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The Advantages, Limitations, and the Future of Marine Carbon Dioxide Removal (mCDR) Techniques

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Abstract

The growing urgency of the climate crisis, coupled with slow progress in emissions reductions, has made large-scale carbon dioxide removal (CDR) essential. Marine CDR (mCDR) offers a range of strategies to enhance the ocean's natural carbon sink, including ocean fertilization, artificial upwelling/downwelling, ocean alkalinity enhancement, coastal blue carbon, and direct ocean air capture. This review evaluated each method's feasibility, scalability, cost, carbon permanence, and ecological trade-offs. A structured literature review was conducted using peer-reviewed studies, government reports, and white papers published between 2002 and 2024, with selection criteria based on ocean relevance, credibility, and recency. While ocean fertilization and artificial upwelling/downwelling are low-cost, they carry significant ecological risks. In contrast, ocean alkalinity enhancement and direct ocean capture offer more durable carbon storage but require substantial energy and infrastructure. Coastal blue carbon provides ecological co-benefits but is limited in scale. These findings suggest that a hybrid approach, combining multiple methods rather than relying on a single one, can mitigate individual drawbacks while maximizing carbon removal potential. To realize this potential, future efforts must prioritize clear regulatory frameworks, robust monitoring, and long-term sustainability planning, ensuring that mCDR contributes meaningfully to climate mitigation.

Keywords: Ocean fertilization, Artificial upwelling, Artificial downwelling, Ocean alkalinity enhancement, Coastal blue carbon, Direct ocean air capture

1. Introduction

Over the past few hundred years, atmospheric levels of carbon dioxide (CO_2) and other greenhouse gasses have increased because of the burning of fossil fuels and alterations of the terrestrial biosphere. Fossil fuels are burned primarily for energy production and transportation, releasing significant amounts of CO_2 and other greenhouse gases into the atmosphere from various sources such as transportation systems, energy generation, industrial processes, and agricultural practices. Due to fossil fuel burning, excessive carbon and other greenhouse gasses trap heat inside of our atmosphere, gradually warming the planet (Kweku et al, 2018). The surge in CO_2 levels since the Industrial Revolution is unprecedented. As shown in Figure 1, in just a few centuries, atmospheric CO_2 has risen over 40%, reaching 400 ppm from 280 ppm (EPA, 2022), which highlights the historical variability of CO_2 and the

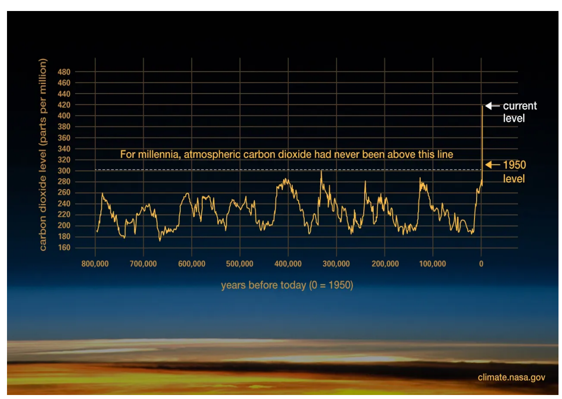

Figure 1 Diagram of atmospheric CO_2 levels over the past 800,000 years. This diagram demonstrates the periodic rises of atmospheric CO_2 followed by the unprecedented increase from anthropogenic emissions. (NASA, 2013)

dramatic post-industrial rise. This level was last seen 5 to 3 million years ago (NOAA, 2024), highlighting the unprecedented change over a remarkably short time period.

Human-driven CO_2 emissions have led to substantial global warming, causing various environmental shifts. Anthropogenic climate change refers to alterations in temperature patterns, weather events, and climate conditions on Earth due to human actions. Over the past century, the effects of climate change have become more severe and increasingly unbearable for vulnerable populations. Climate change has many detrimental impacts. Rising global temperatures lead to more frequent and intense heat waves, droughts, and wildfires, posing risks to human health, agriculture, and water resources (Hardy, 2003). Ice caps and glaciers contribute to sea-level rise, threatening coastal communities and ecosystems (Mimura, 2013). Climate change also disrupts weather patterns, leading to extreme weather events like hurricanes and heavy rainfall, causing widespread destruction (NOAA 2021). Additionally, climate change causes a multitude of impacts on oceans, including ocean acidification, intensifying marine heatwaves, and coral bleaching events, all of which threaten marine ecosystems and biodiversity (Hoegh-Guldberg & Poloczanska, 2017). The consequences of climate change extend beyond environmental issues and affect various aspects of human society as well including economic stability, food security, and geopolitical tensions.

This rapid increase in CO_2 and harmful consequences underscore the urgent need for effective climate change mitigation strategies (Monroe, 2020). Taking a stand against climate change now is important to mitigate the threats. Addressing climate change requires the reduction of greenhouse gas emissions, a transition to clean and renewable energy sources, the promotion of sustainable practices, and adoption of climate-resilient strategies. While multiple countries have agreed to the Paris Agreement, which aims to hold the increase in global average temperature to 2 °C, we are unlikely to reach this goal given our current rate of emissions reduction (IPCC). According to the 6^{th} IPCC report, it is necessary to remove excess carbon dioxide to reach the goals set by the Paris Agreement. Carbon Dioxide Removal (CDR) technologies play a vital role in addressing climate change and this current challenge. By removing carbon from the atmosphere or expanding the ocean's capacity to absorb carbon, CDR can help remove excess carbon from the atmosphere. While CDR technologies can be implemented in the atmosphere, marine CDR (mCDR) technologies have high yet underutilized potential. mCDR refers to the process of capturing and storing carbon dioxide from the ocean, contributing to the reduction of greenhouse gas concentrations in the atmosphere. The oceans already act as a significant sink for carbon dioxide, absorbing almost 25% (Emerson & Hodge, 2008) of the carbon emissions generated by human activities. In addition, mCDR can mitigate the severity of ocean acidification by either sequestering the carbon or solidifying it.

This paper aimed to compare the technical feasibility, scalability, cost, and environmental impact of leading marine carbon dioxide removal (mCDR) techniques while identifying key knowledge gaps that hinder their broader implementation. Although existing literature often examines individual mCDR methods, few reviews provide a comprehensive, comparative framework that captures the trade-offs between each method. By synthesizing data from recent field trials, modeling studies, and policy reports, this review sought to inform climate policy decisions, guide future research priorities, and support the responsible development of mCDR strategies as part of a broader climate mitigation effort.

2. Marine Carbon Dioxide Removal (mCDR) Techniques

2.1 Ocean Fertilization

Ocean fertilization is a well-researched and established mCDR technology, which involves adding micronutrients, such as iron, or macronutrients, such as phosphorus and nitrogen, to the surface of the ocean (NASEM Committee, 2022). The goal is to increase the growth of marine phytoplankton, which first increases the absorption of carbon dioxide in the surface waters, and secondly, facilitates the sequestration of the newly formed organic carbon to the deep sea away from the surface layer exposed to the atmosphere (fig. 2). This occurs as the phytoplankton photosynthesizes, where carbon is absorbed in the form of CO_2 and O_2 is released. This process is illustrated in Figure 2, which shows how nutrient addition stimulates phytoplankton growth and carbon sequestration. The first step of increased photosynthesis is achievable in areas where phytoplankton growth is limited by nutrients, except in nutrient-

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rich regions near coastlines. There is still scientific uncertainty regarding the second step of increased sequestration, which depends on factors like location, depth of carbon export, and the rate at which sinking particles break down (Aumont and Bopp, 2006). Ocean fertilization aims to enhance the ocean's natural biological carbon pump, utilizing solar energy and nutrients from within or outside the ocean. Fertilization with micronutrients like iron requires relatively small amounts of nutrients compared to potential carbon sequestration, while the amount of nitrogen, phosphorus, or silicate needed for fertilization would be significantly larger.

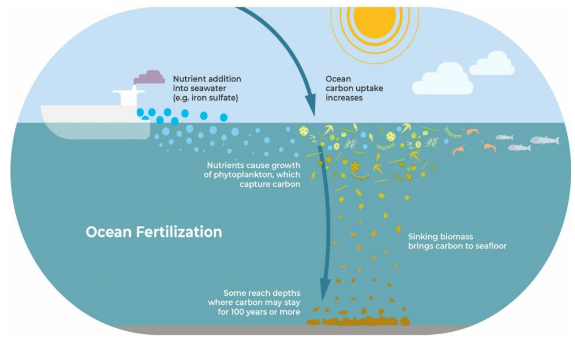

Figure 2. Illustrative diagram of the processes in ocean fertilization. Nutrients, such as iron sulfate, are added to the seawater on the surface, which leads to increased photosynthesis in phytoplankton. This causes increased carbon capture, which then leads to carbon sequestration when the biomass sinks with its increased carbon content. (OceanNets, 2024)

2.2 Artificial Upwelling and Downwelling

Artificial upwelling and downwelling imitate a natural process to improve carbon sequestration. Natural upwelling and downwelling play a crucial role in transferring heat, salt, nutrients, inorganic and organic carbon, and energy between different depths of the ocean. Scientists have been trying to replicate its effects artificially through artificial upwelling and downwelling. As depicted in Figure 3, artificial upwelling aims to supply essential nutrients to the upper ocean, promote increased primary production, and enhance carbon sequestration (NASEM, 2022). Achieving this increased carbon sequestration requires that the biological production of carbon surpasses the input of dissolved inorganic carbon from the upwelled water source. This would mean that the downwelled water would contain more carbon than the upwelled water source, which supplies nutrients, but also some inorganic carbon. Upwelling has also been suggested to sustain fisheries and aquaculture, generating energy, providing cold water for seawater-based air conditioning, and even mitigating the formation or severity of typhoons (Oschlies et al., 2010). Artificial downwelling of oxygen-rich surface water has been proposed to counteract eutrophication and hypoxia in deeper depths by providing oxygen through a downward flow (Liu, 2020). Both of these artificial mechanisms, when combined, can enhance the ocean sequestration of atmospheric carbon dioxide.

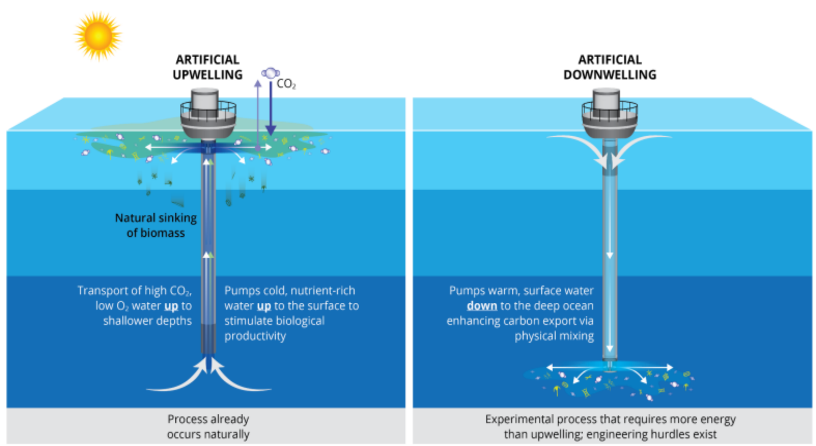

Figure 3. Illustrative diagram of the processes of artificial upwelling and downwelling. Artificial upwelling involves pumping cold, nutrient-rich water up to the surface, while allowing the natural sinking of biomass. Artificial downwelling allows for warm surface water to be pumped down, enhancing carbon sequestration. (Cross et al., 2022)

2.3 Ocean Alkalinity Enhancement

Ocean alkalinity enhancement aims to increase the ocean's alkalinity and therefore enhance the ocean as a carbon sink. This technique involves adding alkaline substances to the ocean, such as crushed rocks or minerals rich in calcium and magnesium (Hartmann et al., 2023). When these alkaline materials dissolve in seawater, they increase their alkalinity and raise the pH level, promoting the conversion of dissolved carbon dioxide into bicarbonate ions. This process ultimately leads to the long-term storage of carbon dioxide in the form of bicarbonate compounds. As

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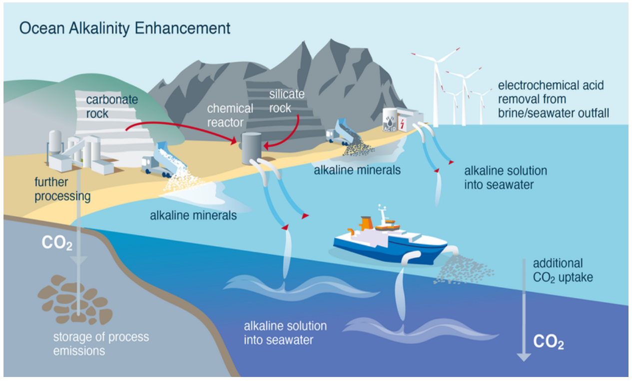

Figure 4. Illustrative diagram of ocean alkalinity enhancement. This diagram demonstrates the weathering of carbonate and silicate rock to create an alkaline solution. This solution allows for an increase in the pH level of water, which promotes the conversion of dissolved carbon dioxide into bicarbonate ions. (State Planet, 2023)

illustrated in Figure 4, ocean alkalinity enhancement facilitates the transformation of CO_2 into bicarbonate ions. Ocean alkalinity enhancement has the potential to effectively remove carbon dioxide from the atmosphere on a large scale. However, careful consideration must be given to the potential ecological impacts and the selection of suitable alkaline substances to ensure responsible implementation and harm reduction for marine ecosystems. Continued research and collaboration are necessary to fully understand the potential of ocean alkalinity enhancement as a viable CDR technique and its implications for global climate change mitigation efforts (NASEM Committee, 2022).

2.4 Coastal Blue Carbon

Coastal blue carbon refers to the carbon captured by coastal ecosystems such as mangroves, tidal marshes, and seagrasses (Siikamäki, 2013). As shown in Figure 5, these ecosystems can sequester and store large amounts of carbon both above and below ground. Mangroves, for instance, are highly efficient in trapping carbon in their biomass and sediments due to their dense root systems and slow decomposition rates in anaerobic conditions (Alongi, 2020). Tidal marshes and seagrasses similarly contribute to carbon sequestration through the accumulation of organic matter in their soil.

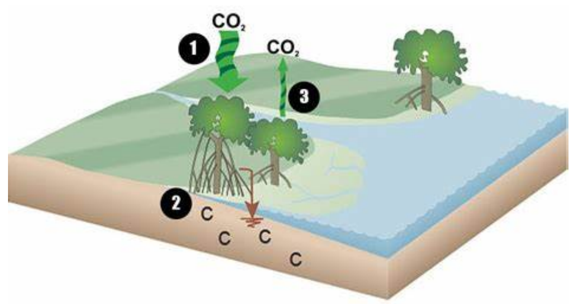

Figure 5. Illustrative diagram of coastal blue carbon. This diagram shows the increased uptake in carbon dioxide by coastal ecosystems that are either conserved or restored. (NOAA, 2022)

Implementation of coastal blue carbon strategies involves the conservation, restoration, and sustainable management of these coastal ecosystems to enhance their carbon sequestration potential. This may include activities such as reforestation of mangrove forests, restoration of degraded tidal marshes, and protection of seagrass beds from coastal development and pollution (Tang et al., 2018). By conserving and restoring these ecosystems, coastal blue carbon initiatives not only contribute to carbon dioxide removal but also provide additional ecosystem services such as coastal protection, habitat for biodiversity, and support for fisheries.

2.5 Direct Ocean Air Capture

Direct Ocean Air Capture (DOAC) is an emerging technology that involves capturing carbon dioxide directly from the atmosphere using ocean-based systems. Unlike land-based Direct Air Capture (DAC) technologies, which typically rely on chemical sorbents or solvents to capture CO_2, DOAC utilizes the natural alkalinity of seawater to absorb and chemically bind carbon dioxide. One proposed method for DOAC involves the deployment of floating platforms equipped with large fans or sprayers that draw in atmospheric air and expose it to a solution of alkaline substances, such as sodium hydroxide or calcium hydroxide (Ametistova, 2002). As shown in Figure 6, these platforms use electrochemical processes to extract CO_2 from our atmosphere. Then, the alkaline solution reacts with the carbon dioxide in the air to form bicarbonate ions, which are then transported into the ocean where they can be stored as dissolved inorganic carbon.

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2.6 Method of Analysis

To evaluate the viability of marine carbon dioxide removal (mCDR) strategies, a structured literature review was conducted. Scientific databases including Google Scholar were queried using keywords such as "marine carbon dioxide removal," "ocean fertilization," "ocean alkalinity enhancement," and "direct ocean air capture." Inclusion criteria included peer-reviewed articles, white papers, and government reports published between 2002 and 2024. Studies were excluded if they lacked ocean relevance or credibility based on peer-review status and citation count. The selected sources were analyzed based on the following key metrics: technological maturity, cost of implementation and monitoring, environmental impacts, and scalability/durability of carbon sequestration. Section 3 integrates these evaluations into a comparative framework (Table 1).

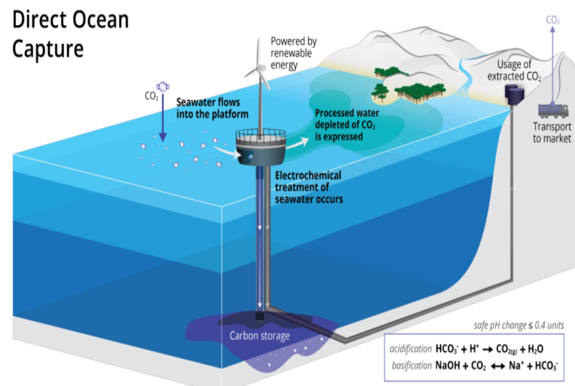

Figure 6. Illustrative diagram of direct ocean capture. Seawater is treated by offshore stations through electrochemical treatment, which removes and stores carbon dioxide. (Cross et al., 2022)

3. Comparison among mCDR Techniques:

The table below summarizes the mCDR methods of ocean fertilization, artificial upwelling/downwelling, ocean alkalinity enhancement, coastal blue carbon, and direct ocean air capture (DOAC) across multiple evaluation criteria. These criteria include maturity, durability of carbon sequestration, scalability, cost of scaling, environmental risks, carbon accounting challenges, and optimal deployment environment. The quantified ratings (1 to 5) are derived from a synthesis of literature cited throughout the paper, particularly the 2022 NASEM Committee report, Ocean Visions database, and NOAA white paper. Where empirical data were lacking, values were supplemented with expert assessments and comparative analyses reported in major review studies. Each rating reflects relative performance within the category: 1 indicates lowest performance or confidence, and 5 indicates highest.

Figure 7 Global Distribution of mCDR studies This figure demonstrates the global distribution of various mCDR studies. (Ocean Vision, 2024)

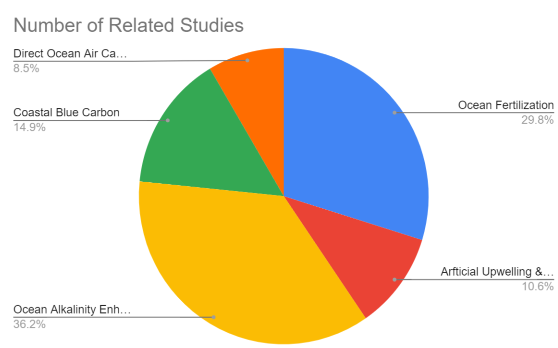

Figure 8 Distribution of mCDR studies This figure demonstrates the distribution of each mCDR technique in the 47 known studies on mCDR. (Ocean Vision, 2024)

4. Results:

To provide a structured comparison of leading marine carbon dioxide removal (mCDR) strategies, Table 1 synthesized key metrics across five primary techniques. These included ocean fertilization, artificial upwelling and downwelling, ocean alkalinity enhancement, coastal blue carbon, and direct ocean air capture (DOAC). The comparative evaluation focused on maturity, durability of carbon sequestration, scalability, cost of scaling, environmental risks, carbon accounting challenges, and optimal deployment environments. To contextualize these

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findings, Figure 7 illustrates the global distribution of mCDR research studies, while Figure 8 breaks down the frequency of each technique's use across the 47 identified studies, highlighting the relative research emphasis placed on each method.

Table 1. Comparative Analysis of mCDR Methods

Method	Ocean Fertilization	Artificial Upwelling/ Downwelling	Ocean Alkalinity Enhancement	Blue Coastal Carbon	Direct Ocean Air Capture (DOAC)
Maturity	4 (Medium to High)	2 (Low)	5 (Medium to High)	3 (Low to Medium)	3 (Low to Medium)
Durability	3 (10 to 100 years)	2 (Less than 10 to 100 years)	5 (High; over 100 years)	4 (10 to over 100 years)	5 (High; over 100 years)
Scalability	4 (Medium to High; >0.1 to 1.0 Gt/year)	2 (Uncertain; requires pilot trials)	3 (Medium; >0.1 to 1.0 Gt/year or more globally)	2 (Low to Medium; <0.1 to 1.0 Gt/year)	4 (Medium to High; >0.1 to 1.0 Gt/year)
Cost of Scaling	2 (<\$50 per ton CO_2)	3 (\$100 to \$150 per ton CO_2)	3 (\$100 to \$150 per ton CO_2)	2 (<\$50 per ton CO_2)	5 (\$150 to \$2,500 per ton CO_2; potentially <\$100)
Environmental Risks	4 (Medium to High risk of algal blooms, oxygen depletion)	4 (Medium to High risk due to altering ocean density fields)	3 (Medium; potential toxic effects, bio-optical impacts)	2 (Low; positive impacts on biodiversity expected)	4 (Medium to High; effluent discharge impacts)
Carbon Accounting Challenges	4 (High difficulty in tracking sequestration beyond application)	4 (High due to nutrient displacement impacts)	3 (Medium due to tracking changes in alkalinity)	5 (High due to complexities in monitoring biomass)	2 (Low to Medium; simpler due to engineered systems)
Recommended Environment	Open ocean, areas with low iron levels (HNLC regions)	Coastal regions, upwelling zones	Open ocean, coral reef areas	Coastal wetlands, mangroves, seagrass beds	Enclosed engineered systems, near industrial hubs

Ocean fertilization exhibited medium to high technological maturity and scalability, with medium durability and a relatively low cost of deployment. However, it presented moderate to high environmental risks, particularly due to the potential for harmful algal blooms and oxygen depletion. The technique also faced challenges in accurately tracking carbon sequestration over time.

Artificial upwelling and downwelling were rated as having low maturity and uncertain scalability. The durability of carbon storage was also low, and implementation may alter ocean density fields and ecosystem balance. This method also showed significant carbon accounting challenges, limiting its viability in the short term.

Ocean alkalinity enhancement was considered to have high durability, with carbon sequestration potentially lasting over a century. It had medium scalability and moderate cost but involved some environmental uncertainties related to toxicity and altered light absorption in the ocean. Carbon accounting was moderately difficult due to the need to track chemical changes in seawater.

Coastal blue carbon strategies offer low cost and environmental benefits while demonstrating low to medium scalability and medium maturity. Although effective at storing carbon in biomass and sediment, these methods encountered complex monitoring requirements due to the variability in natural ecosystems.

Direct ocean air capture (DOAC) demonstrated high durability and scalability, especially in engineered systems where carbon tracking is more feasible. However, the method remains costly and poses environmental concerns from by-product effluents. DOAC is best suited for deployment in controlled environments near industrial or coastal infrastructure.

5. Discussion:

The results reveal distinct trade-offs across mCDR methods, suggesting that no single technique currently offers an ideal balance of scalability, affordability, and ecological safety. Ocean fertilization benefits from a strong research base and relatively low cost, yet its ecological risks and uncertain carbon tracking hinder responsible deployment. This highlights the need for stringent monitoring and more precise modeling before implementation at a large scale.

Artificial upwelling and downwelling remain highly experimental, with unproven efficacy and significant physical risks to marine systems. While these methods may serve specialized functions, such as enhancing fisheries or supporting aquaculture, their current limitations suggest a need for further controlled field trials before being considered viable carbon removal tools.

Ocean alkalinity enhancement emerges as one of the most promising options due to its long-term durability and chemical reliability. Its ability to transform CO_2 into stable bicarbonate makes it a compelling candidate for large-scale deployment. However, the cost, energy inputs, and risks to marine organisms necessitate continued refinement of materials and methods. Future research should prioritize developing safe, sustainable feedstocks and efficient dispersion systems.

Coastal blue carbon presents a compelling case for low-cost, nature-based solutions. Its positive co-benefits of habitat protection, biodiversity support, and shoreline stabilization strengthen its appeal. However, the limited scalability and difficulty in quantifying long-term sequestration outcomes constrain its role in global mitigation. These approaches are best implemented locally, particularly in communities that depend on ecosystem services.

DOAC stands apart as the most controlled and measurable form of marine carbon removal. Despite its high cost, its compatibility with industrial infrastructure and monitoring ease position it as a strong candidate for integration into engineered climate solutions. Innovations in energy efficiency and by-product management could substantially reduce its footprint and increase its cost-effectiveness over time.

6. Conclusion:

These findings suggest that no single technique offers a complete solution to climate change. Instead, an integrated portfolio of mCDR strategies may provide the most effective pathway forward. For such a multi-pronged approach to succeed, robust monitoring systems and adaptive management frameworks will be essential. Advancements in remote sensing, AI-driven ocean modeling, and autonomous monitoring can improve the accuracy of carbon accounting and build trust in long-term deployment.

Importantly, this research highlights the broader significance of mCDR in climate policy. Marine carbon removal must not be viewed as a substitute for emissions reduction but as a necessary complement to it. Including mCDR in national and international climate portfolios can provide much-needed flexibility in achieving net-zero goals. Policymakers should prioritize investment in research, infrastructure, and pilot studies, while simultaneously establishing regulatory frameworks to ensure ecological integrity and equitable implementation. Ensuring that developing nations have access to resources and governance tools is also critical for global participation in mCDR deployment.

In summary, marine carbon dioxide removal has the potential to become a powerful tool in the fight against climate change. With continued scientific innovation, policy alignment, and international cooperation, these techniques can transition from theoretical models to practical climate solutions. This review aims to inform future research priorities and decision-making frameworks that will shape the responsible development of marine-based carbon removal in the decades to come.

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