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Emerging role of microbial geochemistry in subsurface carbon sequestration: A comprehensive review

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ABSTRACT

Carbon capture and sequestration (CCS) is vital for addressing the global challenge of climate change, driven by increasing carbon emissions. Among the emerging strategies, microbial communities are crucial in influencing geochemical processes relevant to CCS, such as mineralization and gas transformation. However, the specific dynamics and impacts of these microbial processes remain underexplored, highlighting a significant research gap. This review examines the role of microbial geochemistry in enhancing carbon sequestration mechanisms. It explores various microbial-induced processes, including microbial-induced carbonate precipitation, biofilm formation, and alterations in biogeochemical cycles that contribute to CO_2 trapping. Case studies from geological formations illustrate the positive effects of microbial activity on CCS performance and the complexities involved in understanding these interactions. Key findings emphasize that microbial communities can enhance the efficiency of CO_2 mineralization and influence the long-term stability of carbon storage through biogeochemical cycling. Furthermore, the review identifies challenges in studying microbial geochemistry, including difficulties in replicating subsurface conditions and limited knowledge of microbial population dynamics over time. In conclusion, understanding microbial contributions to CCS is critical for developing effective strategies to combat climate change. Interdisciplinary research integrating microbiology, geochemistry, and geophysics will be essential in unlocking the full potential of microbial processes for improving the stability and efficiency of carbon capture and storage technologies.

KEYWORDS

Carbon sequestration; Microbial geochemistry; CO_2 mineralization; Biofilm formation; Subsurface microbial community; Climate change mitigation

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Introduction

Carbon emissions from industrial activities and fossil fuel use have significantly contributed to global climate change, causing rising temperatures, extreme weather events, and ecological disruptions. Addressing this issue requires reducing atmospheric CO_2 levels. Carbon capture and storage has emerged as a critical strategy to mitigate climate change by capturing CO_2 from point sources, such as power plants, and storing it in geological formations. This process reduces emissions at the source and can help achieve global carbon neutrality goals. CCS technologies, particularly in subsurface environments, offer promising potential to limit greenhouse gas accumulation and protect the planet's climate system.

Carbon capture and sequestration have emerged as crucial technologies for addressing the global carbon emission problem and mitigating climate change [1]. The increasing atmospheric CO_2 concentration, primarily due to fossil fuel consumption, has led to global warming and ocean acidification [2]. With fossil fuels supplying over 63% of global energy, CCS is pivotal in combating this crisis [1]. The process involves capturing CO_2 from significant sources, such as industrial plants, and storing it in geological reservoirs to achieve a carbon-neutral or negative budget [1,3]. While long-term solutions focus on sustainable energy generation, CCS can provide immediate mitigation for existing fossil fuel infrastructure [4]. The Intergovernmental Panel on Climate Change (IPCC) has endorsed CCS as a viable mitigation strategy for developing countries, highlighting its importance in global efforts to reduce CO_2 emissions [3].

Geologic carbon storage (GCS) in deep saline aquifers, depleted oil and gas fields, and basalt formations are crucial for mitigating greenhouse gas emissions [5]. Deep saline aquifers offer the largest storage potential, storing emissions for at least a century [6]. These formations are evaluated based on safety, storage capacity, and containment integrity [7]. CO_2 injection into saline aquifers creates a complex multiphase flow system, but simplifying assumptions can provide practical insights into system behavior, including storage capacity estimates and leakage risk assessments [6]. The Sleipner project demonstrates successful commercial-scale CO_2 sequestration in saline aquifers [8]. While economic and policy challenges persist, CO_2 storage in deep saline aquifers is a viable technology that can significantly contribute to climate change mitigation efforts.

Microbial communities play a significant role in influencing geochemical processes during carbon capture and storage (CCS). Studies have shown that CO_2 leakage from storage sites can impact microbial diversity and activity in subsurface environments [9,10]. High CO_2 levels can change pH, solute concentrations, and microbial community composition, affecting methanogenesis, metal reduction, and sulfate reduction [9,11]. Microorganisms adapted to high

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salinity and supercritical CO_2 conditions have been observed in potential CCS sites, with implications for reservoir quality and stability [10]. However, knowledge gaps remain regarding the influence of factors such as redox conditions, CO_2 influx rate, and mineralogy on CO_2-induced reactions in potable aquifers and the vadose zone [12]. Understanding these microbial-geochemical interactions is crucial for assessing CCS's environmental impacts and risks. Moreover, microbes can facilitate reactions such as mineral dissolution, carbonate precipitation, and the formation of biofilms, which may enhance or hinder carbon trapping in geological formations. Their metabolic activities alter the chemical environment, potentially improving the efficiency of long-term CO_2 sequestration. This review explores recent advances in microbial geochemistry related to carbon capture and storage (CCS), aiming to assess microbial contributions to CCS, highlight knowledge gaps, and propose future research directions to improve CCS technology through microbial interactions.

Overview of Carbon Sequestration Methods

Carbon sequestration methods focus on storing captured CO_2 in subsurface formations to mitigate atmospheric emissions. Geologic storage traps CO_2 in deep formations like saline aquifers, depleted oil fields, and basalt, while carbon mineralization converts it into stable minerals for permanent storage. Microbial geochemistry enhances these processes, influencing mineralization and long-term storage stability.

Geologic carbon storage (GCS)

GCS involves injecting CO_2 into deep subsurface formations, trapped through various physical and chemical mechanisms. Once injected, the CO_2 is stored in porous rock formations, typically at depths of over 800 meters, where high pressure and temperature keep it in a supercritical state. These formations offer extensive storage capacity, with saline aquifers being the most common, while basalt formations facilitate mineralization due to their reactive nature. Carbon sequestration is crucial to mitigating climate change by reducing atmospheric CO_2 levels. Various methods exist, including geological storage in oil and gas reservoirs, deep coal seams, saline aquifers, and salt caverns [13]. Ocean sequestration and mineral carbonation are potential options [14]. Biological methods involve soil carbon sequestration and phytosequestration through photosynthetic mechanisms in plants, cyanobacteria, and microalgae [15]. Other techniques include pre- and post-combustion CO_2 capture, membrane separation, amine scrubbing, and cryotechnology [16]. Enhancing natural CO_2 sinking rates through terrestrial sequestration, ocean fertilization, and rock weathering can reduce carbon [14]. While these methods offer significant potential for carbon sequestration, each has advantages and disadvantages regarding capacity, cost, time scale, stability, and environmental impacts, necessitating careful evaluation before implementation [14,13].

Carbon mineralization

Carbon mineralization is a process in which CO_2 reacts with minerals, primarily calcium and magnesium silicates, to form stable carbonate minerals like calcite and magnesite. This reaction permanently traps CO_2 within the rock matrix, offering a secure carbon storage method. This process involves converting CO_2 into stable carbonate minerals by reacting with divalent cations like Ca^{2+}, Mg^{2+}, or Fe^{2+} [17]. It offers a more secure alternative to other trapping mechanisms, which can be reversible [18]. Studies have shown that over 95% of injected CO_2 can be mineralized in basaltic rocks within two years, significantly faster than previously thought [19]. Factors influencing mineralization include rock types; temperature, fluid composition, and CO_2 phase [17]. While most carbon capture and storage projects focus on sedimentary basins, reactive rocks like basalts and peridotites offer large potential volumes for carbon storage through mineralization [20]. Ongoing research aims to accelerate the mineralization process and explore its applicability on a global scale [18,20]. Basalt formations are particularly suitable for this process, as they contain high concentrations of reactive minerals. Mineralization locks CO_2 in solid form and prevents its escape over time, providing long-term stability to carbon storage efforts. This process is critical for ensuring the permanent sequestration of captured CO_2.

Role of microbial geochemistry in CCS

Microbial communities in subsurface environments can significantly influence carbon storage and mineralization processes. Methanogenesis can modify fluid composition and dynamics within storage reservoirs, potentially impacting CO_2 storage capacity and trapping mechanisms [21]. Long-term CO_2 leakage can influence microbial communities, affecting subsurface biogeochemistry and carbon cycling [9]. Microorganisms in deep geological systems are relevant for underground gas storage and geothermal energy production, with implications for CCS, renewable energy storage, and geothermal energy [22]. Microbial processes, such as ureolysis, can enhance CCS through mineral-trapping and solubility-trapping. Ureolysis increases brine pH, promoting CO_2 dissolution and carbonate precipitation, thus improving the solubility-trapping capacity of the brine [23]. Understanding these microbial processes is crucial for assessing CCS efficiency and potential risks and developing monitoring strategies for CO_2 storage sites.

Moreover, sulfate-reducing bacteria and methanogens catalyze chemical reactions that alter the geochemical conditions around stored CO_2, impacting mineral trapping and fluid dynamics. For example, microbial-induced carbonate precipitation (MICP) can enhance mineralization by forming stable carbonate minerals. Microbially induced carbonate precipitation (MICP) shows promise for enhancing carbon capture and storage (CCS) through mineral trapping and solubility trapping. Ureolytic bacteria can precipitate dissolved CO_2 as calcite, increasing incorporation rates at higher CO_2 pressures and urea concentrations [23]. MICP can also enhance pH through alkalization, increasing calcite precipitation in porous media [24]. This process can potentially create subsurface hydraulic barriers near CO_2 storage wellbores, improving storage security [25]. MICP offers a rapid alternative to natural carbonate formation, with urease-producing bacteria converting CO_2 into calcium carbonate in various environments [26]. While ureolysis does not directly precipitate gaseous CO_2, it increases brine pH, enhancing solubility trapping and reducing headspace CO_2 concentrations [23]. These findings highlight MICP's potential for climate change

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mitigation through CO_2 sequestration. Additionally, microbial activity may influence rock dissolution, biofilm formation, and gas migration, all affecting the long-term stability and efficiency of carbon sequestration efforts.

Microbial Communities in the Subsurface

Microbial communities in the deep subsurface are crucial to carbon sequestration, as their metabolic activities directly impact geochemical processes. These microbes influence carbon cycling and storage stability through pathways like methanogenesis, sulfate reduction, and iron reduction. Catalyzing or altering reactions can either enhance or inhibit CO_2 mineralization, making their role essential to the long-term success of carbon capture and storage.

Types of microbial communities

Microbial communities in the terrestrial deep subsurface are diverse and influenced by various factors. Globally, aquifer lithology controls bacterial community diversity in deep groundwater, with Betaproteobacteria, Gammaproteobacteria, and Firmicutes dominating [27]. Depth and geological characteristics act as ecological filters for archaeal and bacterial communities, while vertical water movement impacts shallow subsurface microbial assembly [28]. In uranium-contaminated sediments, geochemical conditions are selected for well-adapted taxa with prevalent nitrate-reducing bacteria [29]. Site-specific communities have been observed, such as iron-oxidizing Gallionella dominating bacterial communities in Romuvaara, Finland, alongside methanogenic and ammonia-oxidizing archaea [30]. Functional genes for methane cycling, sulfate reduction, and nitrate reduction have been detected, indicating diverse metabolic potentials in these environments [30]. Understanding these communities is crucial for developing effective bioremediation strategies and comprehending global subsurface element cycling.

Deep subsurface environments harbour diverse microbial communities with various metabolic pathways relevant to carbon cycling. Studies in the Fennoscandian Shield, South African gold mines, and the Iberian Pyrite Belt have revealed the presence of bacteria and archaea involved in methanogenesis, sulfate reduction, and iron oxidation [30-33]. The Wood-Ljungdahl pathway for carbon fixation is prevalent in these environments, along with carbon monoxide dehydrogenase genes that support autotrophic and heterotrophic metabolisms [32]. Metagenomic analyses have identified dominant phyla such as Euryarchaeota and Firmicutes in deep fracture fluids [32]. Molecular biomarkers and DNA microarray techniques have also detected methane oxidizers, sulfate-reducers, and metal oxidizers in these subsurface communities [33]. These findings highlight the complex interplay of microbial metabolisms in deep subsurface environments and their role in biogeochemical cycles.

Anaerobic carbon cycling in wetlands involves several key metabolic pathways, including methanogenesis, sulfate reduction, and iron reduction. The relative importance of these processes varies seasonally and across different wetland types. Iron reduction is typically dominant early in the growing season in tidal freshwater and brackish marshes, gradually giving way to methanogenesis or sulfate reduction [34,35]. Methanogenesis occurs primarily through the aceticlastic pathway, except in more ombrotrophic peatlands early in the season [35]. While plants can influence these processes by releasing oxygen into the rhizosphere, their impact may be limited in some wetland systems [36]. Iron reduction can be the dominant carbon oxidation pathway in lacustrine sediments, followed by sulfate reduction, with methanogenesis playing a negligible role [37]. Factors such as soil chemistry, temperature, and water table depth influence the balance between these anaerobic metabolic pathways.

Microbial influence on geochemistry

Microorganisms are crucial in geochemical reactions relevant to carbon capture and storage (CCS). They can catalyze carbon cycling and biogeochemical reactions in deep subsurface environments, potentially influencing the fate of injected CO_2 [38]. Microbial metabolisms involving redox transformations of metals and metalloids can affect mineral precipitation, transformation, and dissolution, impacting modern and ancient geochemical cycles [39]. Elevated CO_2 levels can alter groundwater pH and chemical speciation, affecting the thermodynamics and kinetics of microbial reactions such as syntrophic oxidation, iron reduction, sulfate reduction, and methanogenesis [40]. Microorganisms can also enhance carbon mineralization through bioalkalinization, increasing the pH of aqueous solutions and promoting calcite precipitation [41]. Understanding the genetic basis of these microbial processes is crucial for predicting their influence on geochemical cycles and their potential impact on CCS strategies [39].

Microbial reactions can significantly influence CO_2 mineralization in geological carbon sequestration. High CO_2 levels can alter groundwater pH and chemical speciation, affecting microbial reactions differently. While syntrophic oxidation and acetoclastic methanogenesis are inhibited, iron reduction and hydrogenotrophic processes may be enhanced [40]. Cyanobacteria can facilitate carbonate mineralization through their carbon dioxide-concentrating mechanism, potentially aiding biological carbon capture and storage [42]. Biomass growth can enhance calcite precipitation through bioalkalinization, offering a promising method for CO_2 immobilization [41]. The survival of microorganisms under high CO_2 pressures varies among species, with some gram-positive bacteria showing higher resilience. Mineral surfaces, particularly quartz sandstones, can protect microbes by facilitating biofilm formation, while certain minerals may release toxic metals that increase microbial mortality under CO_2 stress [43].

Microbial Impact on Carbon Sequestration Mechanisms

Microbes significantly impact carbon sequestration through various mechanisms. Microbial-induced carbonate precipitation (MICP) enhances CO_2 trapping, while microbial activity influences mineral dissolution processes. Additionally, biofilm formation in subsurface environments affects permeability, potentially altering fluid flow and CO_2 migration. Microbes also modify biogeochemical cycles; such as carbon, sulfur, and nitrogen; potentially enhancing mineral trapping and improving sequestration efficiency.

Microbial-Driven mineralization processes

Microbially induced carbonate precipitation (MICP) is a

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promising carbon sequestration and environmental remediation process. MICP involves the conversion of CO_2 into calcium carbonate (CaCO3) by urease-producing bacteria, which can thrive in various environments [26]. The bacterial cell wall acts as a nucleation site for CaCO3 formation, with urease and carbonic anhydrase enzymes mediating the process [44]. MICP has multiple applications, including bio cementation, heavy metal removal, and CO_2 sequestration [45]. The efficiency of CO_2 sequestration during MICP is influenced by biotic factors, such as bacterial species and abiotic factors, including pH and medium components, with urea being the most critical component [46]. While MICP shows great potential for sustainable carbon management and climate change mitigation, challenges remain in implementing the technology commercially [44,45].

The impact of microbial activity on mineral dissolution varies depending on the microorganisms and minerals involved. While some studies suggest a weak effect of microbes on Ca-Mg silicate weathering, others demonstrate that microorganisms can significantly modify mineral dissolution rates and mechanisms [47,48]. Certain microbial extracellular polymers can inhibit or enhance dissolution rates by up to three orders of magnitude, depending on pH and mineral composition [49]. In complex microbial consortia, heterotrophic bacteria may enhance mineral dissolution, while photosynthetic organisms can promote secondary mineral precipitation [50]. Microbial activity can lead to the formation of secondary minerals, including clays and carbonates, which impact soil fertility and CO_2 sequestration [48,50]. The microbial impact on mineral dissolution is complex and depends on the specific microbe-mineral interactions and environmental conditions.

Biofilm formation and its effects

Microbial biofilms in subsurface environments significantly impact transport processes and permeability in porous media [51,52]. Depending on substrate flux and surface loading, biofilm formation can be continuous or discontinuous [53]. During nutrient-rich conditions, biomass accumulation decreases permeability, while starvation conditions lead to biofilm evolution patterns affecting permeability differently [54]. These patterns include initial permeability decrease, stabilization, and potential increase due to biofilm sloughing under shear stress [54]. The critical shear stress for sloughing indicates biofilm strength, with removal occurring when exceeded [54]. Understanding biofilm formation and its effects on permeability is crucial for various applications, including subsurface remediation, enhanced oil recovery, and carbon dioxide sequestration [52]. However, the relationships between microbial growth and changes in porosity and permeability remain poorly understood, necessitating further research [51].

Biofilms in porous media significantly impact fluid flow and transport processes. They can reduce water permeability by up to 95% in biologically active zones [55]. Biofilm growth and gas generation affect flow patterns, with gas moving upwards in discrete fingers and accumulating at the top of porous systems [55]. In CO_2 storage, biofilms have been proposed as bio-barriers to mitigate leakage from geological reservoirs [56]. In hydraulic fracturing, biofilms can cause formation damage, reducing gas flow rates by half when occupying approximately 10% of pore volume [57]. The distribution of biofilms within pores also impacts flow rates. Modeling studies show that overall permeability, flow pathways, and pressure gradients are highly dependent on biofilm ratio and permeability, with moderate impacts from biofilm porosity at higher biofilm levels [58].

Biogeochemical cycles

Microorganisms alter biogeochemical cycles and enhance carbon sequestration in various ecosystems. In landfills, microbes' mediate carbon, nitrogen, and sulphur cycles during waste decomposition, influencing greenhouse gas emissions [59]. Soil inoculation with bacteria and cyanobacteria from biological soil crusts can increase carbon sequestration in degraded dryland soils, potentially removing significant amounts of CO_2 from the atmosphere [60]. While terrestrial ecosystems can be managed for carbon sequestration, manipulating specific microbes remains challenging [61]. Recent research has focused on developing microbial inoculants to enhance soil carbon sequestration, with promising candidates including arbuscular mycorrhizal fungi, melanising endophytic fungi, and plant growth-promoting bacteria [62]. These microorganisms contribute to carbon sequestration through various mechanisms, such as facilitating carbon transition from labile to recalcitrant pools and stimulating plant growth. The "biochar + microbe system" is proposed as a potential solution to overcome limitations in building and retaining soil carbon stocks [62].

Microbial enhancement of CO_2 trapping in geological storage shows promise for mitigating climate change. Ureolysis-induced calcite precipitation can incorporate CO_2 from the gas phase, enhancing solubility trapping by increasing brine pH [23]. Microbes can adapt to extreme subsurface conditions, promoting CO_2 dissolution and mineral corrosion and facilitating mineral trapping [63]. Acceleration methods for mineral trapping include co-injection of carbonic anhydrase-producing microbes or urea bacteria, selecting reservoirs with reactive minerals, and increasing mineral surface area through fracturing [64]. Engineering CO_2-fixing pathways and energy-harvesting systems in autotrophic and heterotrophic microorganisms can improve CO_2 fixation efficiency, while rewiring metabolic pathways can reduce microbial CO_2 emissions and increase the carbon yield of valuable products [65]. These strategies demonstrate the potential of biotechnology to enhance microbial CO_2 sequestration in geological storage sites.

Case Studies of Microbial Geochemistry in CCS Projects

The CarbFix project in Iceland demonstrates the potential of carbon sequestration in basaltic formations. Microbial communities in these environments are diverse and responsive to CO_2 injection [66,67]. While CO_2 injection can decrease microbial richness, it also promotes the growth of certain bacteria, potentially affecting aquifer redox state and carbon fate [67]. Experimental studies show that bacterial presence minimizes basalt dissolution rates and CO_2 sequestration processes [68]. The CarbFix project aims to capture and mineralize CO_2 emissions from geothermal power plants, with extensive research conducted on site characterization, alteration

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mineralogy, and numerical modelling [69]. Monitoring and reactive transport modelling are crucial in optimizing long-term site management and quantifying CO_2 mineralization [69]. Microbial activity in basalt formations has been observed in various case studies. In the oceanic crust at the Mid-Atlantic Ridge, nitrogen addition stimulated the growth of basalt-associated microorganisms, including iron-oxidizing bacteria [70]. The Wallula pilot well in Washington State revealed diverse microbial communities in basalt formation waters, dominated by Proteobacteria, Firmicutes, and Actinobacteria, with microorganisms capable of various metabolic processes [66]. Experimental studies with basaltic rocks from Hawaii demonstrated that microbial activity, specifically by Burkholderia fungorum, enhanced rock alteration and Fe mobilization under nutrient-depleted conditions. Colonization experiments with synthetic basaltic glasses showed that microbial attachment and element dissolution were influenced by Fe redox state and residual stress in the glass [71]. These findings suggest that basaltic formations offer promising opportunities for geological carbon sequestration, with potential applications worldwide.

Microbial processes in saline aquifers and depleted oil fields have been monitored to understand their impact on carbon storage and bioremediation. Studies have examined the effects of CO_2 concentration on microbial communities in various subsurface environments [72]. In depleted oil reservoirs targeted for CO_2 storage, high salinity and supercritical CO_2 concentrations were found to be selected for stress-tolerant microorganisms, potentially affecting reservoir quality and stability [10]. Monitoring techniques have included chemical, isotopic, and biological analyses to characterize microbial processes in contaminated aquifers [73]. The use of Bio-Sep® biotraps has proven effective in collecting biofilms that better represent in situ microbial ecology compared to planktonic organisms from groundwater samples [74]. These studies highlight the importance of understanding microbial community dynamics in subsurface environments for applications in carbon storage, bioremediation, and overall ecosystem management.

Recent studies have highlighted the significant role of microbial communities in carbon capture and storage (CCS) projects. In basalt formations, CO_2 injection can lead to rapid changes in microbial populations, decreasing overall richness but increasing in specific groups like iron-oxidizing bacteria and aromatic compound degraders [67]. These changes can affect aquifer redox states and carbon fate. In hydrocarbon reservoirs, microbial methanogenesis has been shown to convert up to 13-19% of injected CO_2 to methane, with rates of 73-109 mmol CH_4/m^3/year observed [21]. This process may be significant across geological settings, particularly in depleted hydrocarbon fields [21]. Pre-injection microbial communities in basalt formations have been found to include hydrogen oxidizers, methylotrophs, and methanogens, among others [66]. Understanding these microbial dynamics is crucial for effective CCS implementation and monitoring.

Microbial communities can adapt to enhance the degradation of various compounds, including trace organic chemicals (TOrCs) and metals in environmental systems. Adaptation mechanisms may involve changes in carbon use efficiency (CUE) or shifts in community structure [75,76]. However, pre-exposure to TOrCs at ng/L levels does not necessarily affect their attenuation or influence microbial community structure and function in managed aquifer recharge systems [77]. Adaptation to xenobiotic compounds depends on factors such as concentration, exposure time, and chemical structure, with a threshold concentration of 10 ppb observed for some compounds [78]. Adapted microbial communities can achieve higher removal efficiencies for various contaminants, including sulfate and metals [76]. Understanding these adaptation processes is crucial for optimizing bioremediation strategies and predicting ecosystem responses to environmental changes.

Challenges and Research Gaps

Studying microbial geochemistry in carbon sequestration presents significant challenges, including replicating subsurface conditions in labs and monitoring microbial activity at depth. Knowledge gaps persist regarding microbial population dynamics, interactions with host rock formations, and long-term impacts on storage stability. Additionally, predictive models integrating microbial activity with geochemical reactions remain underdeveloped, requiring further research.

Challenges in studying microbial geochemistry in CCS

Studying microbial geochemistry in Carbon Capture and Storage (CCS) presents several challenges. Replicating subsurface conditions in laboratories is difficult, and monitoring microbial activities at depth requires specialized techniques [22]. The long-term impacts of microbial activity on storage stability are not fully understood [21]. Microbial processes, such as methanogenesis, can significantly affect CO_2 storage by modifying fluid composition and dynamics within reservoirs [21]. Deep ecosystems respond quickly to CO_2 injections, with acidic CO_2-charged groundwater causing a decrease in microbial richness while promoting the growth of certain bacterial species [67]. The impact of potential CO_2 leakage on plants and microorganisms varies, with plants showing visible stress responses under high soil CO_2 levels and microorganisms exhibiting more diverse reactions [79]. Further research is needed to understand these complex interactions better and ensure the environmental safety of CCS technology.

Current knowledge gaps

Recent studies highlight significant knowledge gaps in understanding microbial dynamics during carbon capture and storage (CCS). While CCS is crucial for reducing greenhouse gas emissions, microbial processes like methanogenesis can impact CO_2 storage efficiency and fluid dynamics [22]. The bioavailability of H2 is likely to influence methanogenesis rates across different storage sites [21]. Current research lacks comprehensive data on how elevated CO_2 levels affect geochemical processes in aquifers and the vadose zone, with factors such as redox conditions and microbial activity requiring further investigation [12]. Deep subsurface microbiology is increasingly relevant for underground gas storage and geothermal energy production, necessitating more research into microbial interactions with these systems [22]. Field studies have shown that CO_2 injection into basalt can rapidly alter microbial communities, potentially impacting aquifer redox states and carbon fate [67].

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The interactions between microbial processes and host rock formations in subsurface environments are complex and poorly understood. Microorganisms can influence the dissolution and precipitation of minerals in caves and other rock-hosted systems [80]. These processes are controlled by lithology, permeability, and fluid mixing, affecting microbial communities' distribution and diversity [81]. Microbial activities can generate acidity, leading to cave wall dissolution or induce mineralization, forming various mineral deposits [80]. In radionuclide behaviour, microbial processes can impact solid-phase capture mechanisms, including sorption, reductive precipitation, and co-precipitation [82]. However, the specific physiological adaptations, growth rates, and synergistic interactions between microorganisms and minerals in these energy-limited environments remain largely unknown, necessitating further research to understand better these complex geomicrobiological systems [81,82].

Modeling microbial influence

Microbial communities play a crucial role in biogeochemical cycles and ecosystem functions, but predicting their behaviour remains challenging [83,84]. Integrating microbial ecology into ecosystem models can improve predictions of carbon dynamics under environmental changes, such as warming, precipitation changes, and nitrogen enrichment [84]. However, building predictive models that link microbial community composition to function requires close coordination between experimental data collection and mathematical model development [85]. Advances in 'omics' - based approaches and systems biology can help characterize microbial system interactions impacting terrestrial carbon sequestration [86]. While directly linking genomes to global phenomena is challenging, connections at intermediate scales are feasible by integrating new analytical and modelling techniques [86]. This integration could enhance our ability to develop and evaluate microbial strategies for capturing and sequestering atmospheric CO_2 [86].

Future Directions and Opportunities

The future of carbon sequestration presents exciting opportunities to enhance efficiency through microbial processes. By integrating bioengineering, interdisciplinary approaches, and sustainable practices, we can optimize microbial contributions to CCS and develop scalable solutions for effective CO_2 management.

Potential for enhanced microbial carbon sequestration

Microbial carbon sequestration offers promising opportunities for enhancing carbon capture and storage (CCS) efficiency. Bioengineering approaches can improve CO_2 fixation in autotrophic and heterotrophic microorganisms by modifying CO_2-fixing pathways and energy-harvesting systems [65]. Prokaryotes can be utilized for CCS monitoring and CO_2 utilization, with synthetic biology potentially maximizing CO_2 uptake [87]. Microbial ureolysis can enhance solubility-trapping of CO_2 in brines and promote mineral formation, potentially reducing CO_2 leakage [23]. The microbial carbon pump (MCP) plays a crucial role in forming recalcitrant dissolved organic carbon (RDOC) in oceans, which can sequester carbon over long timescales [88]. Future research should focus on integrating the MCP with the biological pump, understanding POC-RDOC interactions, and developing new technologies for in-situ monitoring of microbial activity to improve CCS efficiency [88,87].

Interdisciplinary approaches

Interdisciplinary approaches combining geochemistry, microbiology, and geophysics, offer valuable insights into subsurface microbial behaviour. Studies have demonstrated that geophysical techniques can detect microbial activity and associated biogeochemical processes. Bulk conductivity measurements have been linked to zones of enhanced microbial activity in hydrocarbon-impacted aquifers [89]. Bioremediation experiments have shown that indigenous bacteria can be stimulated to remove heavy metals through precipitation of sulfide phases, with geophysical surveys indicating changes in electrical conductance and magnetic susceptibility [90]. The emerging field of biogeophysics focuses on detecting microbes, microbial growth, and microbe-mineral interactions using geophysical techniques [91]. Electrical-induced polarization measurements have been used to monitor stimulated microbial activity during subsurface bioremediation, revealing correlations between phase response and changes in groundwater geochemistry associated with iron and sulfate reduction and sulfide mineral precipitation [92]. These integrated approaches provide powerful tools for understanding and monitoring subsurface microbial processes.

Sustainable and scalable CCS solutions

Microbial contributions to carbon capture and storage (CCS) offer promising solutions for large-scale CO_2 sequestration. Autotrophic aerobic bacteria can capture CO_2 from industrial sources to produce microbial protein, potentially usable as food, feed, or fertilizer [93]. Natural microbial communities and synthetic biology approaches can enhance CO_2 uptake and monitoring in geological storage sites [87]. Microbes can accelerate silicate weathering, potentially drawing down significant amounts of CO_2 while producing valuable by-products [94]. Engineering CO_2-fixing pathways and energy-harvesting systems in autotrophic and heterotrophic microorganisms can improve CO_2 fixation efficiency, while rewiring metabolic pathways can reduce microbial CO_2 emissions and increase the carbon yield of value-added products [65]. These microbial CCS approaches offer sustainable, scalable solutions for CO_2 sequestration, though further research is needed to determine their economic feasibility and potential for large-scale implementation.

Conclusions

In summary, microbial communities enhance carbon capture and storage (CCS) by influencing geochemical processes such as mineralization, fluid dynamics, and biogeochemical cycling. Their activities, including microbial-induced carbonate precipitation and biofilm formation, can significantly affect CO_2 sequestration effectiveness and long-term stability. Future research must focus on interdisciplinary approaches to better understand microbial geochemistry and its implications for CCS. Addressing current knowledge gaps and developing predictive models incorporating microbial dynamics will be essential for optimizing sequestration strategies. As we advance our understanding of these processes, harnessing microbial activities can enhance the stability and efficiency of carbon

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sequestration, contributing significantly to climate change mitigation efforts.

Disclosure statement

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