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Marine aquaculture and ocean deacidification technology

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Review and comparison of early-stage and commercially available technologies



Authors review and compare early-stage and commercially available technologies for ocean deacidification in marine aquaculture, and report that current techniques are limited to bench scale, highlighting the need for sustained R&D before implementation is possible. Photo of Nori seaweed farm on the shore of Mie Prefecture, Japan, by H. Grobe, via Wikimedia Commons.

Anthropogenic greenhouse gas (GHG) emissions continue to alter the global climate. As it stands, CO₂ contributes the most toward the rise in global temperature when compared to any other GHG. Since the end of the preindustrial age (1750), levels of CO₂ **in the atmosphere** (<https://www.ipcc.ch/report/ar6/wg1/#FullReport>), have risen by 47 percent, and, even within just the last decade, **levels have risen** (<https://www.unep.org/emissions-gap-report-2020>), by 1.4 percent per year on average.

Much of the global society is still reliant on carbon-based fossil fuels, and to keep the rise in global temperature under the 1.5 degrees-C goal set by the **Paris Climate Agreement** (<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>), a transition to carbon-neutral energy sources must be made quickly, but meeting this audacious goal will also require the simultaneous development of negative-emission technologies (NETs) and the implementation of progressive policies, regulations, and incentive structures for **rapid technology adoption** (<https://doi.org/10.1098/rsta.2016.0447>).

Significant attention and resources have been devoted to terrestrial NETs, with several strategies developed and demonstrated at varying scales, ranging from age-old afforestation/reforestation to hybrid bioenergy with carbon capture and storage (BECCS) and modular direct air capture (DAC) technologies. While the widespread adoption of afforestation and BECCS is limited by competing land-use challenges, the use of DAC is limited due to high cost. Most importantly, while these strategies address CO₂ emissions, they fail to tap into the planet's largest CO₂ sink—the oceans.

This article – adapted and summarized from the **original publication** (<https://doi.org/10.3390/jmse10040523>). (Myers, C.R. and V.S. Chinmayee. 2022. Ocean Deacidification Technologies for Marine Aquaculture. J. Mar. Sci. Eng. 2022, 10(4), 523 – reviews and compares early-stage and commercially available technologies for the deacidification of seawater and their suitability for aquaculture.



(<https://events.globalseafood.org/responsible-seafood-summit>).

CO₂ in the ocean

The oceans absorb about 33 percent of all anthropogenic CO₂ emissions. When compared in equivalent units, bulk CO₂ in air and ocean environments is about 720 Gt and 38,400 Gt, respectively. The higher average CO₂ concentration and significant CO₂ reserves in global oceans offer an

opportunity for ocean-based climate solutions. CO_2 absorbed by the oceans is converted to carbonic acid and subsequently, H^+ and bicarbonate, which decreases the saturation state of calcium carbonate and results in a reduced availability of carbonates for marine organisms to build their shells, leading to decreased productivity and quality of many aquacultured shellfish.

Ocean acidification also has direct impacts on coastal ecosystems, communities and marine-based economies. Hence, ocean-based carbon-capture solutions not only offer opportunities to utilize a concentrated CO_2 source for high-impact NETs, but are also a means to address anthropogenic ocean acidification. All the forms of CO_2 including bicarbonate (HCO_3^-) and carbonate ion (CO_3^{2-}) are in equilibrium with each other; however, slight changes in pH, temperature, and salinity affect the relative concentrations of those carbon species. Manipulating this carbonate/bicarbonate equilibrium is central to the operation of many ocean CO_2 capture technologies.



Ocean acidification can hinder the formation of their shells in bivalves like mussels, oysters and clams, as well as crustaceans. Photo of oyster farm in Tasmania by Darryl Jory.

Ocean acidification impacts on marine aquaculture

In addition to the broader impacts of ocean-based CO_2 removal, there are direct ecosystem and economic benefits from ocean deacidification. Coastal industries, particularly marine aquaculture, are highly sensitive to ocean CO_2 levels and pH changes, which can lower the saturation state of aragonite, a crystalline form of calcium carbonate that many organisms use to build their shells. Shellfish, a general term used to describe aquatic shelled mollusks and crustaceans used for food, are directly impacted by the reduced availability of aragonite to build shells, leading to decreased aquaculture quality and productivity.

Although localized parameters such as ocean current, water temperature, and alkalinity play a role in the rate and extent of acidification, the overall trend of decreasing pH has been seen almost everywhere in the world. Studies have clearly demonstrated the link between CO_2 levels and aquaculture quality and productivity. As a result, hatcheries have developed mitigation strategies to minimize uncertainty

and to better protect their assets. With consistent monitoring and early detection, localized buffering, site and breeding selectivity, and nutritional enhancements, the aquaculture industry has been able to curtail some of the effects of ocean acidification; however, those methods only offer temporary relief.

Capturing CO₂ from the ocean, often referred to as marine carbon dioxide removal (mCDR) could allow for ocean-based climate solutions while simultaneously addressing ocean acidification. Furthermore, when mCDR methods are applied in existing coastal industries such as algal cultivation or coastal infrastructure, a clear economic incentive to deploy ocean-based climate solutions can be established.



As ocean acidification threatens the shellfish industry, this California oyster farm is raising oysters resistant to climate change

Despite the dangers to shellfish posed by ocean acidification, a forward-thinking California oyster farm is producing oysters resistant to climate change.



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Marine carbon dioxide removal methods

Various mCDR strategies (Fig. 1) have been considered, ranging from artificial upwelling and ocean alkalinity enhancement to seaweed cultivation and electrochemical CO₂ stripping. However, given that all the approaches are in the early stages of development and the scarcity field demonstrations to date, their estimated potential for impact is highly variable, and the risks associated with large-scale implementation are not known. The benefits and suitability of these techniques also depend on the local industry (onshore vs. offshore), ecosystem, and competing resource needs.

Given considerations of fish health and food safety, chemical alkalinity enhancement of feedwaters resulting in calcium carbonate (CaCO₃) precipitation (i.e., calcium depletion) seems nonideal. On the other hand, for seaweed cultivation, despite being a chemical input-free carbon capture strategy, the

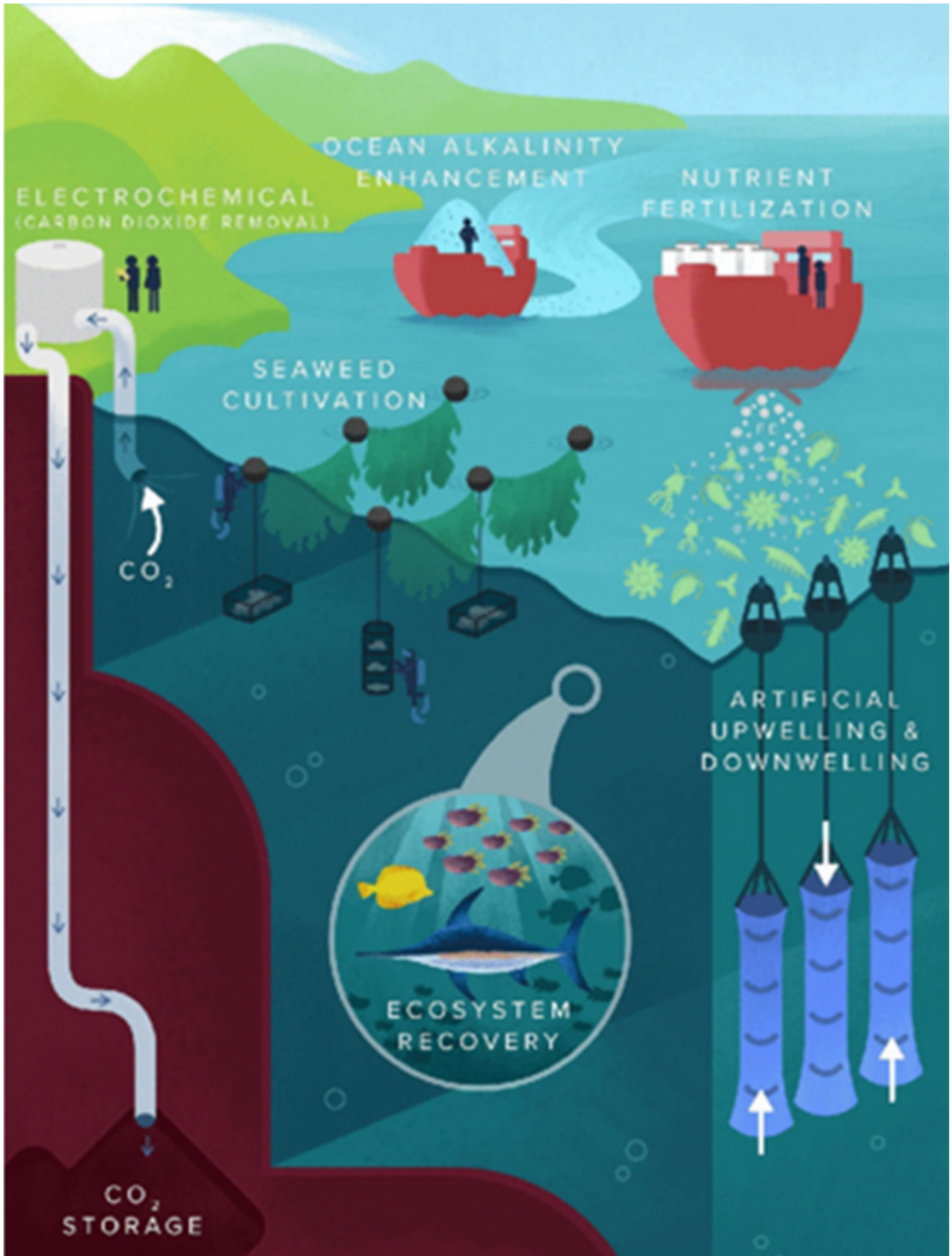


Fig. 1: Strategies for ocean carbon dioxide removal. Credit: National Academies of Sciences, Engineering, and Medicine. 2021. A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration. <https://doi.org/10.17226/26278> (accessed on 9 February 2022). Reproduced in the original publication with permission from the National Academy of Sciences, courtesy of the National Academies Press, Washington, D.C., USA. Adapted from the original.

spatiotemporal pH changes generated are not known. Furthermore, aquaculture facilities may need additional resources to grow and manage seaweed, making it less attractive. Hence, several promising mCDR strategies may not be suitable for the deacidification of aquaculture feedwaters.

Specific to marine aquaculture, which is expected to significantly grow by 2050, coupling with modular mCDR systems that can be easily added to existing seawater intake at the facilities would be preferable. Additionally, systems that can be operated using renewable energy and with minimal chemical inputs would allow for sustainable seafood production. Here we review technologies suitable for deacidifying feedwaters for coastal aquaculture.

Technologies for CO₂ removal from aquaculture feedwaters

There are CO₂ removal methods suitable for the deacidification of marine aquaculture feedwaters, both commercially available technologies and methods in the early stages of development. These methods can be broadly classified into physical (trickling filter), chemical (ion exchange), and electrochemical (bipolar membrane electrodialysis and electrolytic cation exchange) approaches.

Trickling filter and recirculation aquaculture systems

Recirculating aquaculture systems (RAS) involves growing fish in a closed-loop set of tanks where water is recycled, and the addition/removal of nutrients/toxins is heavily controlled by different types of filters. As a result, the oxygen concentration in the water decreases over time due to respiration, while CO₂ and nitrogen concentrations increase. Elevated levels of CO₂ in the water are highly toxic to fish; thus, its cost-effective removal is very important.

While RAS offer a relatively simple physical method for the reduction of dissolved CO₂ in water, they only remove CO₂ from water when the relative concentration is higher in the water than in the surrounding air. Albeit simple and commercially available, the implementation of large-scale TF and RAS to remove CO₂ from ocean water will also require subsequent CO₂ capture strategies in order to be environmentally sustainable.

Ion-exchange resins

Ion-exchange resins (IERs) are widely used in water treatment and in industrial processes. The resins are sold as anion- and cation-exchange types. Both resin types need to be regenerated upon saturation using chemical solutions (acid, base, salt solution). IERs for carbon capture may be an option in the future if electrical resin regeneration either directly via water splitting or indirectly via electrochemical onsite acid/base generation from seawater and renewable energy is used. Given the limited promise of IER at this stage, the method is not discussed further in this review.

Bipolar membrane electro dialysis

A bipolar membrane electro dialysis (BPMED) unit is made up of multiple membrane layers stacked between an anode and cathode. When adequate energy is supplied to the unit, water at the surface of the bipolar membrane (an ion-exchange membrane made up of a cation- and an anion-exchange layer) dissociates into hydrogen and hydroxide ions. The movement of the ions is dictated by the applied potential, causing cations to move in the direction of the cathode and anions to move toward the anode.

Fig. 2: Figure reprinted from <https://doi.org/10.1038/s41467-020-18232-y>. Copyright (2020) Nature Communications. Licensed under Creative Commons Attribution 4.0 International Public License. (a) Schematic drawing of seawater in a BPMED cell. (b) Process flow diagram of an experimental setup for carbon dioxide extraction from seawater.

Various BPMED prototypes have been designed and tested using synthetic seawater, operating on the same fundamental principles but differing in membrane configuration and electrolyte solutions, leading to different energy efficiencies for CO₂ removal.

Although BPMED offers an elegant solution to ocean deacidification, the technology is in its very early stages. The pathway has not yet been tested in an ocean environment; instead, only synthetic seawater and brine solutions in the lab have been used. Thus, the technology performance in harsh marine conditions is unknown. Both methods rely heavily on membranes which are expensive and highly susceptible to fouling/scaling.

Electrolytic cation exchange

The electrolytic cation exchange module (E-CEM) was designed primarily to generate fuels from seawater for naval applications. E-CEMs have been tested in different configurations involving the presence/type of ion exchange resin in the compartment, the electrode compartment volume, and the endplate material. E-CEM technology in its current configuration is not optimized for CO₂ capture from seawater, and if CO₂ generation is the ultimate goal, decoupling the process from hydrogen and oxygen production may improve overall process efficiency.

Comparison of technologies

Technologies for CO₂ removal from seawater are in their early stages of development, with only one technology being successfully demonstrated in field settings. As a result, it is important to note the benefits and drawbacks of the different approaches to recognize how they can be tailored for marine aquaculture (Table 1).

Myers, Deacidification, Table 1

CO ₂ Removal Method	Feedwater Used	Flow Rate	CO ₂ Capture Efficiency	Product
Trickling filter (TF) in RAS	Freshwater, seawater	100 L/min	CO not captured	CO ₂
BPMED (via acidification)	Synthetic seawater, brine	2100 mL/min	80.80%	CO ₂
BPMED (via basification)	Synthetic seawater	Not reported	Not reported	CaCO ₃
BPMED (via acidification)	Synthetic seawater	37 mL/min	71%	CO ₂
BPMED (with reactive crystallization)	Synthetic seawater	667 mL/min	50%	CaCO ₃
E-CEM	Natural seawater	1900 mL/min	92%	CO ₂ , H ₂

Table 1: Summary of technologies for seawater deacidification by CO₂ removal. BPMED: bipolar membrane electro dialysis. electrolytic cation exchange module. Adapted and summarized from the original.

Perspectives

RAS technology has already demonstrated CO₂ removal from fresh and seawater systems, and it is the most cost-effective deacidification approach for aquaculture; however, it is not designed to capture CO₂. The energy consumption by RAS operations is high relative to other methods, which is most likely caused by the need for temperature equilibration after evaporative cooling within the trickling filter. Adding a membrane contactor would enable CO₂ capture and make RASs more sustainable, but **membrane contactors** (<https://doi.org/10.1205/cherd.04203>), are expensive and add energy and maintenance costs. It should be noted that the other methods included in Table 1 either do not integrate pumping costs into the overall energy calculations or assume colocation with a desalination plant to minimize pumping-related capital and operating expenses. Hence, a direct comparison of RAS energy use to that of the other (emerging) technologies may not be very meaningful.

Although achieved in different ways, electrochemical methods rely on a pH swing to release CO₂ by altering the carbonate/bicarbonate equilibrium. If operated using renewable energy, BPMED can offer a sustainable solution to deacidification with CO₂ capture, by producing either gaseous CO₂ (acidified approach) or solid CaCO₃ (basified approach). The CO₂ produced can be used as a precursor for chemicals or as a feedstock for algae growth. While capture via CaCO₃ precipitation produces an easy-to-handle solid product and eliminates the need for expensive membrane contactors, the process decreases calcium availability in feedwater, thus negatively impacting aquaculture quality and productivity.

Current mCDR technologies that are suitable for the deacidification of aquaculture feedwaters are in their very early stages of development and must improve energy efficiency, enhance material durability in harsh marine conditions, and decrease component costs to be viable for aquaculture applications.

The lack of specialized infrastructure and the difficulty in accessing reliable and inexpensive sources of carbon-neutral energy are additional considerations.

Although the technologies are in their early stages of development, their modular design and distributed deployment potential offer a promising outlook. However, significant research and development are required to take these technologies from lab to market, and given the pressing need for sustainable deacidification solutions, making the systems cost-effective in the near term may depend on the availability of government subsidies or tax credits.

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