$CO_2+H_2O \rightarrow HCO_3^-$ Ca_2^+ $+2HCO_3- \rightarrow CaCO_3+CO_2+H_2O$

In these reactions, CO_2 is converted to bicarbonate ions, and then the bicarbonate ions react with calcium ions to form calcium carbonate, which precipitates as solid mineral phases[44].

Types of microbial communities involved in carbonate rock formation

Microbial communities play a major role in carbonate rock formation through bio mineralization within subsurface porous media. Microorganisms that affect the mineralization and precipitation of carbonate minerals are involved in this process[45]. A variety of microbial communities are involved in this process of bio mineralization

Cyanobacteria

Through bio mineralization, these photosynthetic bacteria can help in the formation of carbonate minerals[46]. These bacteria have the capability of fixing carbon dioxide and precipitating carbonate minerals such as calcium carbonate in their extracellular polymeric substance (EPS). Cyanobacteria create biofilms in subsurface environments, which leads to the precipitation of carbonate minerals and the formation of microbialite structures[47].

Sulfate-reducing bacteria

Through microbial sulfate reduction, certain sulfate-reducing bacteria are known to encourage the precipitation of carbonate minerals[48]. Formation of calcium carbonate takes place when these bacteria react with dissolved calcium ions to produce sulfide (S_2^-) from reduced sulfate (SO_4^{+2}).

Iron-Reducing Bacteria

By encouraging the reduction of iron minerals, iron-reducing bacteria can affect the precipitation of carbonate minerals. This process contributes to the precipitation of carbonate minerals by releasing bicarbonate ions and dissolved iron into the surrounding environment[49].

Ureolytic Bacteria

Ureolytic bacteria, including some Bacillus species, can produce urease enzymes, which hydrolyze urea and release ammonium and carbonate ions. Carbonate minerals, especially calcium carbonate, may precipitate as a result of this rise in carbonate ions[49].

Denitrifying Bacteria

By modifying the chemical environment in their surroundings, denitrifying bacteria indirectly affects carbonate precipitation. During denitrification, nitrate (NO_3^-) is reduced to nitrogen gas (N_2), which increases pH and encourages the precipitation of carbonate minerals[50].

Microbial Consortia

Complex microbial consortia in which various microbial species work synergistically, are frequently involved in the formation of carbonate rocks. For example, a group of fungi, bacteria, and archaea may help in the general biomineralization process in subsurface settings[51].

Biofilm Formation

In subsurface porous media, microorganisms frequently create biofilms on the surface. The environment that creates these biofilms is favorable for microbial activity, which includes the precipitation of carbonate minerals. For carbonate mineral growth EPS which is produced by biofilm-forming microorganisms can act as nucleation sites. In addition to subsurface geology, these microbial processes affect environmental remediation and carbon sequestration[52].

Factors affecting carbonate biomineralization process

Abiotic factors

Texture of soil sub-strata or rock types

The texture of the rock types and soil substrata in porous media strongly influences the carbonate biomineralization process during CO_2 sequestration. Contact between CO_2 and minerals are made easier by the soil or rock porosity and permeability, which control fluid movement[53]. The mineral compositions of different types of rock vary, which influences the availability of ions necessary for carbonate mineralization in mineral reactivity with injected CO_2 and other solution components[54]. The chemical composition of pore fluids also influences the carbonate biomineralization process[55]. Carbonate biomineralization may be impacted by secondary minerals created by earlier geological processes. The subsurface fluid movement of injected fluids is influenced by hydraulic conductivity[56].

Amount of CO2 concentration in subsurface porous media

The carbonate biomineralization process during CO_2 sequestration is strongly influenced by the concentration of CO_2 in subsurface porous media. Carbonic acid is created when CO_2 dissolves in water and reacts with the minerals in the porous medium to produce carbonate mineral precipitation[57]. Increased carbonic acid formation from higher dissolved CO_2 concentrations encourages mineral dissolution and releases the ions required for carbonate precipitation. The concentration of dissolved CO_2 affects the equilibrium between carbonic acid, bicarbonate ions, and carbonate ions. The concentration of reactants, such as dissolved CO_2, affects the rate of carbonate mineralization reactions[58]. The ideal mineralization depends on the pH of the pore fluids, which is influenced by the CO_2 concentration as well. Limitations on mass transfer, like flow dynamics and injection rate, also affect the mass transfer of CO_2.

Level of O_2 concentration in subsurface porous media

During CO_2 sequestration, carbonate biomineralization may be impacted by the oxygen content of subsurface porous media. Microbial activity and respiration can be impacted by the oxidation of organic carbon, which is facilitated by oxygen. Additionally, oxygen affects redox conditions, which in turn affects the possibility of mineralization reactions[59]. Maintaining a stable pH is necessary to encourage carbonate biomineralization. Anaerobic processes can be inhibited by oxygen, which lowers the amount of carbonate ions available for precipitation[60]. The total amount of oxygen available for biomineralization can vary depending on oxygen consumption. Oxygen can also catalyze oxidative reactions, allowing certain minerals to undergo oxidative dissolution, releasing ions that contribute to carbonate mineral precipitation[61]. Oxygen plays a complicated role in carbonate biomineralization. Understanding the possible influence of oxygen on the overall success of carbonate mineralization in porous media requires site-specific evaluations[62].

Temperature of subsurface porous media

In the carbonate biomineralization process during CO_2 sequestration, temperature is critical. It affects microbial activity, thermodynamics, and reaction kinetics all of which are critical for the mineralization of carbonate[63]. Higher temperatures increase the kinetic of reactions, which causes minerals to dissolve and precipitate more quickly. Lower temperatures increase CO_2 solubility in water, which is temperature-dependent[64]. The thermodynamics of mineral precipitation are influenced by temperature as well; certain carbonate minerals are more stable at higher temperatures. The metabolic rates of the microorganisms involved in the carbonate biomineralization process are also influenced by temperature. Maintaining the ideal conditions for carbonate precipitation requires careful pH control[65]. The physical and chemical characteristics of water are also influenced by temperature, which affects how it interacts with minerals. Carbonate mineralization is also influenced by thermal gradients and temperature distribution[66].

Moisture of subsurface porous media

Moisture content in subsurface porous media significantly impacts the carbonate biomineralization process during CO_2 sequestration[67]. It influences mineral dissolution, microbial activity, water transport, CO_2 solubility, and transport efficiency. Elevated moisture content causes CO_2 to dissolve more readily, raising the concentration of carbonic acid[68]. Water transport ensures uniform contact between reactants and minerals, and microbial activity supports the growth and metabolic activity of microorganisms involved in mineralization reactions[69]. Moisture content also affects the transport and dissolution of mineral[70]. Determining the dynamics of the carbonate biomineralization process requires an understanding of these interactions. Thus, keeping the moisture content at a suitable level is crucial to the success of carbonate biomineralization during CO_2 sequestration.

PH of subsurface porous media

During CO_2 sequestration, the carbonate biomineralization process is greatly impacted by the pH of subsurface porous media. Carbonic acid formation, mineral solubility, saturation state, bicarbonate and carbonate ion availability, microbial metabolism, buffering capacity, chemical equilibria, stability of silicate minerals, and injection material corrosion are all impacted by ph. Higher concentrations of bicarbonate and carbonate ions result from lower pH values, which encourages the formation of more carbonic acid[71]. The availability of bicarbonate and carbonate ions, which are necessary for carbonate precipitation reactions, is also influenced by ph. The metabolic activity of microorganisms involved in carbonate biomineralization is also influenced by pH levels. To ensure the long-term stability of carbonated formations and to promote carbonate biomineralization, pH conditions must be optimized[72].

ORP level of subsurface porous media

Subsurface porous media's Oxidation-Reduction Potential (ORP) level has a major effect on the carbonate biomineralization process during CO_2 sequestration. Higher values to ORP indicate oxidizing conditions, while lower values indicate reducing conditions. ORP is a measure of redox conditions. The overall efficiency of carbonate biomineralization can be impacted by anaerobic processes being inhibited by positive ORP conditions. To guarantee the integrity of injection materials and infrastructure during CO_2 sequestration, ORP can also indicate corrosion potential[73].

Biotic factors

Organic carbon situation in subsurface porous media

Carbonate biomineralization is strongly influenced by the organic carbon state of subsurface porous media, particularly in the context of carbon capture and storage operations. This is brought on by the metabolic activity of ureolytic bacteria, which create urease enzymes by using organic carbon as a substrate[74]. This raises pH levels and produces carbonate ions. Carbonate biomineralization is facilitated by the energy that organic carbon provides to microbial communities. Organic acids that are released when microorganisms break down organic carbon can have an impact on the formation of carbonate minerals by regulating pH. By acting as substrates for microbial metabolism, promoting ureolysis, and raising the availability of carbonate ions, organic carbon amendments can improve microbial activity and encourage carbonate biomineralization[75].

Microbial composition in subsurface porous media

Carbonate biomineralization is greatly influenced by the microbial composition of subsurface porous media, particularly in carbon capture and storage initiatives. Sporosarcina, Bacillus, and certain strains of Clostridium are examples of ureolytic bacteria. These bacteria produce urease enzymes, which hydrolyze urea to produce carbonate ions and raise pH[76]. Utilizing sulfate as a terminal electron acceptor, sulfate-reducing bacteria (SRB) produce sulfide ions, which combine with carbonate ions and metal cations to form carbonate minerals. PH and redox conditions are impacted by the reduction of ferric ions to ferrous ions by iron-reducing bacteria. Acetate is produced by acetogenic bacteria and provides other microbial communities involved in carbonate biomineralization with an organic carbon source. Methane produced by methanogenic archaea modifies redox conditions, which in turn affects carbonate precipitation indirectly[77]. Autotrophic bacteria use CO_2 as a carbon source, whereas heterotrophic bacteria obtain their energy and growth from organic carbon sources. The formation of biofilms, competition, and adaptation to harsh environments all affect carbonate biomineralization[78].

Enrichment of carbonate biomineralization involving functional genes within the microbial community in subsurface porous media

Metabolism and certain functional genes promote carbonate biomineralization in subsurface porous media. The enrichment of carbonate minerals is facilitated by genes that encode urease, carbonic anhydrase, alkaline phosphatase, polyphosphate kinase, sulfate-reducing, methanogenic, organic carbon metabolism, biofilm-forming, and metal-related functions[79]. Urease-producing bacteria release carbonate ions and elevated pH, promoting carbonate mineral precipitation. Phosphate ions are released by alkaline phosphatase enzymes during hydrolysis which influences the formation of carbonate minerals. By adjusting redox conditions, methanogenic archaea indirectly help in the biomineralization of carbonate. It is essential to comprehend the genetic and metabolic capacities of microbial communities to forecast and improve carbonate mineral precipitation in processes such as CO_2 sequestration[80].

Microbial activity (especially urase enzyme) in subsurface porous media

Microbial activity, particularly urease enzymes, is crucial in carbonate biomineralization in subsurface porous media. Urease enzymes catalyze the hydrolysis of urea, releasing carbonate ions and ammonium ions[81]. This process increases pH, which is favorable for carbonate mineral precipitation. Urease activity directly contributes to the production of carbonate ions, which are essential building blocks for carbonate minerals[82]. Urease-mediated carbonate biomineralization has implications for carbon capture and storage strategies. Environmental factors like temperature, pH, and nutrient availability can influence urease activity. Microbial community dynamics also impact ureolysis efficiency. Understanding these aspects is essential for applications like CO_2 sequestration and environmental remediations[83].

EPS (Extracellular polymeric substances) production rate in subsurface porous media

Microorganisms produce complex, high-molecular-weight polymers known as extracellular polymeric substances (EPS), which are essential for subsurface porous media, including carbonate biomineralization. Carbonate minerals use EPS as nucleation sites to form biofilms, which offers a safe site for microbial activity[84]. They serve as a barrier of defense, encouraging cell survival and improving the uptake and retention of nutrients. EPS also contributes to microbial adhesion to minerals, which will change the permeability and pore structure[85]. It also controls redox and pH levels, which influence the microenvironment surrounding microbial cells. The rate and degree of carbonate biomineralization in subsurface porous media can be influenced by EPS-mineral interactions. Understanding the relationship between EPS production rate and carbonate biomineralization is vital for optimizing microbial processes for applications like CO_2 sequestration[86].

Carbonate Mineral formation through MICP process

Microorganisms cause the precipitation of calcium carbonate minerals in the subsurface through a biomineralization process known as Microbially Induced Calcium Carbonate Precipitation (MICP)[87]. This process can impact CO_2 sequestration efficiency by decreasing subsurface porous media's porosity in several ways:

Porosity Reduction

The physical filling of the pore spaces in subsurface media is caused by the precipitation of calcium carbonate minerals in these spaces[88]. The media's overall porosity decreases as carbonate minerals, such as calcite, build up and sometimes fill the pore spaces that were once filled with gas or water.

Cementation of Sediments

The carbonate minerals formed by MICP can bind sediment particles together naturally like cement. A more compact and solid subsurface structure is formed as a result of the cementation process, which helps to consolidate loose sediments[89].

Pore Throat Occlusion

Smaller pore throats in the subsurface media may become obstructed as a result of the precipitation of carbonate minerals. As a result, the pore network's connectivity decreases, which restricts the flow of fluids including CO_2 through the porous media[90]. The occlusion of the pore throat can improve CO_2 trapping below the surface.

Increase in Mechanical Strength

The subsurface media's mechanical strength increases as a result of porosity reduction and particle cementation. This increased strength lowers the possibility of subsurface deformations or collapses, which is especially important for stability concerns[91].

Enhanced Caprock Integrity

To stop CO_2 leakage in the context of CO_2 sequestration, the subsurface may be covered with a layer of caprock, or impermeable rock. The formation of carbonate minerals induced by MICP can strengthen the integrity of the caprock by sealing potential pathways for CO_2 migration and filling fractures[92].

CO_2 Trapping within Minerals

When CO_2 is dissolved in pore water, it can react with calcium ions to precipitate as carbonate minerals, which is a long-term storage medium for sequestered CO_2. This chemical trapping of CO_2 within the mineral strength adds an extra layer of permanence to the sequestration process[93].

Controlled Release of CO_2

Although immobilizing carbon dioxide is the main objective of CO_2 sequestration, it's also important to take into account the possibility of controlled CO_2 release from the carbonate minerals[94]. Changes in pressure or pH could cause the CO_2 that has been stored to leak back into the solution[95].

Enhanced Sealing of Faults and Fractures

MICP-induced carbonate precipitation can help seal faults and fractures in geologic formations. This sealing improves the containment of injected CO_2 within the target storage zone and lowers the possibility of CO_2 migration along these preferred flow paths[96].

It is important to note that although MICP presents potential advantages for CO_2 sequestration, the process-specific efficacy is contingent upon several variables, such as the selection of microorganisms, the accessibility of reactants, and the subsurface geological features[97]. To maximize MICP for real-world application of CO_2 sequestration projects, research is ongoing to maximize[98].

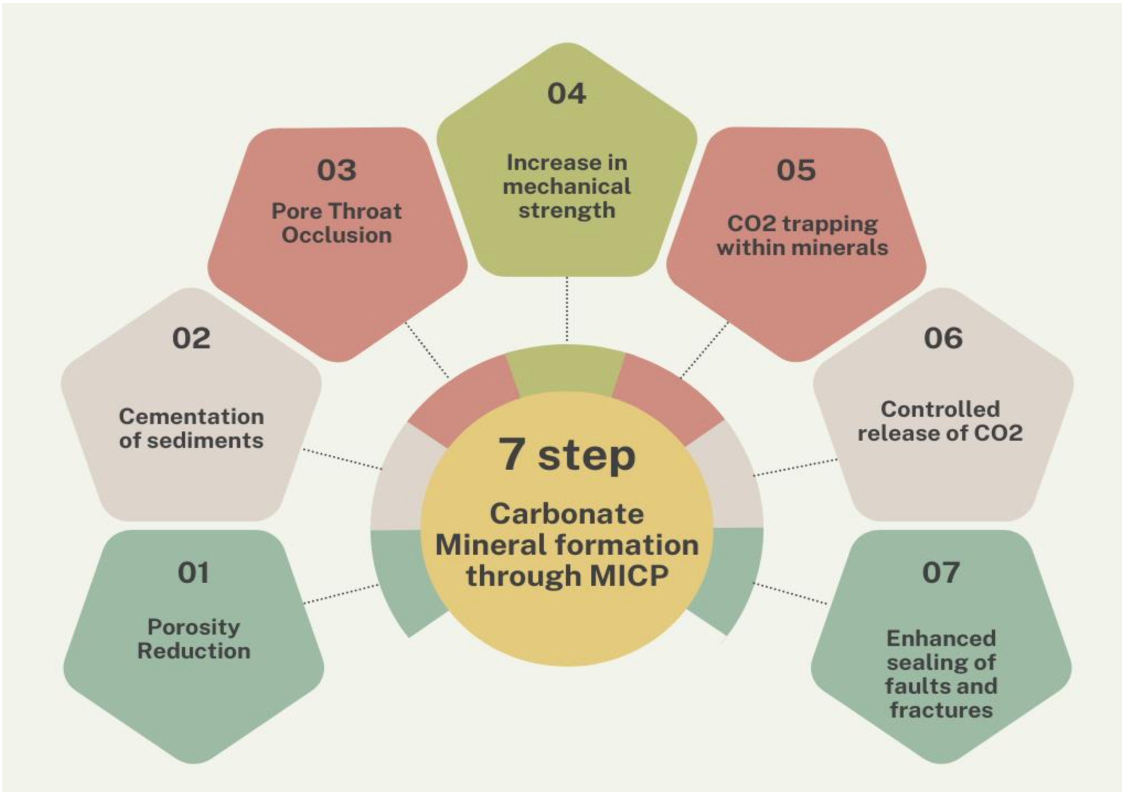

Fig: Carbonate Mineral Formation through MICP.

Methane gas generation

Through the metabolic activities of microorganisms, a process known as MICP precipitates calcium carbonate ($CaCO_3$). This process is widely applied in several contexts, such as CO_2 sequestration, where it improves the storage of carbon dioxide in geological formations[99]. One of the less common outcomes of MICP is the direct generation of methane gas in subsurface porous media. The following steps are involved in the MICP process:

The following steps are involved in the MICP process:

Carbon dioxide (CO_2) uptake

Certain types of bacteria and other microorganisms commonly involved in MICP absorb CO_2 from their environment[100].

Calcite Precipitation

The microorganisms transform the absorbed CO_2 into carbonate ions (CO_3^{2-}). Following their reaction with calcium ions (Ca_2^{+}) in the surrounding water, these carbonate ions produce calcium carbonate ($CaCO_3$), which precipitates as solid particles[101].

The following reaction represents the overall process:

$Ca_2 + Ca_3^{2-} \rightarrow CaCO_3$

Now, methane (CH_4) is not directly generated through the MICP process. Complex biochemical processes are usually involved in the formation of methane, and this process is usually linked to the anaerobic breakdown of organic matter by certain microorganisms called methanogens. Methane can be produced in subsurface porous media through processes like microbial methanogenesis if organic matter is present and the environment is conducive to methanogenic activity[102]. This is a different kind of microbiological process from MICP that breaks down organic materials into carbon dioxide and methane[103].

In conclusion, MICP is not a direct source of methane in subsurface porous media, even though it helps in the formation of carbonate minerals during CO_2 sequestration[104]. Methane production is more strongly linked to particular microbial processes involved in the anaerobic breakdown of organic materials[105].

Discussion

In MICP, urease-producing bacteria are usually the driving force behind the formation of carbonate minerals through microbial activity. This process affects porosity, subsurface CO_2 sequestration, and the production of biomethane, but it also has potential uses in soil stabilization and groundwater remediation. In addition to changing fluid flow patterns and causing cementation and pore blockage, these effects may have an impact on the efficiency of methane production and CO_2 injection[106]. MICP lowers subsurface formation porosity, which affects the effectiveness of CO_2 sequestration. Reduced permeability, pressure accumulation, and possible seismicity may result from this. To avoid unforeseen consequences, it is essential to monitor changes in pressure. To stop the dissolution and re-release of CO_2, biogenically precipitated carbonate minerals must remain stable over the long term. Reduced porosity and permeability in subsurface formations can have an impact on fluid transport, microbial communities, and methane migration limitation[108]. Porosity variations can impact methanogenic bacteria's access to nutrients, substrates, and electron acceptors. Carbonate mineralization-induced pore blockage may restrict the production of sustainable biomethane. Mitigation techniques include maximizing MICP conditions, keeping an eye on and modeling subsurface conditions, and investigating technical fixes like smart injection techniques or permeability enhancers. Maintaining sustainable CO_2 sequestration and bio-methane production requires striking a balance between the advantages of MICP and its effects on subsurface processes[109].

Future Direction

Studying the formation of methane and calcium carbonate from CO_2 sequestration in deep subsurface porous media has enormous potential to advance science and improve energy and environmental applications. The subsequent path of investigation encompasses comprehensive characterization of microbial communities, integration of omics, extended stability of biomineralized products, modeling and simulation, engineering tactics, biotechnological implementations, field-scale exhibits, interdisciplinary cooperation, and surveillance and risk evaluation[110]. These areas will center on addressing climate change, creating efficient and sustainable technologies for CO_2 sequestration and methane generation, and comprehending the complex interactions between microbes and minerals in deep subsurface porous media[111].

Incorporating omics data, evaluating the long-term stability of biomineralized products, creating sophisticated modeling and simulation techniques, investigating engineering tactics, and carrying out field-scale demonstrations are further areas of investigation for this research.

Conclusion

The intricate interactions between bacteria, minerals, and molecular mechanisms involved in biomineralization are highlighted in this review on the formation of methane and calcium carbonate derived from CO2 sequestration in deep subsurface porous media. It draws attention to how microbial activity affects how methane and calcium carbonate are formed in these conditions. The review deciphered molecular biomineralization processes, shedding light on enzymes, and metabolic pathways used by microorganisms during CO2 sequestration and methane generation. Additionally, it highlights how extracellular polymeric substances help in microbial interactions and biomineralization. This review examines how geochemical and environmental controls affect microbial activity and biomineralization, emphasizing the importance of sustainability and long-term stability. To fully comprehend CO2 sequestration and methane generation in deep subsurface environments, the review also emphasizes the significance of field-scale demonstrations and interdisciplinary collaborations.

References

1. Olalere, O.A., Gan, C.Y., Yap, P.G., Alenezi, H., Abdulhasan, M.J. and Babalola, S.O., 2023. Leveraging microalgae utilization for anthropogenic CO2 emission abatement in Malaysian urban centre: Revisiting the sustainable development goal (SDG-13). Physics and Chemistry of the Earth, Parts A/B/C, p.103356. https://doi.org/10.1016/j.pce.2022.103356
2. Joseph, E.T., Ashok, A., Singh, D., Ranganathan, A., Pandey, G., Bhan, U. and Singh, Y., 2023, May. Carbon sequestration: Capture, storage & utilization of CO2 emissions from anthropogenic sources. In AIP Conference Proceedings (Vol. 2521, No. 1). AIP Publishing. https://doi.org/10.1063/5.0117056
3. Voumik, L.C., Mimi, M.B. and Raihan, A., 2023. Nexus between urbanization, industrialization, natural resources rent, and anthropogenic carbon emissions in South Asia: CS-ARDL approach. Anthropocene Science, 2(1), pp.48-61. https://doi.org/10.1007/s44177-023-00047-3
4. Gulyaev, E., Antonov, K., Markelov, Y., Poddubny, V., Shchelkanov, A. and Iurkov, I., 2023. Short-term effect of COVID-19 lockdowns on atmospheric CO2, CH4 and PM2. 5 concentrations in urban environment. International Journal of Environmental Science and Technology, 20(5), pp.4737-4748. https://doi.org/10.1007/s13762-022-04314-5
5. Ballard, C.R. and Junior, M.R.M., 2019. Health benefits of flavonoids. In Bioactive compounds (pp. 185-201). Woodhead Publishing. https://doi.org/10.1002/adma.201907833

6. Banwo, K., Olojede, A.O., Adesulu-Dahunsi, A.T., Verma, D.K., Thakur, M., Tripathy, S., Singh, S., Patel, A.R., Gupta, A.K., Aguilar, C.N. and Utama, G.L., 2021. Functional importance of bioactive compounds of foods with Potential Health Benefits: A review on recent trends. Food Bioscience, 43, p.101320. https://doi.org/10.1016/j.bgtech.2023.100020
7. Ripanda, A., Luanda, A., Sule, K.S., Mtabazi, G.S. and Makangara, J.J., 2023. Galinsoga parviflora (Cav.): A comprehensive review on ethnomedicinal, phytochemical and pharmacological studies. Heliyon. https://doi.org/10.1371/journal.pone.0271761
8. Saharan, A., Dhanawat, M., Parkash Dora, C., Sindhu, R.K. and Verma, I., 2023. Natural Products Used in the Treatment of Autoimmune Disorder. In Bioprospecting of Tropical Medicinal Plants (pp. 1247-1263). Cham: Springer Nature Switzerland. https://doi.org/10.1016/j.est.2023.108405
9. Patel, S., Baltodano, P., Webster, T. and Roth, S., 2021. DIEP Flap and Breast Reconstruction Systematic Review Search Strategy. https://doi.org/10.1680/jgeot.19.P.350
10. Chae, H.S., Xu, R., Won, J.Y., Chin, Y.W. and Yim, H., 2019. Molecular targets of genistein and its related flavonoids to exert anticancer effects. International Journal of Molecular Sciences, 20(10), p.2420. https://doi.org/10.1016/j.jcou.2023.102443
11. Kauntz, H., Bousserouel, S., Gosse, F., Marescaux, J. and Raul, F., 2012. Silibinin, a natural flavonoid, modulates the early expression of chemoprevention biomarkers in a preclinical model of colon carcinogenesis. International journal of oncology, 41(3), pp.849-854. https://doi.org/10.1016/j.jcou.2022.102372
12. Sodiq, A., Abdullatif, Y., Aissa, B., Ostovar, A., Nassar, N., El-Naas, M. and Amhamed, A., 2023. A review on progress made in direct air capture of CO2. Environmental Technology & Innovation, 29, p.102991. https://doi.org/10.1016/j.eti.2022.102991
13. Voumik, L.C., Islam, M.A., Ray, S., Mohamed Yusop, N.Y. and Ridzuan, A.R., 2023. CO2 emissions from renewable and non-renewable electricity generation sources in the G7 countries: static and dynamic panel assessment. Energies, 16(3), p.1044. https://doi.org/10.3390/en16031044
14. Yoro, K.O. and Daramola, M.O., 2020. CO2 emission sources, greenhouse gases, and the global warming effect. In Advances in carbon capture (pp. 3-28). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-819657-1.00001-3
15. Gür, T.M., 2022. Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. Progress in Energy and Combustion Science, 89, p.100965. https://doi.org/10.1016/j.pecs.2021.100965
16. Nazir, M.J., Li, G., Nazir, M.M., Zulfiqar, F., Siddique, K.H., Iqbal, B. and Du, D., 2024. Harnessing soil carbon sequestration to address climate change challenges in agriculture. Soil and Tillage Research, 237, p.105959. https://doi.org/10.1016/j.still.2023.105959
17. Rodrigues, C.I.D., Brito, L.M. and Nunes, L.J., 2023. Soil carbon sequestration in the context of climate change mitigation: A review. Soil Systems, 7(3), p.64. https://doi.org/10.3390/soilsystems7030064
18. Elkhlifi, Z., Iftikhar, J., Sarraf, M., Ali, B., Saleem, M.H., Ibranshahib, I., Bispo, M.D., Meili, L., Ercisli, S., Torun Kayabasi, E. and Alemzadeh Ansari, N., 2023. Potential role

of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: a review. Sustainability, 15(3), p.2527. https://doi.org/10.3390/su15032527
19. Kazemian, M. and Shafei, B., 2023. Carbon sequestration and storage in concrete: A state-of-the-art review of compositions, methods, and developments. Journal of CO2 Utilization, 70, p.102443. https://doi.org/10.1016/j.jcou.2023.102443
20. Kumar, S., Priyadarshini, M., Ahmad, A. and Ghangrekar, M.M., 2023. Advanced biological and non-biological technologies for carbon sequestration, wastewater treatment, and concurrent valuable recovery: A review. Journal of CO2 Utilization, 68, p.102372. https://doi.org/10.1016/j.jcou.2022.102372
21. Gayathri, R., Mahboob, S., Govindarajan, M., Al-Ghanim, K.A., Ahmed, Z., Al-Mulhm, N., Vodovnik, M. and Vijayalakshmi, S., 2021. A review on biological carbon sequestration: A sustainable solution for a cleaner air environment, less pollution and lower health risks. Journal of King Saud University-Science, 33(2), p.101282. https://doi.org/10.1016/j.jksus.2020.101282
22. Nowicki, M., DeVries, T. and Siegel, D.A., 2022. Quantifying the carbon export and sequestration pathways of the ocean's biological carbon pump. Global Biogeochemical Cycles, 36(3), p.e2021GB007083. https://doi.org/10.1029/2021GB007083
23. Fagorite, V.I., Onyekuru, S.O., Opara, A.I. and Oguzie, E.E., 2023. The major techniques, advantages, and pitfalls of various methods used in geological carbon sequestration. International Journal of Environmental Science and Technology, 20(4), pp.4585-4614. https://doi.org/10.1007/s13762-022-04351-0
24. Dai, Z., Xu, L., Xiao, T., McPherson, B., Zhang, X., Zheng, L., Dong, S., Yang, Z., Soltanian, M.R., Yang, C. and Ampomah, W., 2020. Reactive chemical transport simulations of geologic carbon sequestration: Methods and applications. Earth-Science Reviews, 208, p.103265. https://doi.org/10.1016/j.earscirev.2020.103265
25. Zheng, L., Nico, P., Spycher, N., Domen, J. and Credoz, A., 2021. Potential impacts of CO2 leakage on groundwater quality of overlying aquifer at geological carbon sequestration sites: A review and a proposed assessment procedure. Greenhouse Gases: Science and Technology, 11(5), pp.1134-1166. https://doi.org/10.1002/ghg.2104
26. Sodiq, A., Abdullatif, Y., Aissa, B., Ostovar, A., Nassar, N., El-Naas, M. and Amhamed, A., 2023. A review on progress made in direct air capture of CO2. Environmental Technology & Innovation, 29, p.102991. https://doi.org/10.1016/j.eti.2022.102991
27. Gupta, S., Kashani, A., Mahmood, A.H. and Han, T., 2021. Carbon sequestration in cementitious composites using biochar and fly ash–Effect on mechanical and durability properties. Construction and Building Materials, 291, p.123363. https://doi.org/10.1016/j.conbuildmat.2021.123363
28. Yuan, Q., Yang, G., Zhang, Y., Wang, T., Wang, J. and Romero, C.E., 2022. Supercritical CO2 coupled with mechanical force to enhance carbonation of fly ash and heavy metal solidification. Fuel, 315, p.123154. https://doi.org/10.1016/j.fuel.2022.123154
29. Xue, Y., Ranjith, P.G., Chen, Y., Cai, C., Gao, F. and Liu, X., 2023. Nonlinear mechanical characteristics and damage constitutive model of coal under CO2 adsorption during geological sequestration. Fuel, 331, p.125690. https://doi.org/10.1016/j.fuel.2022.125690
30. Khandoozi, S., Hazlett, R. and Fustic, M., 2023. A critical review of CO2 mineral trapping in sedimentary reservoirs–from theory to application: Pertinent parameters, acceleration

methods and evaluation workflow. Earth-Science Reviews, p.104515. https://doi.org/10.1016/j.earscirev.2023.104515

31. Al-Khdheeawi, E.A., Mahdi, D.S., Yuan, Y. and Iglauer, S., 2023. Influence of Clay Content on CO2-Rock Interaction and Mineral-Trapping Capacity of Sandstone Reservoirs. Energies, 16(8), p.3489. https://doi.org/10.3390/en16083489
32. Kumar, S., Foroozesh, J., Edlmann, K., Rezk, M.G. and Lim, C.Y., 2020. A comprehensive review of value-added CO2 sequestration in subsurface saline aquifers. Journal of Natural Gas Science and Engineering, 81, p.103437. https://doi.org/10.1016/j.jngse.2020.103437
33. Payton, R.L., Sun, Y., Chiarella, D. and Kingdon, A., 2022. Pore scale numerical modelling of geological carbon storage through mineral trapping using true pore geometries. Transport in Porous Media, 141(3), pp.667-693. https://doi.org/10.1007/s11242-021-01741-9
34. Zhu, D., Peng, S., Zhao, S., Wei, M. and Bai, B., 2021. Comprehensive review of sealant materials for leakage remediation technology in geological CO2 capture and storage process. Energy & Fuels, 35(6), pp.4711-4742. https://doi.org/10.1021/acs.energyfuels.0c04416
35. Guo, S., Zhang, J., Li, M., Zhou, N., Song, W., Wang, Z. and Qi, S., 2021. A preliminary study of solid-waste coal gangue based biomineralization as eco-friendly underground backfill material: Material preparation and macro-micro analyses. Science of The Total Environment, 770, p.145241. https://doi.org/10.1016/j.scitotenv.2021.145241
36. Mineral activity in biomineralization
37. Yuan, R., Zhang, Y., Liao, L., Ge, Y., Li, W. and Zhi, Q., 2023. Biomineralization-Inspired Anti-Caries Strategy Based on Multifunctional Nanogels as Mineral Feedstock Carriers. International Journal of Nanomedicine, pp.4933-4947. https://doi.org/10.2147/IJN.S418465
38. Erdmann, N. and Strieth, D., 2023. Influencing factors on ureolytic microbiologically induced calcium carbonate precipitation for biocementation. World Journal of Microbiology and Biotechnology, 39(2), p.61. https://doi.org/10.1007/s11274-022-03499-8
39. Lin, H., Zhou, M., Li, B. and Dong, Y., 2023. Mechanisms, application advances and future perspectives of microbial-induced heavy metal precipitation: A review. International Biodeterioration & Biodegradation, 178, p.105544. https://doi.org/10.1016/j.ibiod.2022.105544
40. Zhang, H., Zhang, S.S., Zhang, W., Zhu, L., Li, Y.P. and Pan, Y., 2023. Biomineralization and AHLs-guided quorum sensing enhanced phosphorus recovery in the alternating aerobic/anaerobic biofilm system under metal ion stress. Journal of Environmental Management, 325, p.116583. https://doi.org/10.1016/j.jenvman.2022.116583
41. Yue, J., Song, N., Meng, C., Xie, L. and Chang, D., 2023. An Experimental Study to Improve the Nutrients and the Mechanical Properties of Copper Tailings Sand in China's Arid Zone by Biomineralization of Locally Isolated Urease-Producing Bacteria. Sustainability, 15(13), p.10077. https://doi.org/10.3390/su151310077
42. Wang, L., van Paassen, L., Pham, V., Mahabadi, N., He, J. and Gao, Y., 2023. A (Simplified) Biogeochemical Numerical Model to Predict Saturation, Porosity and

Permeability During Microbially Induced Desaturation and Precipitation. Water Resources Research, 59(1), p.e2022WR032907. https://doi.org/10.1029/2022WR032907
43. Liu, N., Haugen, M., Benali, B., Landa-Marbán, D. and Fernø, M.A., 2023. Pore-scale spatiotemporal dynamics of microbial-induced calcium carbonate growth and distribution in porous media. International Journal of Greenhouse Gas Control, 125, p.103885. https://doi.org/10.1016/j.ijggc.2023.103885
44. Konstantinou, C. and Wang, Y., 2023. Unlocking the Potential of Microbially Induced Calcium Carbonate Precipitation (MICP) for Hydrological Applications: A Review of Opportunities, Challenges, and Environmental Considerations. Hydrology, 10(9), p.178. https://doi.org/10.3390/hydrology10090178
45. Zhang, Y.S., Liu, Y., Sun, X.D., Zeng, W., Xing, H.P., Lin, J.Z., Kang, S.B. and Yu, L., 2024. Application of microbially induced calcium carbonate precipitation (MICP) technique in concrete crack repair: A review. Construction and Building Materials, 411, p.134313. https://doi.org/10.1016/j.conbuildmat.2023.134313
46. Zhuang, W., Song, X., Liu, M., Wang, Q., Song, J., Duan, L., Li, X. and Yuan, H., 2023. Potential capture and conversion of CO2 from oceanwater through mineral carbonation. Science of The Total Environment, 867, p.161589. https://doi.org/10.1016/j.scitotenv.2023.161589
47. Khandoozi, S., Hazlett, R. and Fustic, M., 2023. A critical review of CO2 mineral trapping in sedimentary reservoirs–from theory to application: Pertinent parameters, acceleration methods and evaluation workflow. Earth-Science Reviews, p.104515. https://doi.org/10.1016/j.earscirev.2023.104515
48. Eyinla, D.S., Leggett, S., Badrouchi, F., Emadi, H., Adamolekun, O.J. and Akinsanpe, O.T., 2023. A comprehensive review of the potential of rock properties alteration during CO2 injection for EOR and storage. Fuel, 353, p.129219. https://doi.org/10.1016/j.fuel.2023.129219
49. Soumare, A., Djibril, S.A.R.R. and DIéDHIOU, A.G., 2023. Potassium sources, microorganisms and plant nutrition: Challenges and future research directions. Pedosphere, 33(1), pp.105-115. https://doi.org/10.1016/j.pedsph.2022.06.025
50. Pusparizkita, Y.M., Schmahl, W.W., Ambarita, M., Kholid, H.N., Sadewa, A.Y., Ismail, R., Jamari, J. and Bayuseno, A.P., 2023. Mineralizing CO2 and producing polymorphic calcium carbonates from bitumen-rock asphalt manufacturing solid residues. Cleaner Engineering and Technology, 12, p.100602. https://doi.org/10.1016/j.clet.2023.100602
51. Akam, S.A., Swanner, E.D., Yao, H., Hong, W.L. and Peckmann, J., 2023. Methane-derived authigenic carbonates–A case for a globally relevant marine carbonate factory. Earth-Science Reviews, p.104487. https://doi.org/10.1016/j.earscirev.2023.104487Mather, C.C., Lampinen, H.M., Tucker, M., Leopold, M., Dogramaci, S., Raven, M. and Gilkes, R.J., 2023. Microbial influence on dolomite and authigenic clay mineralisation in dolocrete profiles of NW Australia. Geobiology. https://doi.org/10.1111/gbi.12555
52. Konstantinou, C. and Wang, Y., 2023. Unlocking the Potential of Microbially Induced Calcium Carbonate Precipitation (MICP) for Hydrological Applications: A Review of Opportunities, Challenges, and Environmental Considerations. Hydrology, 10(9), p.178. https://doi.org/10.3390/hydrology10090178

53. Zhang, Y.S., Liu, Y., Sun, X.D., Zeng, W., Xing, H.P., Lin, J.Z., Kang, S.B. and Yu, L., 2024. Application of microbially induced calcium carbonate precipitation (MICP) technique in concrete crack repair: A review. Construction and Building Materials, 411, p.134313. https://doi.org/10.1016/j.conbuildmat.2023.134313
54. Jain, S., 2024. Suitability of various ureolytic microbes for potential soil strengthening via biocementation. Journal of Hazardous, Toxic, and Radioactive Waste, 28(1), p.04023034. https://doi.org/10.1061/JHTRBP.HZENG-1233
55. Bhurtel, A., Salifu, E. and Siddiqua, S., 2024. Composite biomediated engineering approaches for improving problematic soils: Potentials and opportunities. Science of The Total Environment, p.169808. https://doi.org/10.1016/j.scitotenv.2023.169808
56. Abdullah, S.M., Kolo, K., Konhauser, K.O. and Pirouei, M., 2022. Microbial Domains and Their Role in the Formation of Minerals. In Mineral Formation by Microorganisms: Concepts and Applications (pp. 1-39). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-80807-5_1
57. Akyel, A., Coburn, M., Phillips, A.J. and Gerlach, R., 2022. Key applications of biomineralization. Mineral Formation by Microorganisms: Concepts and Applications, pp.347-387. https://doi.org/10.1007/978-3-030-80807-5_10
58. Samuels, T., Bryce, C., Landenmark, H., Marie-Loudon, C., Nicholson, N., Stevens, A.H. and Cockell, C., 2020. Microbial weathering of minerals and rocks in natural environments. Biogeochemical cycles: Ecological drivers and environmental impact, pp.59-79. https://doi.org/10.1002/9781119413332.ch3
59. Joshi, S.R. and Baskar, S., 2022. Factors Affecting Biomineralization. In Mineral Formation by Microorganisms: Concepts and Applications (pp. 283-314). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-80807-5_8
60. Jain, S., 2021. An overview of factors influencing microbially induced carbonate precipitation for its field implementation. Building materials for sustainable and ecological environment, pp.73-99. https://doi.org/10.1007/978-981-16-1706-5_5
61. Liu, N., Haugen, M., Benali, B., Landa-Marbán, D. and Fernø, M.A., 2023. Pore-scale spatiotemporal dynamics of microbial-induced calcium carbonate growth and distribution in porous media. International Journal of Greenhouse Gas Control, 125, p.103885. https://doi.org/10.1016/j.ijggc.2023.103885
62. Zhang, Y., Hu, X., Wang, Y. and Jiang, N., 2023. A critical review of biomineralization in environmental geotechnics: Applications, trends, and perspectives. Biogeotechnics, p.100003. https://doi.org/10.1016/j.bgtech.2023.100003
63. Morais, S., Cario, A., Liu, N., Bernard, D., Lecoutre, C., Garrabos, Y., Ranchou-Peyruse, A., Dupraz, S., Azaroual, M., Hartman, R.L. and Marre, S., 2020. Studying key processes related to CO 2 underground storage at the pore scale using high pressure micromodels. Reaction Chemistry & Engineering, 5(7), pp.1156-1185. https://pubs.rsc.org/en/content/articlelanding/2020/re/d0re00023j/unauth
64. Zhang, Y.S., Liu, Y., Sun, X.D., Zeng, W., Xing, H.P., Lin, J.Z., Kang, S.B. and Yu, L., 2024. Application of microbially induced calcium carbonate precipitation (MICP) technique in concrete crack repair: A review. Construction and Building Materials, 411, p.134313. https://doi.org/10.1016/j.conbuildmat.2023.134313

65. Brasileiro, P.P.F., Roque, B.A.C., Brandão, Y.B., Converti, A., Benachour, M. and Sarubbo, L.A., 2023. Determination of the limiting step in the biomineralization of calcium carbonate by Bacillus cereus. Construction and Building Materials, 409, p.134057. https://doi.org/10.1016/j.conbuildmat.2023.134057
66. Guo, S., Zhang, J., Li, M., Zhou, N., Song, W., Wang, Z. and Qi, S., 2021. A preliminary study of solid-waste coal gangue based biomineralization as eco-friendly underground backfill material: Material preparation and macro-micro analyses. Science of The Total Environment, 770, p.145241. https://doi.org/10.1016/j.scitotenv.2021.145241
67. Wang, Y., Konstantinou, C., Tang, S. and Chen, H., 2023. Applications of microbial-induced carbonate precipitation: A state-of-the-art review. Biogeotechnics, p.100008. https://doi.org/10.1016/j.bgtech.2023.100008
68. Mele, I., McGill, R.A., Thompson, J., Fennell, J. and Fitzer, S., 2023. Ocean acidification, warming and feeding impacts on biomineralization pathways and shell material properties of Magallana gigas and Mytilus spp. Marine Environmental Research, 186, p.105925. https://doi.org/10.1016/j.marenvres.2023.105925
69. Aytekin, B., Mardani, A. and Yazıcı, Ş., 2023. State-of-art review of bacteria-based self-healing concrete: Biomineralization process, crack healing, and mechanical properties. Construction and Building Materials, 378, p.131198. https://doi.org/10.1016/j.conbuildmat.2023.131198
70. Zhang, Y., Hu, X., Wang, Y. and Jiang, N., 2023. A critical review of biomineralization in environmental geotechnics: Applications, trends, and perspectives. Biogeotechnics, p.100003. https://doi.org/10.1016/j.bgtech.2023.100003
71. Jain, S., Mishra, P.N., Tiwari, S., Wang, Y., Jiang, N., Dash, H.R., Chang, I., Kumar, A., Das, S.K., Scheuermann, A. and Bore, T., 2023. Biological perspectives in geotechnics: theoretical developments. Reviews in Environmental Science and Bio/Technology, 22(4), pp.1093-1130. https://doi.org/10.1007/s11157-023-09671-2
72. Stallings Young, E.G., Mahabadi, N., Zapata, C.E. and Van Paassen, L.A., 2021. Microbial-induced desaturation in stratified soil conditions. International Journal of Geosynthetics and Ground Engineering, 7(2), p.37. https://doi.org/10.1007/s40891-021-00276-9
73. Jimenez-Martinez, J., Nguyen, J. and Or, D., 2022. Controlling pore-scale processes to tame subsurface biomineralization. Reviews in Environmental Science and Bio/Technology, 21(1), pp.27-52. https://doi.org/10.1007/s11157-021-09603-y
74. Zhang, D., Chen, X., Larson, S.L., Ballard, J.H., Knotek-Smith, H.M., Ding, D., Hu, N. and Han, F.X., 2020. Uranium biomineralization with phosphate—biogeochemical process and its application. ACS Earth and Space Chemistry, 4(12), pp.2205-2214. https://doi.org/10.1021/acs.est.0c05437
75. Wang, Y., Zhang, G., Wang, H., Cheng, Y., Liu, H., Jiang, Z., Li, P. and Wang, Y., 2021. Effects of different dissolved organic matter on microbial communities and arsenic mobilization in aquifers. Journal of hazardous materials, 411, p.125146. https://doi.org/10.1016/j.jhazmat.2021.125146
76. González, F.J., Rincón-Tomás, B., Somoza, L., Santofimia, E., Medialdea, T., Madureira, P., López-Pamo, E., Hein, J.R., Marino, E., De Ignacio, C. and Reyes, J., 2020. Low-temperature, shallow-water hydrothermal vent mineralization following the recent

submarine eruption of Tagoro volcano (El Hierro, Canary Islands). Marine Geology, 430, p.106333. https://doi.org/10.1016/j.margeo.2020.106333

77. Qiao, Z., Sheng, Y., Wang, G., Chen, X., Liao, F., Mao, H., Zhang, H., He, J., Liu, Y., Lin, Y. and Yang, Y., 2023. Deterministic factors modulating assembly of groundwater microbial community in a nitrogen-contaminated and hydraulically-connected river-lake-floodplain ecosystem. Journal of Environmental Management, 347, p.119210. https://doi.org/10.1016/j.jenvman.2023.119210
78. Zhang, Y., Hu, X., Wang, Y. and Jiang, N., 2023. A critical review of biomineralization in environmental geotechnics: Applications, trends, and perspectives. Biogeotechnics, p.100003. https://doi.org/10.1016/j.bgtech.2023.100003
79. Dong, H., Yu, L., Xu, T., Liu, Y., Fu, J., He, Y., Gao, J., Wang, J., Sun, S., She, Y. and Zhang, F., 2023. Cultivation and biogeochemical analyses reveal insights into biomineralization caused by piezotolerant iron-reducing bacteria from petroleum reservoirs and their application in MEOR. Science of The Total Environment, 903, p.166465. https://doi.org/10.1016/j.scitotenv.2023.166465
80. Qian, C., Ren, X., Rui, Y. and Wang, K., 2021. Characteristics of bio-CaCO3 from microbial bio-mineralization with different bacteria species. Biochemical Engineering Journal, 176, p.108180. https://doi.org/10.1016/j.bej.2021.108180
81. Chen, J., Liu, B., Zhong, M., Jing, C. and Guo, B., 2022. Research status and development of microbial induced calcium carbonate mineralization technology. PloS one, 17(7), p.e0271761. https://doi.org/10.1371/journal.pone.0271761
82. Guo, S., Zhang, J., Li, M., Zhou, N., Song, W., Wang, Z. and Qi, S., 2021. A preliminary study of solid-waste coal gangue based biomineralization as eco-friendly underground backfill material: Material preparation and macro-micro analyses. Science of The Total Environment, 770, p.145241. https://doi.org/10.1016/j.scitotenv.2021.145241
83. Hu, X.M., Liu, J.D., Feng, Y., Zhao, Y.Y., Wang, X.W., Liu, W.H., Zhang, M. and Liu, Y., 2023. Application of urease-producing microbial community in seawater to dust suppression in desert. Environmental Research, 219, p.115121. https://doi.org/10.1016/j.envres.2022.115121
84. Ali, M., Arif, M., Sedev, R., Sánchez-Román, M., Keshavarz, A. and Iglauer, S., 2023. Underground hydrogen storage: The microbiotic influence on rock wettability. Journal of Energy Storage, 72, p.108405. https://doi.org/10.1016/j.est.2023.108405
85. Robles-Fernández, A., Areias, C., Daffonchio, D., Vahrenkamp, V.C. and Sánchez-Román, M., 2022. The Role of microorganisms in the nucleation of carbonates, environmental implications and applications. Minerals, 12(12), p.1562. https://doi.org/10.3390/min12121562
86. Ramachandran, A.L., Polat, P., Mukherjee, A. and Dhami, N.K., 2020. Understanding and creating biocementing beachrocks via biostimulation of indigenous microbial communities. Applied microbiology and biotechnology, 104, pp.3655-3673. https://doi.org/10.1007/s00253-020-10474-6
87. Dong, H., Huang, L., Zhao, L., Zeng, Q., Liu, X., Sheng, Y., Shi, L., Wu, G., Jiang, H., Li, F. and Zhang, L., 2022. A critical review of mineral–microbe interaction and co-evolution: mechanisms and applications. National science review, 9(10), p.nwac128. https://doi.org/10.1093/nsr/nwac128

88. Akyel, A., Coburn, M., Phillips, A.J. and Gerlach, R., 2022. Key applications of biomineralization. Mineral Formation by Microorganisms: Concepts and Applications, pp.347-387. https://doi.org/10.1007/978-3-030-80807-5_10
89. Ma, L., Pang, A.P., Luo, Y., Lu, X. and Lin, F., 2020. Beneficial factors for biomineralization by ureolytic bacterium Sporosarcina pasteurii. Microbial cell factories, 19(1), pp.1-12. https://doi.org/10.1186/s12934-020-1281-z
90. Qin, W., Wang, C.Y., Ma, Y.X., Shen, M.J., Li, J., Jiao, K., Tay, F.R. and Niu, L.N., 2020. Microbe-mediated extracellular and intracellular mineralization: environmental, industrial, and biotechnological applications. Advanced Materials, 32(22), p.1907833. https://doi.org/10.1002/adma.201907833
91.
92. Wang, X. and Nackenhorst, U., 2020. A coupled bio-chemo-hydraulic model to predict porosity and permeability reduction during microbially induced calcite precipitation. Advances in Water Resources, 140, p.103563. https://doi.org/10.1016/j.advwatres.2020.103563
93. Lin, H., Suleiman, M.T. and Brown, D.G., 2020. Investigation of pore-scale CaCO3 distributions and their effects on stiffness and permeability of sands treated by microbially induced carbonate precipitation (MICP). Soils and Foundations, 60(4), pp.944-961. https://doi.org/10.1016/j.sandf.2020.07.003
94. Hataf, N. and Baharifard, A., 2020. Reducing soil permeability using microbial induced carbonate precipitation (MICP) method: A case study of shiraz landfill soil. Geomicrobiology Journal, 37(2), pp.147-158. https://doi.org/10.1016/j.jece.2022.107770
95. Su, Y., Zha, M., Jiang, L., Ding, X., Qu, J., Jin, J. and Iglauer, S., 2022. Pore structure and fluid distribution of tight sandstone by the combined use of SEM, MICP and X-ray micro-CT. Journal of Petroleum Science and Engineering, 208, p.109241. https://doi.org/10.1016/j.petrol.2021.109241
96. Wani, K.S. and Mir, B.A., 2021. A laboratory-scale study on the bio-cementation potential of distinct river sediments infused with microbes. Transportation Infrastructure Geotechnology, 8(1), pp.162-185. https://doi.org/10.1007/s40515-020-00131-w
97. Clarà Saracho, A., Haigh, S.K. and Ehsan Jorat, M., 2021. Flume study on the effects of microbial induced calcium carbonate precipitation (MICP) on the erosional behaviour of fine sand. Géotechnique, 71(12), pp.1135-1149. https://doi.org/10.1680/jgeot.19.P.350
98. Song, C. and Elsworth, D., 2020. Microbially induced calcium carbonate plugging for enhanced oil recovery. Geofluids, 2020, pp.1-10. https://doi.org/10.1155/2020/5921789
99. Greene, J., Viamontes, J. and Hill, B., 2020, December. The Connected Pore Space Paradigm: An Evaluation of the Effect of Crushing on Pore Volume and Structure. In Unconventional Resources Technology Conference, 20–22 July 2020 (pp. 4416-4431). Unconventional Resources Technology Conference (URTEC). https://doi.org/10.15530/urtec-2020-3009
100. Karimian, A. and Hassanlourad, M., 2022. Mechanical behaviour of MICP-treated silty sand. Bulletin of Engineering Geology and the Environment, 81(7), p.285. https://doi.org/10.1007/s10064-022-02780-2

101. Tian, X., Xiao, H., Li, Z., Li, Z., Su, H. and Ouyang, Q., 2022. Experimental Study on the Strength Characteristics of Expansive Soils Improved by the MICP Method. Geofluids, 2022. https://doi.org/10.1155/2022/3089820

102. Kolawole, O., Ispas, I., Kumar, M., Weber, J., Zhao, B. and Zanoni, G., 2021. How can biogeomechanical alterations in shales impact caprock integrity and CO2 storage?. Fuel, 291, p.120149. https://doi.org/10.1016/j.fuel.2021.120149

103. Mastalerz, M., Drobniak, A. and Hower, J.C., 2021. Controls on reservoir properties in organic-matter-rich shales: Insights from MICP analysis. Journal of Petroleum Science and Engineering, 196, p.107775. https://doi.org/10.1016/j.bgtech.2023.100020

104. Hadian, P. and Rezaee, R., 2021, October. Experimental Study on the Effect of Supercritical CO2 on Shaly Caprocks. In 82nd EAGE Annual Conference & Exhibition (Vol. 2021, No. 1, pp. 1-5). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202010341

105. Wu, H., Jayne, R.S., Bodnar, R.J. and Pollyea, R.M., 2021. Simulation of CO2 mineral trapping and permeability alteration in fractured basalt: Implications for geologic carbon sequestration in mafic reservoirs. International Journal of Greenhouse Gas Control, 109, p.103383. https://doi.org/10.1016/j.ijggc.2021.103383

106. Ahmmed, B., Karra, S., Vesselinov, V.V. and Mudunuru, M.K., 2021. Machine learning to discover mineral trapping signatures due to CO2 injection. International Journal of Greenhouse Gas Control, 109, p.103382. https://doi.org/10.1016/j.ijggc.2021.103382

107. Gholami, R. and Raza, A., 2022. CO2 sequestration in sandstone reservoirs: How does reactive flow alter trapping mechanisms?. Fuel, 324, p.124781. https://doi.org/10.1016/j.fuel.2022.124781

108. Choi, S.G., Chang, I., Lee, M., Lee, J.H., Han, J.T. and Kwon, T.H., 2020. Review on geotechnical engineering properties of sands treated by microbially induced calcium carbonate precipitation (MICP) and biopolymers. Construction and Building Materials, 246, p.118415. https://doi.org/10.1016/j.conbuildmat.2020.118415

109. Liu, B., Zhu, C., Tang, C.S., Xie, Y.H., Yin, L.Y., Cheng, Q. and Shi, B., 2020. Bio-remediation of desiccation cracking in clayey soils through microbially induced calcite precipitation (MICP). Engineering geology, 264, p.105389. https://doi.org/10.1016/j.enggeo.2019.105389

110. Nasser, A.A., Sorour, N.M., Saafan, M.A. and Abbas, R.N., 2022. Microbially-Induced-Calcite-Precipitation (MICP): A biotechnological approach to enhance the durability of concrete using Bacillus pasteurii and Bacillus sphaericus. Heliyon, 8(7). https://doi.org/10.1016/j.heliyon.2022.e09879

111. Gholami, R. and Raza, A., 2022. CO2 sequestration in sandstone reservoirs: How does reactive flow alter trapping mechanisms? Fuel, 324, p.124781. https://doi.org/10.1016/j.fuel.2022.124781Almajed, A., Lateef, M.A., Moghal, A.A.B. and Lemboye, K., 2021. State-of-the-art review of the applicability and challenges of microbial-induced calcite precipitation (MICP) and enzyme-induced calcite precipitation (EICP) techniques for geotechnical and geoenvironmental applications. Crystals, 11(4), p.370. https://doi.org/10.3390/cryst11040370