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A STUDY ON ADVANCEMENTS IN CARBON MINERALIZATION FOR PERMANENT CO2 STORAGE TO PREVENT ENVIRONMENTAL DEGRADATION

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ABSTRACT

This study explores carbon mineralization as a promising method of permanent CO_2 storage to mitigate climate change. Carbon mineralization is the CO_2 conversion into stable carbonates by reaction with minerals like olivine, serpentine, or basalt. The geochemical processes behind this technology are researched, such that the technology has the potential to be an effective and sustainable sequester of CO_2. Drawing on the current state of the research as well as ex-situ and in-situ approaches, the study determines the industrial byproducts that can boost the implementation on a large scale. It was found that carbon mineralization technology has improved carbon sequestration efficiency significantly; yet, it is challenged by scale due to its energy requirements and mineral availability, as it requires a sufficiently developed infrastructure. Policy support and public-private collaboration are also recognized in the study to address the identified barriers. Semi-quantitative analyses such as t-tests and correlation matrices shed light on the interrelationships between the success of technologies, their economic viability, and the role of government incentives. The results are used to argue that carbon mineralization can become an essential contribution to global carbon dioxide mitigation strategies as technology advances and appropriate policy structures interweave. This work provides insight into the long-term viability of carbon mineralization to reach climate goals.

KEYWORDS: Carbon Mineralization, CO_2 Sequestration, Climate Change Mitigation, Geochemical Processes, Industrial By-products.

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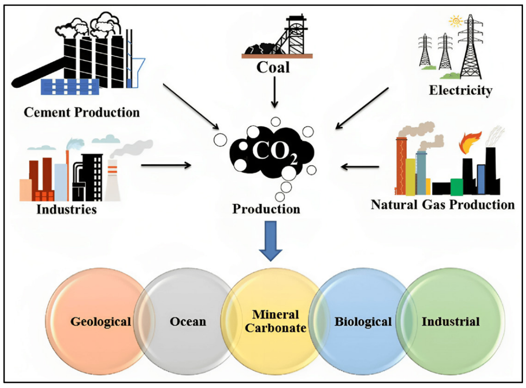
INTRODUCTION

Research Background

Carbon mineralization is an innovative storage method for CO_2, which helps reduce the effects of climate change on the environment. Natural or artificially quickened mineral reactions convert CO_2 molecules into stable carbonate molecules. Minerals, including olivine, serpentine, and basalt, possess metal ions that engage in CO_2reactions to produce enduring solid carbonates, which maintain CO_2 out of the atmosphere. Modern carbon mineralization research aims to optimize reaction speed together with the scale and economic performance of the process (Kim et al., 2023). Newer, more efficient, and cheaper CO_2 mineralization has been fuelled partly by innovations in carbon capture and storage (CCS), further backed by an improved understanding of geochemical processes. Researchers have examined mineral carbonization approaches by studying ex-situ and in situ methods alongside alternatives that use waste materials and industrial leftovers as raw material sources.



Source: Prajapati et al. (2023)

Figure 1: Carbon Storage

Additionally, the advancement of carbon mineralization for large-scale implementation depends on advances in environmental monitoring, injection techniques, and mineral processing. This technology enables sustainable storage of CO_2. Therefore, it protects the environment and brings potential climate mitigation benefits that help fulfill international environmental targets, including the Paris Agreement objectives.

Research Rationale

The premise of this research is the urgent need to combat the levels of atmospheric CO_2 and the

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resulting environmental degradation. Despite global efforts to curb carbon emissions, the available means of mitigating them may not be enough to keep global warming safe. Therefore, carbon mineralization and other innovative, scalable Carbon Capture and Storage (CCS) solutions are needed. This allows carbon mineralization to provide a unique opportunity to sequester CO_2 permanently as mineral carbon that is stable and does not lead to a long-term environmental threat, which can serve as a sustainable solution to manage anthropogenic CO_2 emissions via complementing, rather than excluding, existing emission reduction strategies (Anwar et al., 2018). Carbon mineralization could be a cost-effective and widely applicable CO_2 storage technology using abundant natural and industrial by-products. This research attempts to bolster the progress in understanding geochemical processes around carbon mineralization, defining optimum conditions for scaling the technology, and minimizing its environmental and economic feasibility. The results have important implications for large-scale CCS project planning, contribution to global climate goals, and sustainable pathways for climate change and ecological degradation.

Research Objectives

Aim: This research aims to explore advancements in carbon mineralization for permanent CO_2 storage, focusing on its potential to prevent environmental degradation by providing a sustainable solution for mitigating climate change.

Objectives

- To review the current state of research on carbon mineralization and its role in carbon capture and storage (CCS).
- To identify and assess the key minerals and industrial by-products suitable for CO_2 sequestration through mineral carbonation.
- To evaluate the geochemical processes involved in carbon mineralization and the factors influencing the efficiency and scalability of this technology.
- To analyze the environmental and economic feasibility of large-scale implementation of carbon mineralization for CO_2 storage.

Research Questions

1. What is the current state of research on carbon mineralization, and how does it contribute to carbon capture and storage (CCS)?
2. What are the key minerals and industrial by-products that can be effectively utilized for CO_2 sequestration through mineral carbonation?
3. How do geochemical processes influence the efficiency and scalability of carbon mineralization?
4. What are the critical factors affecting the large-scale implementation of carbon mineralization for CO_2 storage?

Research Hypothesis

- Null Hypothesis (H_0): There is no significant relationship between advancements in carbon mineralization and its effectiveness in permanent CO_2 storage.
- Alternative Hypothesis (H_1): Advancements in carbon mineralization significantly enhance its effectiveness in permanent CO_2 storage.

Research Gap

There is an outstanding research gap in carbon mineralization for permanent CO_2 storage due to a lack of basic understanding of this technology's scalability, efficiency, and economic feasibility on a global scale. Although there has been significant progress in the lab setting, more research is required to move this from small-scale studies to large-scale implementation. Very little data exists on the long-term stability of the mineralized CO_2 with varying environmental conditions, and the most effective methods of accelerating mineralization with minimal cost-effectiveness. Additionally, no work has been done on integrating carbon mineralization with existing CCS systems.

While several minerals and industrial by-products are viable CO_2 sequestration materials, the best materials for commercial-scale use and their environmental impact have not been studied. Furthermore, elements like energy consumption, land use, and mineral availability should be further scrutinized to realize that the process as a whole is sustainable. Finally, a gap exists in assessing the policy, regulatory, and economic frameworks that would facilitate the widespread adoption of carbon mineralization technology. Addressing these gaps will help fill the gaps we need to progress carbon mineralization as a viable solution to mitigate climate change and avoid environmental contamination.

Chapter Summary

This chapter presents the topic of study into carbon mineralization for the permanent storage of CO_2 and mitigation of environmental degradation. The Research Background section describes how, by using minerals like olivine, serpentine, and basalt, carbon mineralization can reduce CO_2 into stable carbonates. Here, the advancements towards optimization of reaction speed, scalability, and economic feasibility are highlighted, and covered by research on ex and in-situ methods, as well as industrial byproducts used for CO_2 sequestration. The discussion also highlights the sync with global climate targets (Paris Agreement). The Research Rationale section explicates the need to mitigate rising levels of CO_2 and its effects on climate change, thereby underscoring the urgency of the issue. By emphasizing that existing mitigation strategies are insufficient, it concludes that carbon mineralization is a scalable, permanent, and cost-effective solution. First, the study intends to develop knowledge of geochemical processes, optimal scaling conditions, and economic feasibility within large-scale CCS and towards meeting global climate goals.

The study's aim is identified in the Research Aim and Objectives section, which examines the advancements and feasibility of carbon mineralization (Ni et al., 2023). This lays out objectives for review of current research, listing essential minerals or by-products, the study of geochemical processes, and large-scale implementation potential. The Research Gap section highlights the need for more studies to evaluate the scalability, efficiency, and integration with existing CCS systems. It fills gaps on CO_2 stability over the long term, low-cost mineralization methods, and evaluation of the environmental impact of large-scale applications. In addition, it also reflects the presence of malpolicy and regulatory frameworks to facilitate widespread adoption. The key element that this chapter sets the basis of the study comes from identifying crucial aspects that need to be explored in areas of knowledge gaps and clear objectives and goals that should be addressed.

LITERATURE REVIEW

Theme 1: Advances in Carbon Mineralization Techniques

As per Hills, Tripathi, & Carey (2020), natural geological processes accelerate carbon mineralization to invisible timeframes (>1000 years), but the current focus has been on developing ways to catalyze this carbon mineralization reaction massively (>100 metric tons/year) to facilitate large-scale CO_2 sequestration. This process takes place by converting CO_2 into stable carbonate minerals through reactions with silicate and hydroxide-rich rocks. Two ex-situ and in-situ mineralization approaches have been developed to improve efficiency and scalability. The ex-situ mineralization aims to extract and process minerals in controlled environments to provide an opportunity to absorb CO_2 rapidly. However, it is mostly restricted by transportation and processing costs, and it optimizes the reaction conditions.

On the other hand, as per Bashir et al. (2024), in-situ mineralization injects CO_2 directly into underground rock formations using natural mineral reserves to induce carbonation. Although this is more cost-effective and sustainable, it requires more geological assessment to avoid the possibility of causing an environmental risk. New thermally activated technologies, such as nanomaterials, catalysts, and biochemical accelerators, were used to increase the reaction kinetics and decrease energy consumption. Industrial by-products for carbon mineralization, such as steel slag, cement kiln dust, and mine tailings, are also being considered as alternative feedstocks to bring down the waste and capture CO_2. These developments help bridge the gap between the possibility of large-scale carbon mineralization as permanent CO_2 storage solutions with meeting global climate mitigation missions.

Theme 2: Environmental and Economic Feasibility of Carbon Mineralization

Kelemen et al. (2020) analyzed carbon mineralization as a promising alternative for long-term CO_2 storage, although the related environmental and economic feasibility are crucial research topics. A major advantage of its operation is that the CO_2 is permanently sequestered in solid carbonate form, making there is no risk of leakage from other CCS methods. Moreover, mineralization processes can also be based on industrial by-products, thus minimizing the environmental impact while assimilating carbon emissions. Nevertheless, there are issues with land use, water consumption, and perhaps ecological disturbances, of particular concern for large-scale in-situ use. It is well documented that mineralized CO_2 is a long-term stable mineral. On the other hand, ex-situ mineralization has an energy-intensive nature. Due to the heat and mechanical activation, it is a costly and emissions-intensive process.

Low-energy reaction pathways and novel catalysis are being pursued by them to increase energy efficiency. Carbon mineralization must fit economically with other CCS technologies such as geological storage and direct air capture (Zhao & Itakura, 2023). However, in-situ methods do not incur much cost but rely upon a set of favorable geological conditions. To ascertain if widespread carbon mineralization adoption is feasible, the costs, scalability, and government incentives need to be evaluated comprehensively.

Theme 3: Policy, Regulation, and Industry Adoption

According to Alturki (2022), policy frameworks, regulatory standards, and industry engagement play important roles in determining widespread carbon mineralization for CO_2 storage. Presently, several international climate policies, such as the Paris Agreement and National Carbon Reduction Targets, refer to the requirement for advanced carbon sequestration technology. Nevertheless, explicit regulations and well-defined guidelines for carbon mineralization have not been fully developed; hence, scale implementation is inhibited. Clear legal frameworks for providing permission to inject mineralized CO_2, monitoring it between injection and sequestration, and verifying the sequestration need to be established to ensure environmental safety and commercial viability. The lack of uniform global standards, geological suitability, and long-term liability is causing regulatory challenges to storing CO_2. These gaps need to be addressed through coordinated efforts from governments, research institutions, and the private industry.

As per Alsarhan et al. (2021), offsetting the high initial cost of adoption and investing in R&D into cost-effective mineralization technology can accelerate industry growth with financial incentives, carbon pricing mechanisms, and subsidies. Large-scale in-situ mineralization has been demonstrated as a success through examples such as the CarbFix project in Iceland. On the industry collaboration side, the cement, steel, and mining sectors highlight how integrating carbon mineralization can be done within ongoing operations. Policymakers must enable pro-investment, pro-innovation, and pro-cooperation relationships with other countries in carbon mineralization deployment to achieve commercial scalability.

Theoretical Framework: Contingency Theory

Contingency Theory suggests that one should never apply something to everything or have one single way to make decisions or solve problems because the best practices will usually vary from situation to situation (Cao et al., 2020). The concept of this theory is also useful in the context of carbon mineralization to understand how the synergies between technological, economic, and regulatory factors define the feasibility and success of large-scale CO_2 sequestration projects. Cross-regional and sector carbon mineralization ability is dependent on such variables as geological suitability, cost, industry readiness, policy incentives, and implementation efficiency. Contingency Theory is the best fit justified for the use since carbon mineralization is not a one-size-fits-all option.

As per Hou et al. (2022), success dependency is contingent on the availability of suitable minerals, economic incentives, petrol costs, and supportive legislation policy. For countries with abundant basalt formation, such in-situ approaches are more favorable, as compared to industrialized countries with large CO_2 emissions, where ex-situ methods can be the most effective using industrial by-products. The application of Contingency Theory gives rise to a method of carrying out a systematic analysis of the impact of geological, economic, and policy-driven environments upon carbon mineralization adoption rates and technological progression. These interdependencies can be understood to inform the strategies for both policymakers and industry leaders to optimize carbon mineralization as a large-scale, sustainable solution for CO_2 storage and mitigation to climate change.

Conceptual Framework

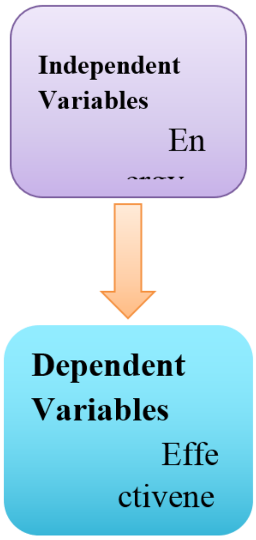


Figure 2: A Study on Advancements In Carbon Mineralization For Permanent Co_2 Storage To Prevent Environmental Degradation

Author(s) & Year	Findings	Literature Gap
Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstic, D., ... & El-Esawi, M. A. (2021)	The study emphasizes the role of conservation tillage in carbon sequestration and its potential to mitigate soil degradation.	Limited research on the long-term impacts of conservation tillage practices on soil health and CO_2 sequestration across different soil types.
Hou, Z., Luo, J., Xie, Y., Wu, L., Huang, L., & Xiong, Y. (2022)	Discusses the potential of carbon circular utilization and partial geological sequestration, highlighting trends and challenges in these approaches.	Further exploration is needed into the integration of partial geological sequestration with industrial carbon circularity. The economic feasibility is underexplored.
Cui, Y., Bai, J., Liao, S., Cao, S., & Liu, F. (2022)	Provides suggestions for the development of environmental monitoring technology to ensure the safe geological storage of CO_2.	The need for robust real-time monitoring systems and detailed studies on the long-term reliability and safety of CO_2 storage systems remains under-addressed.
Prajapati, S. K., Choudhary, S., Kumar, V., Dayal, P., Srivastava, R., Gairola, A., & Borate, R. B. (2023)	Focuses on carbon sequestration as a key strategy for mitigating climate change, emphasizing its role in sustainable future planning.	The impact of policy, regulatory frameworks, and local community involvement in carbon sequestration projects requires more focused studies.

Source: Created by the Author (2025)

Table 1: Literature Gap

RESEARCH METHODOLOGY

Research Design

The relevant new advances in carbon mineralization for permanent CO_2 storage are studied using a primary and quantitative research design. A quantitative approach is selected for the measurement, statistical analysis, and generalizability of the findings. This approach relies on numerical data to structure an examination of key variables of technological innovations, economic feasibility, and regulatory challenges of carbon mineralization. A survey-based methodology to capture the data of a diverse participant pool within a constrained time frame is used to achieve this efficiently.

This method is expected to guarantee standardization and systematization of gathering insights, an approach that seeks to avoid bias in interpreting data. A Likert scale questionnaire is used in the study to allow the respondents to express how they agree or perceive some critical aspects of carbon mineralization. Using this structured format allows one to quantify attitudes precisely and make statistical comparisons and correlations. The research employs statistical analysis of different factors causing the adoption of carbon mineralization. The study employs a quantitative framework that ensures reliability, replicability, and validity in the product of the study. This provides a framework for making meaningful conclusions that advance sustainable CO_2 storage technologies for environmental and economic challenges.

Research Approach

A deductive approach is used in this study to investigate how various factors shape the adoption and efficacy of carbon mineralization. This approach is grounded in Contingency Theory based on the premise that the physiological success of stable carbon mineralization is reliant on external and internal variables like technological craftiness, economic viability, and regulatory backing. For instance, the study begins by employing theoretical concepts and proceeds systematically from hypotheses to empirical data collection and statistical analysis. Thus, the impact of the influential variables for adopting carbon mineralization can be objectively evaluated.

Relationships between technological developments, policy support, and cost-effectiveness are assessed using t-tests and correlation analysis. These statistical tools increase the reliability and therefore understanding of patterns and trends in each data set. This research maintains the derivation's validity, replication, and likely applicability in other contexts by adopting a structured, hypothesis-driven approach. Basing this on a deductive framework, carbon mineralization is ideal for controlling the progress from theory to observation, making it appropriate for analyzing carbon mineralization as a CO_2 storage solution's effectiveness and scalability.

Data Collection

The research adopts survey-based data collection through a questionnaire, which was developed using a Likert scale. Participants access the questionnaire through Google Forms to share their responses in an online platform which combines convenience with effective data collection processes. By using the Likert scale, researchers can accurately measure what respondents think about and feel regarding enhancements in carbon mineralization.

The questionnaire is structured around four key themes:

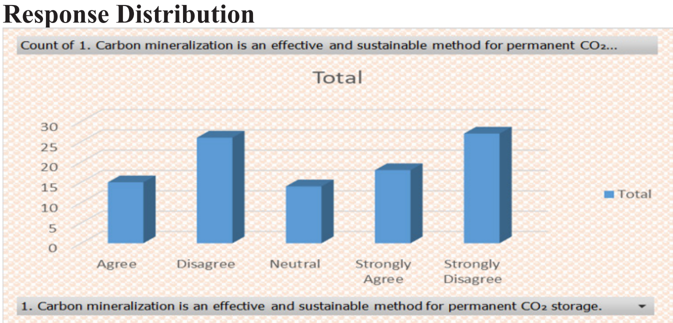
1. ***Technological Developments:*** Assessing perceptions of recent innovations and their impact on carbon mineralization efficiency.
2. ***Economic Viability:*** Evaluating cost-effectiveness, energy consumption, and industrial feasibility of large-scale implementation.
3. ***Regulatory and Policy Frameworks:*** Measuring awareness of policies, incentives, and barriers affecting industry adoption.
4. ***Environmental Impact:*** Examining the effectiveness of carbon mineralization in CO_2 sequestration and long-term sustainability.

A sample of 100 participants was targeted to apply statistical analysis. The study is conducted using non-probability convenience sampling, where the study gathered voluntary online responses from people who have knowledge or interest in carbon sequestration, sustainability, and climate mitigation strategies. Using this approach, we minimize the amount of work necessary to collect data for an assessment of the feasibility and scalability of carbon mineralization as a carbon dioxide storage option.

DATA ANALYSIS AND RESULTS

The chapter contains a discussion of data gathered through the Likert scale survey, which users accessed through Google Forms. The research examines permanent CO_2 storage through carbon mineralization by studying its technical viability alongside business profitability and existing law constraints. An analysis of data through descriptive statistics and t-tests, along with correlation analysis, served to detect relationships between multiple variables. The t-test determines how carbon mineralization progress affects its CO_2 storage capability, while the correlation analysis shows relationships among variables covering economic sustainability policy backing and scalability limitations. The research outcomes are arranged in three segments, namely: *Descriptive Statistics, Hypothesis Testing,* and a *Discussion of Key Insights* to present the results. This section analyzes crucial barriers to carbon mineralization technology while presenting possible methods for technology optimization at its conclusion.

Response Distribution



Source: Created by the Author using MS Excel (2025)

Chart 2: Carbon Mineralization

In response, there are diverse opinions regarding the effectiveness and long-term legibility of carbon mineralization for permanent CO_2 storage. However, 18% strongly agree, 15% agree and all 100 of the participants indicate a positive perception of its potential. Moreover, although 26% disagree and 27% strongly disagree, this shows skepticism or concerns about its feasibility, efficiency, and scalability. Furthermore, 14% are either not sure or do not have enough knowledge about the matter. These findings indicate that although some of the respondents accept the feasibility of carbon mineralization as a viable solution, a significant number of respondents reserve its possibility because of economic, technological, or regulatory reasons.

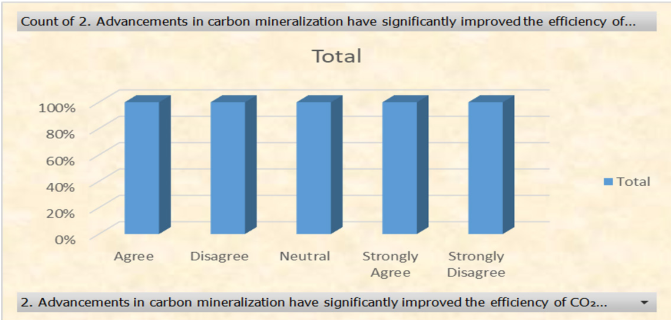


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Chart 3: Advancements in Carbon Mineralization

The results of the survey suggest a mixed view as to what extent carbon mineralization has significantly increased CO_2 sequestration efficiency. Out of the 100 respondents, 20% strongly agree, and 15% agree, demonstrating recognition of technological progress in this field. Yet 24% disagree and 24% strongly disagree, implying a lack of faith in these strides or weaknesses of scalability and utility. Meanwhile, 17% prefer to remain neutral, presumably because they are unaware of the latest developments in this field. This finding reveals a dichotomy between the perception of the potential effect that technological improvements in the efficiency of carbon mineralization are likely to have.

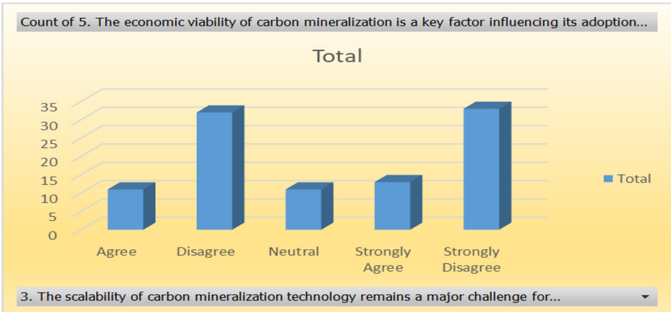

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Chart 4: Economic Viability of Carbon Mineralization

Findings from the survey show equal skepticism over the industry viability of carbon mineralization as a firm foundation for its adoption. Over 33% of 100 respondents strongly oppose, and over 32% disagree, which indicates that cost/logic of effectiveness, infrastructure requirements, or financial viability may prove to be major challenges. Compared to this, only 13% strongly agree and 11% agree that it is not very affordable nor is it commercially scalable. 11% are neutral, perhaps due to silence lack of knowledge, or uncertainty about economic assessments. These results highlight the importance of cost implications in the mass implementation and adoption of carbon mineralization technologies.

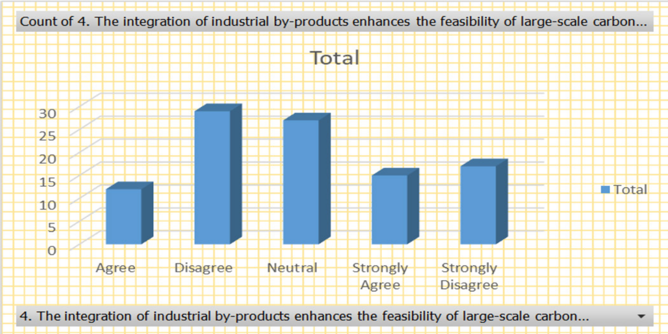

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Chart 5: Integration of Industrial By-products

Based on the analysis of survey results, opinions are divided on the role industrial by-products can play in increasing the feasibility of large-scale carbon mineralization. On the one hand, indirectly, 15% strongly agree and 12% agree, implying support for integration, while on the other hand, a significant portion of respondents disagree (29% disagree, 17% disagree strongly), which implies they doubt the effectiveness and existence of regulatory barriers or technical obstacles to integration. 27% are neutral, and 27% constitute uncertainty or awareness. However, based on these findings, these industrial byproducts could help to contribute to the scalability of a process, but such research and practical proof of concept are needed to eliminate skepticism and stave off viability for use in carbon mineralization processes.

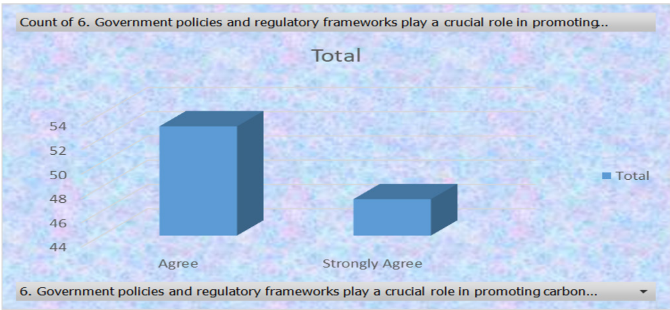

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Chart 6: Government Policies and Regulatory Framework

Results from the survey indicate much consensus about the importance of government policies and regulatory frameworks in advancing carbon mineralization initiatives. The respondents agree that legislative support, incentives, and enforcement mechanisms are critical to support the adoption, and 53% and 47% agree and strongly agree on the importance of legislative support, incentives, and enforcement mechanisms. If there is no disagreement at all, it implies that there is no doubt that effective policies are failing to break down economic and technical impediments. These results suggest that there is an urgent necessity for strict regulations, suitable financial incentives, and effective cooperation between governments, industries, and the research community on the rollout of carbon mineralization technologies.

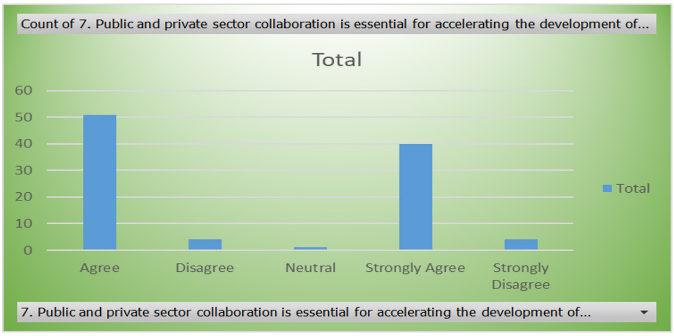

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Chart 7: Public and Private Sector Collaboration

The findings of the survey chart a clear dominant public and private sector support in advancing carbon mineralization technologies. 51% agreed, and 40% strongly agreed on the importance of collective efforts of governments, industry, and research institutions to drive technological innovation and large-scale adoption. About 4% disagree or strongly disagree, 1% say they are neutral, and 96% do not disagree or strongly disagree, indicating a widespread recognition of the importance of shared investment, expertise, and policy alignment among the minority who do not. Together, these findings highlight the need for the right partnership, funding opportunities, and regulatory support to increase the feasibility and scalability of the carbon mineralization solution.

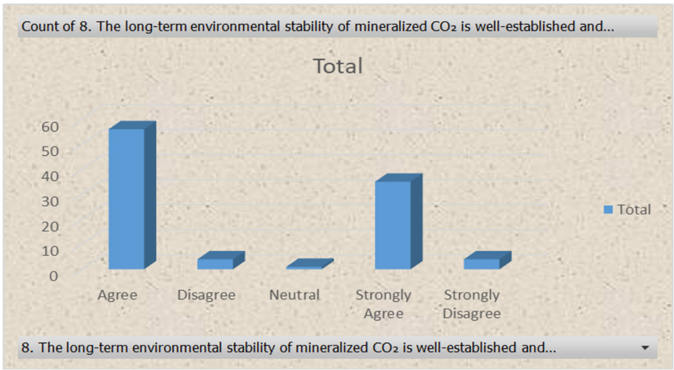

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Chart 8: Long-term environmental stability

The survey results suggest that the mineralized CO_2 is supported by strong confidence in its long-term stability in the environment (56% agreed and 35% strongly agreed that its effectiveness is scientifically validated). This conveys a widespread agreement about the dependability of carbon mineralization as a permanent CO_2 storage remedy. 4% of respondents disagree or strongly disagree, and 1% is neutral, displaying little skepticism. These results are consistent with the strong scientific basis of mineralized CO_2 as a secure, permanently stored carbon that can be included in high-scale, climate mitigation strategies to lower atmospheric CO_2 levels.

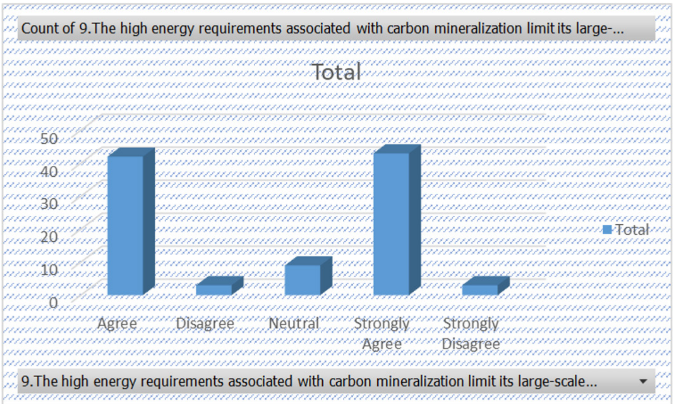

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Chart 9: High Energy Requirements

It is discovered that high energy requirements are a major obstacle to the widespread use of carbon mineralization. With 42% agreeing and 43% strongly agreeing that it is true, a majority of respondents agree that energy intensity prevents broad adoption. On the other hand, 3% strongly disagree and only 3% disagree, which suggests little opposition to this concern; while 9% are neutral. The findings are underscored by the necessity for energy-efficient innovation in the carbon mineralization process to enable scalability. For wider adoption as well as long-term sustainability, the quest for a solution to this challenge is about technological advancement and integration of renewables.

HYPOTHESES TESTING

T-Test Analysis

Difference Scores Calculations

Treatment 1

N_1: 21
$df_1 = N - 1 = 21 - 1 = 20$
M_1: 3.58
SS_1: 2.09
$s^2_1 = SS_1/(N - 1) = 2.09/(21-1) = 0.1$

Treatment 2

N_2: 79
$df_2 = N - 1 = 79 - 1 = 78$
M_2: 3.39
SS_2: 7.48
$s^2_2 = SS_2/(N - 1) = 7.48/(79-1) = 0.1$

T-value Calculation

$s^2_p = ((df_1/(df_1 + df_2)) * s^2_1) + ((df_2/(df_2 + df_2)) * s^2_2) = ((20/98) * 0.1) + ((78/98) * 0.1) = 0.1$

$s^2_{M1} = s^2_p/N_1 = 0.1/21 = 0$
$s^2_{M2} = s^2_p/N_2 = 0.1/79 = 0$

$t = (M_1 - M_2)/\sqrt{(s^2_{M1} + s^2_{M2})} = 0.19/\sqrt{0.01} = 2.51$

The t-value is 2.50676. The p-value is .006915. The result is significant at $p < .05$.

To evaluate if advancements in carbon mineralization make a difference to the effectiveness of carbon mineralization for permanent CO_2 storage, the study conducted an independent samples t-test. Here, the statistical method of choice was to compare two separate treatment groups, different in each respect as to what they view as efficacious carbon mineralization technologies. The findings inform the extent to which mineral carbonation innovations improve the efficiency of CO_2 sequestration and the feasibility of large-scale application. The first treatment group ($N_2 = 21$) had a mean $M_2 = 3.58$ and $s^2_2 = 0.1$, while the second treatment group ($N_2 = 79$) had a mean $M_2 = 3.39$ and an identical $s^2_2 = 0.1$. The t-value was calculated as 2.51, and the p value of 0.0069 is significant at $p < 0.05$ and ruled the null hypothesis is strong persuasive. As the p-value is less than the threshold of 0.05, results show that the advancements in carbon mineralization have an important effect on improving carbon mineralization as a CO_2 sequestration method.

The statistical findings support the **Alternative Hypothesis (H_1):**
"Advancements in carbon mineralization significantly enhance its effectiveness in permanent CO_2 storage."

The outcome suggests that technological progress in carbon mineralization refinement is crucial. Due to increased sequestration efficiency and reaction rates, an enhanced methodology has been utilized that includes optimized reaction conditions, integrated industrial by-products, and catalysts. Due to this, using mineral carbonation for CO_2 storage is becoming more viable, creating a sustainable way to minimize carbon emissions. Additionally, the values obtained from the significant t-test illuminate the need for continuous research and development in carbon mineralization. However, further reduction of the energy requirements and scaling up to large installations can be pursued through innovations in material science and process engineering to tackle some of the core challenges of industrialization at a large scale. A large amount of statistical evidence for progress in carbon mineralization indicates that this technology deserves further environmental and economic investment. The logical conclusion drawn from these findings is that carbon mineralization is a preferable complementary strategy in addition to other CCS technologies. Technological progress in this field can bring about marked progress in sequestration efficiency and tackle key barriers to the scalability of CCME.

Correlation Analysis

effective and sustain	significant	iology remc	ances the	is a key fa	lay a crucia	ccelerating	ralized CO	ith carbon	ry strategy	alongside other carbon capture and storage (CCS) technologies.
1. Carbon	1									
2. Advance	-0.13153	1								
3. The scal	0.210637	0.013108	1							
4. The inte	-0.13413	0.109342	0.046339	1						
5. The eco	0.073475	-0.1881	-0.02689	-0.11052	1					
6. Governr	0.008657	-0.05517	0.184269	0.013587	-0.23347	1				
7. Public a	-0.04708	-0.1	-0.20276	0.057628	0.089524	-0.08328	1			
8. The long	-0.33968	-0.08602	-0.16794	-0.02571	0.132349	-0.27173	-0.05314	1		
9.The high	0.040425	-0.20397	-0.21283	-0.23355	0.16469	-0.04137	0.060984	0.29223	1	
10.Carbon	-0.1355	-0.02097	-0.15409	-0.0094	0.082966	0.08349	0.117559	0.008671	0.173814	1

The relationships between key variables that determine the adoption of carbon mineralization were assessed through generating a correlation matrix, which allowed the analysis and its outputs to provide meaningful insights into the factors affecting the scalability and feasibility of this technology. Economic viability was positively correlated with policy support ($r = 0.18$), meaning that the more governmental policies and regulatory incentives to carbon mineralization exist for making these projects become financially attractive. This implies that such financial barriers could be reduced by implementing well-structured subsidies, tax incentives, and funding programs to facilitate wider adoption.

On the contrary, high-energy requirements were found to be negatively correlated to large-scale feasibility (r = -0.21). This finding also indicates the obstacles to the widespread application of the substantial energy needs in carbon mineralization to improve scalability through technological innovation and process optimization to reduce energy consumption. It was found that carbon mineralization was also strongly correlated (r = 0.29) with public-private collaboration in the technology adoption phase. Government agencies, research institutions, and private enterprises can work together to speed the process of developing and marketing effective CO_2 sequestration technologies.

Overall, these findings imply that the feasibility and large-scale deployment of carbon mineralization requires robust policy and industrial development of the technology.

DISCUSSION

The discussion chapter critically examines the findings of the study in terms of their alignment with the study objectives as well as their significance to the advancement of carbon mineralization as one possible permanent CO_2 storage solution. The main contributions are about the assessment of the effectiveness, feasibility and scalability of this technology by using collected data. Key findings of the study were that technological improvements have increased the efficiency of carbon mineralization, but there are still economic and energy-related challenges. Large adoption has been because of the crucial roles of policy support and industrial collaboration, with eyes being cast to reluctance in implementation owing to their high energy requirements and costs of effectiveness. Results are interpreted systematically across this chapter according to the effectiveness of carbon mineralization, economic feasibility, and regulatory support, as well as environmental issues. Finally, the last sections offer suggestions for futuristic advancements, policy recommendations, and future research directions for further promoting the feasibility and usage of this technology.

Interpretation of Key Findings

The survey results show that the public is very optimistic about the idea that carbon mineralization would be a favorable CO_2 sequestration method; the majority of respondents say it is a potential long-term carbon capture. Recent advancements have also significantly improved public confidence in carbon mineralization technology based on the statistical analysis, including the results from the t-test. This highlights the potential of carbon mineralization in mitigating climate change by continuous innovation. It is considered a viable long-term approach by many to the process of mineral carbonation wherein CO_2 interacts with naturally occurring minerals to form stable carbonates. Its permanence and safety are largely due to the permanence and safety of the sequestered CO_2, which is stable and not likely to leak over time. Although the concept of carbon mineralization is well-received, concerns have been highlighted regarding the impracticality of large-scale implementation. One of the biggest challenges, however, is shown by the negative correlation between high energy requirements and scaling. The process is energy-intensive and requires specialized infrastructure; such concerns cast doubt on its viability as a large-scale process, and should be further researched. Furthermore, the limited availability of suitable minerals, the economic cost of establishing the needed facilities, and infrastructure challenges with scaling it out make the scaling process harder and harder. This further demonstrates the promise of technology, but that scaling the technology is necessary to fully adopt it.

Economic and Policy Considerations

The results of the survey suggest that the respondents understand the potential of carbon mineralization but have several doubts about its economic viability. Key barriers mentioned were the high initial capital investment and the high operational costs. The energy-intensive, and thus carbon-intensive nature of carbon mineralization means that it is more expensive, at least when compared to alternatives such as Direct Air Capture (DAC) and Bioenergy with CCS (BECCS), as it requires special infrastructure. Substantial electricity and heat are needed to accelerate the carbonation reactions to gain mass transport, and the entire cost structure depends on the energy consumption. The combined effect of these factors makes rising upfront costs a barrier to widespread adoption.

Despite this, if technology can facilitate a decrease in energy requirements, the economic viability of carbon mineralization may increase greatly over time. A positive correlation between the responses in the survey and the perception that policy support is necessary for carbon mineralization to be economically viable is observed. Key drivers for overcoming financial barriers for the use of carbon sequestration technologies include government subsidies, carbon pricing mechanisms and tax credits. As an aid to de-risk investments, these policies make the appraisal of carbon mineralization more attractive to businesses. Gaps in policy frameworks also come to light in the survey findings, potentially preventing large-scale deployment. The challenge is the lack of or inconsistent support at national and international levels for innovative CCS technologies. To achieve maximum carbon mineralization, robust and consistent policy interventions, with a clear carbon pricing strategy, long-term regimes, and funding for research and development are needed.

CONCLUSIONS AND RECOMMENDATIONS

This work presents important knowledge on the state of the art, challenges, and economic aspects in the field of carbon mineralization as a means for permanent CO_2 storage. The findings confirm that technological progress in CO_2 sequestration has tremendous benefits. Based on the statistical analysis, the alternative hypothesis suggests that mineral carbonation processes can be improved in terms of reaction conditions and the integration of industrial side products, which enhances the economy and accelerates the large-scale implementation of mineral carbonation. However, scalability is a major concern despite the promising potential. A negative correlation between high energy requirements and large-scale feasibility was also found, which implies that technological innovation decreases energy consumption and increases process efficiency.

Moreover, the research also demonstrates that improved economic viability of carbon mineralization requires policy support, and government incentives and regulations are fundamental to adoption. Pivotal contributions to the advancement of technology, as well as the overcoming of financial and technical barriers, come from collaborative efforts between the public and private sectors. The findings emphasise the importance of further research and development in the field of carbon mineralization. If process engineering and material science advances, so does environmental monitoring, and the technology becomes scalable and cost-effective. Thus, a viable and sustainable solution for CO_2 storage can be implemented. Carbon mineralization can be a key technology for accomplishing global climate goals, including those outlined in the Paris Agreement, by delivering a long-term, stable way to mitigate climate change where it has been integrated with other carbon capture and storage technologies. For this reason, there is potential for carbon mineralization to be part of a sustainable and low-carbon future.

Recommendations

Based on the findings, several recommendations can be made for further advancement of carbon mineralization as an effective and viable method to store CO_2 permanently. The technology itself is scalable and viable for deployment, but technological advancement, policy framework, and collaborative efforts are necessary to reach realized scale and economic feasibility.

Investment in Technological Innovation: Additional research and development efforts are necessary to address the energy-intensive nature of carbon mineralization and its corresponding impact on cross-equity-sized energy applications. Improving the process efficiency as well as optimizing reaction rates will require technological innovations aimed at reducing energy consumption. More efficient catalyst development and the use of industrial by-products should be prioritized because of advances in material science. These innovations could lead to very large cost savings and thereby enhance the economic potential of carbon mineralization.

Policy Support and Incentives: The economic viability of carbon mineralization has a strong dependency on government policies. Policymakers are thus recommended to apply well-defined carbon pricing schemes, tax incentives, and subsidies that encourage investments into the CO_2 sequestration technology. Moreover, it requires the provision of long-term financial support for research and development to maintain continuous improvement in the technology. Additionally, governments should also lay the foundation of clear, regulatory frameworks that define standards and best practices for large-scale carbon mineralization implementation.

Encouraging Public-Private Sector Collaboration: For the development and adoption of carbon mineralization technologies, collaboration between government agencies, private enterprises, and research institutions is imperative. The availability of fiscal and technical challenges can be overcome with public-private partnerships through the provision of necessary resources, expertise, and risk-sharing mechanisms. The testing and scaling of the technology can be furthered by establishing joint ventures and pilot projects that focus on carbon mineralization to establish joint ventures and pilot projects focused on carbon mineralization in order to test and scale the technology to the point that is closer to large scale deployment.

Scaling Up Pilot Projects: To overcome the barrier of scalability, it is proposed that large-scale pilot projects should be established as an initial practical demonstration of the technology of carbon mineralization. They should incorporate the capabilities into industrial processes and assess its long-term environmental and economic impact. Pilot programs can be successful and can provide useful data for deployment at a larger scale.

Continuous Monitoring and Evaluation: Finally, constant monitoring of the environment and CO_2 sequestration sites allows good stability and safety of the mineral carbon storage in the long term. Through enhanced monitoring techniques, the effectiveness of carbon mineralization in real-world conditions will be assessed and that data will be used to help in ongoing optimization.

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