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Carbon Sequestration in Mineralogy: Potential of Ultramafic Rocks for CO_2 Storage

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Abstract

The increasing concentration of atmospheric carbon dioxide (CO_2) due to anthropogenic activities has necessitated the development of effective carbon sequestration strategies. Mineral carbonation, particularly utilizing ultramafic rocks, has emerged as a promising approach for long-term CO_2 storage. This review explores the potential of ultramafic rocks in sequestering CO_2, discussing their mineral composition, reaction mechanisms, advantages, and challenges associated with their utilization in carbon capture and storage (CCS). Additionally, advancements in enhancing mineral carbonation efficiency, including pre-treatment techniques and microbial-assisted sequestration, are examined. The use of ultramafic rocks offers a natural and permanent solution for CO_2 mitigation, with significant implications for climate change mitigation. The ability of these rocks to form stable carbonate minerals upon reacting with CO_2 makes them a reliable option for reducing greenhouse gas emissions. However, improving reaction rates and addressing energy and economic constraints remain key research areas. Furthermore, understanding the geological distribution of ultramafic rocks and integrating their use with industrial processes can enhance their practical applicability. In order to speed up carbonation, it is crucial to optimize reaction conditions and investigate novel catalysts, as demonstrated by recent developments in laboratory and field tests. The incorporation of microbial and enzymatic processes further presents a novel avenue for enhancing CO_2 sequestration efficiency. This review emphasizes the need for interdisciplinary research to bridge gaps between geology, chemistry, and engineering to maximize the effectiveness of mineral carbonation. Future efforts should focus on pilot-scale projects, life cycle assessments, and policy frameworks to ensure the sustainable implementation of this technology. Overall, ultramafic rock-based carbon sequestration presents a viable and durable strategy for combating global carbon emissions while contributing to the advancement of CCS technologies.

Keywords: Mineral carbonation, ultramafic rocks, carbon dioxide sequestration, geological CO_2 storage, carbon mineralization, climate change mitigation

INTRODUCTION

The escalating concerns over climate change have intensified global research efforts to develop effective carbon sequestration techniques. Anthropogenic CO_2 emissions, primarily from fossil fuel combustion and industrial activities, have significantly contributed to global warming and ocean acidification. Addressing this issue requires innovative solutions that can capture and store carbon dioxide in a stable and long-term manner. Various carbon capture and storage (CCS) methods have been explored, including geological storage, oceanic sequestration, and mineral carbonation. Among these, mineral carbonation has emerged as a highly promising approach due to its ability to convert CO_2 into stable solid carbonates, preventing

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its re-release into the atmosphere [1]. Mineral carbonation is a natural process that mimics the weathering of silicate rocks, a phenomenon that occurs over geological timescales. However, by accelerating this process through engineered techniques, scientists have demonstrated the potential for large-scale CO_2 sequestration. The basic principle of mineral carbonation involves the reaction of CO_2 with metal oxides, primarily magnesium and calcium, to form thermodynamically stable carbonate minerals such as magnesite ($MgCO_3$) and calcite ($CaCO_3$). This reaction is exothermic, meaning it releases energy, which further enhances its feasibility as a sustainable carbon sequestration method. Unlike other CCS techniques that pose the risk of leakage or require continuous monitoring, mineral carbonation offers a permanent and secure solution for CO_2 storage.

Ultramafic rocks, which are rich in magnesium and calcium-bearing silicate minerals, have been identified as highly suitable candidates for mineral carbonation. These rocks primarily consist of olivine ($(Mg, Fe)_2SiO_4$), serpentine ($Mg_3Si_2O_5(OH)_4$), and pyroxene ($(Mg, Fe)SiO_3$), all of which exhibit strong reactivity with CO_2 under appropriate conditions. Their natural abundance and widespread availability further enhance their potential for large-scale application. Ultramafic rocks are commonly found in ophiolite complexes and mantle peridotites, making them an attractive resource for carbon sequestration initiatives [2].

Despite its numerous advantages, the feasibility of mineral carbonation depends on various factors, including reaction kinetics, energy requirements, and economic viability. Naturally occurring mineral carbonation is a slow process, but researchers have explored different strategies to accelerate reaction rates. These include mechanical activation (grinding to increase surface area), thermal treatment, and the use of chemical catalysts. Additionally, *in situ* mineral carbonation, where CO_2 is injected directly into rock formations, has been proposed as an alternative to *ex situ* methods, which involve mining and processing rock material before carbonation. While *in situ* approaches minimize environmental disturbances associated with mining, they require precise control over reaction conditions to achieve optimal results.

This study provides a comprehensive overview of the fundamental principles of mineral carbonation and evaluates the feasibility of ultramafic rocks as a viable medium for large-scale CO_2 sequestration. By examining recent advancements in reaction engineering, process optimization, and field applications, this study aims to contribute to the growing body of knowledge on sustainable carbon sequestration techniques. Given the urgent need to mitigate climate change and reduce atmospheric CO_2 levels, mineral carbonation using ultramafic rocks represents a promising avenue that warrants further exploration and investment [3, 4].

MINERALOGY OF ULTRAMAFIC ROCKS

Ultramafic rocks are characterized by their high magnesium (Mg) and calcium (Ca) content, making them particularly suitable for carbon sequestration applications. These rocks primarily consist of silicate minerals that readily react with carbon dioxide (CO_2) to form stable carbonate minerals. The key mineral constituents include:

- *Olivine* (Mg_2SiO_4)*:* This mineral is highly reactive with CO_2, making it a prime candidate for mineral carbonation. When exposed to CO_2, olivine undergoes a transformation into magnesite ($MgCO_3$) and silica (SiO_2), a process that occurs naturally but can be accelerated under specific conditions.
- *Serpentine* ($Mg_3Si_2O_5(OH)_4$)*:* This hydrated magnesium silicate is less reactive than olivine in its natural state, requiring additional activation to enhance its carbonation efficiency. Thermal or mechanical treatments can improve its reactivity.
- *Pyroxene* $\{(Mg, Fe, Ca)SiO_3\}$*:* While less reactive compared to olivine and serpentine, pyroxene still contributes to the overall sequestration potential of ultramafic rocks by providing additional magnesium and calcium for carbonation reactions.

The mineralogical composition of ultramafic rocks directly influences their effectiveness in carbon sequestration. The presence of iron (Fe) in some mineral structures may introduce variability in reactivity, affecting the overall efficiency of the carbonation process. Understanding the mineralogy of these rocks is essential for optimizing their use in CO_2 sequestration projects. Additionally, various geological formations worldwide contain extensive ultramafic rock deposits, making them a widely available resource. Given their natural abundance and chemical properties, these rocks represent a viable option for large-scale carbon capture and storage efforts, particularly when combined with advanced treatment and processing techniques to enhance reaction kinetics [5–7].

MECHANISM OF CO_2 SEQUESTRATION IN ULTRAMAFIC ROCKS

Mineral carbonation is a naturally occurring process in which CO_2 reacts with magnesium- and calcium-rich minerals to form stable carbonate compounds. This reaction mimics the geological weathering of ultramafic rocks but occurs at an accelerated rate under controlled conditions. The fundamental reaction governing olivine carbonation can be represented as follows:

$$Mg_2SiO_4+2CO_2 \rightarrow 2MgCO_3+SiO_2$$

This reaction is exothermic, meaning it releases energy as it progresses. While thermodynamically favourable, the reaction kinetics are inherently slow under natural conditions, making it necessary to implement strategies that enhance carbonation rates. Various factors influence the efficiency of CO_2 sequestration, including mineral surface area, temperature, pressure, and the presence of catalysts or reactive fluids.

When ultramafic rocks come into contact with CO_2 in the presence of water, they undergo a series of dissolution and precipitation reactions. The minerals dissolve, releasing magnesium and calcium ions, which then react with dissolved CO_2 to form carbonates such as magnesite ($MgCO_3$) and calcite ($CaCO_3$). Over geological timescales, this process plays a crucial role in regulating atmospheric CO_2 levels. However, for industrial applications, it is essential to accelerate these reactions through artificial means.

Furthermore, mineral carbonation offers a permanent method of carbon sequestration since the resulting carbonate minerals are *stable over geological timescales* and do not pose risks of leakage, unlike some other storage methods such as underground CO_2 injection. As research in this field advances, scientists are continuously exploring ways to optimize the carbonation process, ensuring it becomes a more practical and economically feasible solution for large-scale CO_2 mitigation efforts [8, 9].

METHODS TO ENHANCE CARBONATION EFFICIENCY

Although the carbonation process occurs naturally, its rate is too slow for effective CO_2 sequestration on an industrial scale. Several techniques have been developed to enhance the efficiency of mineral carbonation, ensuring rapid and sustained CO_2 capture. These methods include:

- *Thermal and Mechanical Activation:* Heat treatment and grinding are commonly used to increase mineral surface area and reactivity. Serpentine, for example, can be thermally activated by removing its hydroxyl groups, making it more reactive toward CO_2. Mechanical grinding increases the exposed surface area, accelerating dissolution and carbonation rates.
- *Aqueous Carbonation:* This method involves dissolving ultramafic minerals in water to enhance the availability of Mg^{2+} and Ca^{2+} ions, which then react with dissolved CO_2. Various additives, including acids, chelating agents, or alkali solutions, can be used to further improve dissolution rates. The process can be conducted at elevated temperatures and pressures to maximize efficiency.
- *Biologically Induced Carbonation:* Certain microorganisms, such as cyanobacteria and fungi, play a role in promoting carbonate precipitation by altering pH and increasing mineral solubility. Biogenic processes have been explored as a potential low-energy alternative for enhancing carbonation efficiency.

In addition to these methods, reactor-based approaches have been designed to facilitate CO_2 sequestration under controlled conditions. Industrial-scale carbonation reactors aim to optimize temperature, pressure, and mineral reactivity to achieve rapid CO_2 capture. The integration of these techniques can significantly improve the feasibility of ultramafic rock-based sequestration, making it a viable solution for reducing atmospheric CO_2 levels [10].

ADVANTAGES OF ULTRAMAFIC ROCK-BASED CARBON SEQUESTRATION

Ultramafic rock-based carbon sequestration presents several advantages that make it an attractive option for long-term CO_2 storage:

- *Abundance and Availability:* Ultramafic rocks are widely distributed across the globe, particularly in ophiolite belts and other geological formations. This widespread availability ensures that sourcing raw materials for carbon sequestration remains cost-effective.
- *Permanence of Storage:* Unlike some other carbon storage methods that involve the risk of leakage, mineral carbonation results in the formation of stable carbonate minerals, which remain locked in solid form for millions of years.
- *Potential for Industrial Integration:* Mining and industrial operations often produce ultramafic rock waste, which can be repurposed for CO_2 sequestration. This not only reduces waste disposal costs but also contributes to sustainable resource utilization.
- *Exothermic Nature of Carbonation Reactions:* Since the carbonation process releases energy, it has the potential to be integrated with energy recovery systems, improving overall process efficiency.

Additionally, the use of ultramafic rocks aligns with the circular economy concept, where waste materials are repurposed to create valuable end-products. By leveraging these advantages, ultramafic rock carbonation could become a cornerstone technology for global CO_2 mitigation efforts [11–14].

CHALLENGES AND LIMITATIONS

Despite its promise, ultramafic rock-based carbon sequestration faces several challenges:

- *Slow Reaction Rates:* The natural carbonation process occurs over geological timescales, necessitating artificial acceleration to make it commercially viable.
- *Energy and Cost Considerations:* Pre-treatment techniques such as grinding, heating, or pressure-enhanced carbonation require significant energy input, impacting economic feasibility.
- *Environmental Impacts:* Large-scale mining and processing of ultramafic rocks could lead to habitat destruction, water usage concerns, and carbon footprint issues, which must be managed sustainably.

Addressing these challenges is crucial for ensuring that ultramafic rock carbonation becomes a scalable and cost-effective CO_2 sequestration strategy.

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Ongoing research aims to address the current limitations of ultramafic rock carbonation. Future directions include:

- *Development of Catalysts:* Scientists are investigating novel catalytic materials that can accelerate carbonation reactions, reducing energy requirements.
- *Utilization of Industrial Wastes:* Mining and metallurgical industries generate significant ultramafic rock waste, which can be repurposed for carbon sequestration, turning waste into a valuable resource.
- *Field Demonstrations:* Large-scale pilot projects are being conducted to assess the real-world feasibility of ultramafic rock-based sequestration, ensuring process optimization and economic viability.

CONCLUSION

Ultramafic rocks offer a promising and sustainable solution for CO_2 sequestration through mineral carbonation, making them a valuable resource in mitigating climate change. These rocks, rich in magnesium and calcium silicates, naturally react with carbon dioxide to form stable carbonate minerals, ensuring long-term storage without the risk of leakage. Unlike other carbon storage methods, such as underground injection, mineral carbonation using ultramafic rocks provides a permanent and geochemically stable solution, significantly reducing the atmospheric concentration of CO_2 over time.

Despite their promise, a number of issues need to be resolved to improve this strategy's effectiveness and financial sustainability. The natural carbonation process is slow, and enhancing reaction rates requires various activation techniques such as thermal treatment, chemical pre-treatment, or mechanical grinding to increase the surface area and reactivity of the minerals. Furthermore, combining ultramafic rock-based sequestration with industrial operations like mining, cement, and steel production offers a chance to absorb and store CO_2 at the source of emissions, increasing efficiency even more.

Recent advancements in experimental and pilot-scale projects have demonstrated the feasibility of large-scale implementation. However, further research is needed to optimize reaction conditions, reduce energy consumption, and develop cost-effective methods for large-scale deployment. To guarantee sustainable implementation, environmental factors including land use, water consumption, and other ecological effects must also be properly assessed.

Going forward, continued investment in research, technological innovation, and policy support will be critical in determining the role of ultramafic rocks in global carbon management strategies. If effectively harnessed, this approach could become an integral part of climate change mitigation efforts, contributing to carbon neutrality goals and reducing the long-term impact of anthropogenic greenhouse gas emissions on the planet.

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