Microalgae – A Solution for Biological Carbon Capture in Aquaculture

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1. Introduction

Aquaculture is the world's most rapidly developing food production industry, supplying more than 50% of global fish consumption. It serves to bring essential nutrition and economic returns, but aquaculture also affects the environment by emitting greenhouse gases mainly in the form of CO_2 and methane, and effluents that are rich in nutrients and lead to eutrophication and water body degradation (Jones et al., 2022). Conventional treatment technologies are commonly ineffective in mitigating these effects or reclaiming valuable nutrients. These emissions need to be addressed, and biological carbon capture presents a green alternative to traditional carbon capture and storage processes with greater sustainability and cost-effectiveness (Biermann et al., 2020). Biological carbon capture employing microalgae has been a prospecting solution.

2. Overview of Microalgae

Microalgae are tiny, single-celled creatures that grow quickly and have a high photosynthetic efficiency in a variety of aquatic habitats. It will fix inorganic carbon into organic biomass while detoxifying aquatic ecosystems through uptake of nitrogenous and phosphorous wastes. When introduced into aquaculture systems, they can offer several ecosystem services such as carbon sequestration, improvement of water quality, and biomass yield for feed or energy production. Microalgae fix CO2 with 10-50 times greater efficiency than land plants because they grow fast and have high photosynthetic rates. They also can be cultivated on non-cultivable lands, utilize wastewater nutrients, and generate varied biomass components like lipids, proteins, and carbohydrates. The primary components of algal biomass lipids, carbohydrates, and proteins are what enable its transformation into food, cosmetics, medications, and biofuels (Yadav et al., 2021, Zafar et al., 2021, Shahid et al., 2020). Figure 1 shows Microalgae based wastewater treatment and its uses. Because of their lipid and carbohydrate contents high energy density and proven thermochemical processing techniques, biofuels are often the most promising biofuels made from microalgae (Walsh et al., 2018).

3. Environmental Challenges in Aquaculture

3.1 Greenhouse Gas Emissions

Aquaculture faces environmental challenges such as competition for land and water, feed production impacts, and water pollution. Global aquaculture production resulted in approximately 261.3 million tonnes of greenhouse gas emissions in 2018. Greenhouse gas emissions primarily arise from feed production and aquatic nitrous oxide, with aquaculture accounting for approximately 0.49% of global anthropogenic emissions. Intensive aquaculture produces significant amounts of GHGs directly and indirectly. Fish respiration, microbial activity in sediments, and feed production contribute to CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions (Li et al., 2021). Unlike terrestrial agriculture, aquaculture's aquatic environment provides opportunities for direct biological sequestration of CO_2 via aquatic plants and algae, offering a unique mitigation pathway.

3.2 Nutrient Pollution and Eutrophication

Traditional feeds enhanced with protein and carbohydrates are commonly provided to fish to increase their growth rate; nevertheless, a significant amount of the nutrients in the feed may not be used by aquatic animals, which causes feed residues to build up in the aquaculture system. Nutrient pollution in aquaculture occurs when excess nitrogen and phosphorus from uneaten feed, fish waste, and organic decomposition enter water bodies. These nutrients stimulate excessive algae growth, leading to eutrophication. This process causes harmful algal blooms, oxygen depletion, loss of biodiversity, and degradation of water quality. Ultimately, nutrient pollution disrupts aquatic ecosystems, harms fish health, and results in economic losses in fisheries and water treatment. Controlling nutrient discharge is pivotal for minimizing eutrophication and preserving aquatic ecosystem health (Chatvijitku et al., 2017).

4. Biological Carbon Capture Mechanisms

4.1 Photosynthesis and Carbon Assimilation

Photosynthesis is the fundamental natural mechanism for biological carbon capture, playing a pivotal role in the global carbon cycle by converting atmospheric carbon dioxide into organic matter. In this process the microalgae use sunlight to power the fixation of CO_2 through a complex series of biochemical reactions. The light-dependent reactions generate energy in the form of ATP and NADPH, which drive the subsequent carbon fixation phase. The most prevalent pathway for carbon assimilation is the Calvin-Benson-Bassham (C3) cycle, where the enzyme Rubisco catalyzes the incorporation of CO_2 into ribulose-1,5-bisphosphate (RuBP), eventually producing organic compounds like sugars and starches that fuel growth and metabolic functions. The products of carbon assimilation not only form the base of food webs but also serve as renewable sources for biofuels and bioproducts, enhancing prospects for sustainable carbon management and climate mitigation strategies. (Raines 2011).

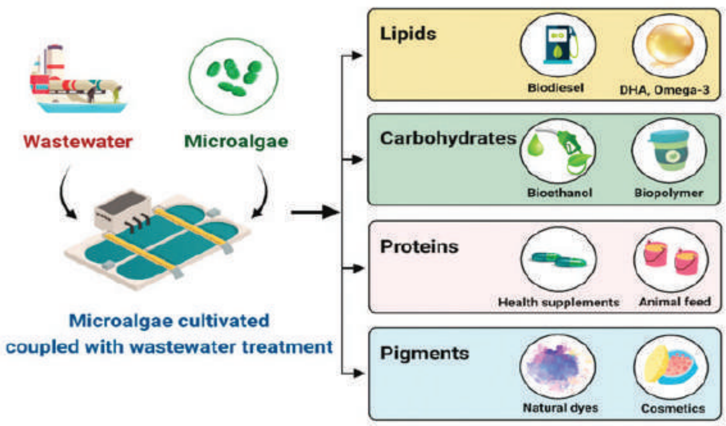

Figure 1: Microalgae based wastewater treatment and its uses

4.2 Carbon Sequestration Pathways

Carbon sequestration refers to the process by which carbon dioxide is captured from the atmosphere and stored in various natural reservoirs, effectively reducing its concentration and helping to mitigate climate change. Key biological sequestration pathways include the use of plant biomass to capture CO_2 through photosynthesis, incorporation of organic carbon into soils and sediments, and the export of organic matter to the deep sea via the biological pump. Biomass can be utilized directly as a renewable resource or processed for long-term storage, while sediment burial isolates carbon for centuries to millennia by trapping it in low-oxygen environments where decomposition is slow. Export to the deep sea, largely driven by the sinking of organic particles and marine snow, sequesters carbon in ocean depths for extended periods, playing a crucial role in regulating the Earth's carbon cycle and climate. These pathways make biological carbon capture in aquaculture a viable climate mitigation strategy (Rani et al., 2021).

5. Algal-Based Treatment Technologies in Aquaculture

5.1 Microalgae Cultivation Systems

Microalgae like Chlorella, Nannochloropsis and Scenedesmus grow rapidly and exhibit high CO_2 fixation efficiencies. Algal-based treatment technologies have gained prominence in aquaculture for their ability to address nutrient pollution and promote sustainable water management. Microalgae can assimilate inorganic nutrients such as nitrogen and phosphorus from aquaculture effluent, thereby reducing the potential for eutrophication and supporting water quality improvement. This approach not only maintains a healthier setting for cultured organisms but also converts waste nutrients into valuable algal biomass, fostering circular resource use. Integrating microalgae cultivation with aquaculture wastewater treatment offers synergistic benefits (Singh et al., 2019). Beyond water remediation the captured carbon will be stored it as organic matter within their cells. This biomass can be harvested for use as feed additives, biofuels, or other value-added bioproducts, converting a waste stream into an economic resource and closing nutrient and carbon loops (Anikuttan et al., 2016).

5.1.1 High-Rate Algal Ponds (HRAPs)

High-Rate Algal Ponds (HRAPs) are engineered, shallow raceway-type ponds designed for efficient aquaculture wastewater treatment through the cultivation of algal-bacterial consortia. HRAPs harness sunlight and CO_2 to promote rapid algae growth, which assimilates nutrients like nitrogen and phosphorus from wastewater, effectively reducing nutrient pollution and eutrophication risks.

They typically have short hydraulic retention times, making them much faster than conventional stabilization ponds, while using minimal mechanical energy, thus offering a sustainable and low-cost wastewater treatment option (Ramli et al., 2020). Benefits of HRAPs include high nutrient removal efficiency, low energy requirements compared to mechanical treatments, and simultaneous CO_2 capture via photosynthesis, functioning as a natural carbon sink. Additionally, the system yields valuable biomass and reduces the overall carbon footprint of wastewater treatment. Overall, HRAPs represent a promising integrated approach to wastewater remediation, nutrient recycling, and carbon sequestration.

5.1.2 Photobioreactors

Photobioreactors are specialized closed systems designed for the controlled cultivation of microalgae by optimizing light exposure, gas exchange, nutrient supply, and environmental conditions to maximize biomass productivity and quality. Unlike open pond systems, photobioreactors allow precise control over light intensity and duration, temperature, pH, and carbon dioxide concentration, reducing contamination risks and improving photosynthetic efficiency. They are used both at lab scale and industrial scale for producing biomass for biofuels, aquaculture feed, pharmaceuticals, and wastewater treatment (Shaikh Abdur Razzak et al., 2024).

6. Performance and Efficiency of Algal Carbon Capture

6.1 Carbon Fixation Rates

Microalgae's ability to biofix CO2 is largely dependent on the carbon sources and growth substrates used in the growing system. Apart from inorganic carbon sources like bicarbonate (HCO3-) and CO2 (33), microalgae like Chlorella can also use organic carbon sources like glucose and acetate. Microalgae need sufficient amounts of both macronutrients and micronutrients to grow and fix CO2. While micronutrients like vitamins and trace metals are needed in lesser amounts but are just as crucial for the best growth and CO2 fixation of microalgae, macronutrients like nitrogen and phosphorus are necessary for the general growth and development of microalgae. Microalgae systems can fix carbon at highly variable rates depending on species, cultivation conditions, and CO_2 availability. Generally, microalgae have CO_2 fixation rates that can range roughly from 250 to 500 mg CO_2 per litre per day (mg L^{-1} day^{-1}) in controlled cultivation settings. For example, Botryococcus braunii has demonstrated the highest CO_2 fixation among studied species, with rates around 497 mg L^{-1} day^{-1}, followed by Spirulina platensis (~319 mg L^{-1} day^{-1}), Dunaliella tertiolecta (~272 mg L^{-1} day^{-1}), and Chlorella vulgaris (~252 mg L^{-1} day^{-1}) under laboratory conditions.

6.2 Nutrient Removal Efficiencies

Studies show that microalgae grown in membrane photobioreactors or integrated cultivation systems can achieve nitrogen removal efficiencies of about 76.7% to 94% and phosphorus removal efficiencies between 66.2% and 80%. Co-cultivation with bacteria can enhance these performances further by promoting symbiotic nutrient cycling and reducing operational energy costs. Light cycles and hydraulic retention times (HRT) also significantly influence nutrient uptake rates, with continuous light and longer HRTs generally supporting better removal efficiencies. For instance, ammoniacal nitrogen removal of 94% and soluble phosphorus removal about 67.6% were observed in a system combining microalgae with constructed wetlands over a 24-hour light cycle (Goh et al., 2022).

6.3 Water Quality Improvements

Studies show that increasing microalgal species diversity correlates with enhanced nitrogen removal efficiencies; richer microalgal communities can remove nitrogen more effectively due to complementary nutrient uptake strategies among species, which improves water purification outcomes in eutrophic systems. Specific species like Tetradesmus obliquus have demonstrated phosphorus and nitrogen removal rates up to 98% and 100% respectively, within a few days during batch cultivation in urban wastewater. Furthermore, microalgae contribute to reducing biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), with removal efficiencies varying depending on the algal biomass density and system design (Songlin et al., 2023).

8. Conclusion

Biological carbon capture in aquaculture using microalgae offers a promising, sustainable approach to mitigate CO_2 emissions and improve water quality. Microalgae exhibit highly efficient photosynthesis processes, enabling rapid assimilation of carbon while simultaneously removing excess nutrients from aquaculture effluents. This dual function not only reduces eutrophication risks but also contributes to biomass production that can be utilized for biofuels, animal feed, or fertilizers, closing nutrient and carbon cycles within aquaculture systems. This approach not only addresses environmental challenges but also offers economic benefits through biomass valorization, positioning microalgae as integral players in the future of sustainable aquaculture and carbon management.

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