(ISSN: 0973-7049(P))

The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES

21(3): S.I (3), 1483-1494, 2026

www.thebioscan.com

Design and Optimization of Microalgal Systems for Direct Air CO_2 Capture: Emerging Strategies for Sustainable Carbon Removal

Pinky[1], Shalu Saini[2], Puja Singh[3], Sachin Gupta[4*]

[1]Ph.D. Scholar, Amity School of Earth & Environmental Sciences, Amity University Haryana, India.
[2]Ph.D. Scholar, Amity School of Earth & Environmental Sciences, Amity University Haryana, India.
[3]Associate Professor, Amity School of Earth & Environmental Sciences, Amity University Haryana, India.
[4*]Corresponding Author: Director, Sustainable Energy Environment Innovation, Lucknow

Corresponding Author: Sachin Gupta

DOI: https://doi.org/10.63001/tbs.2026.v21.i03.S.I(3).pp1483-1494

KEYWORDS
Microalgae, Direct air capture, CO_2 capture, Photobioreactor, Carbon sequestration, Biomass productivity, Sustainability

Received on: 02/08/2026
Revised on: 18/08/2026
Accepted on: 29/08/2026
Published on: 04/09/2026

Abstract

In recent years, we have experienced significant increases in greenhouse gas emissions and with this, we face grave consequences worldwide. Transitioning to renewable energy is essential but to be fully effective at reducing GHG emissions from very hard to decarbonise industries, deployment of additional technologies like carbon capture technology will also be required. Microalgal growing systems are another viable carbon capture technology due to their very high capture rates and ability to grow in many different types of conditions. Microalgal growing systems have a lot of potential to mitigate climate change and are an effective and sustainable method of sequestering CO_2 on a large scale. Therefore, in order to optimize microalgae's CO_2 capture efficiency, key factors such as light levels, pH, temperature, availability of nutrients and strain selection must be considered. Photobioreactors with advanced configurations, including flat-plate designs with PIAT internals and sequential-flow bubble column reactors, will have greater CO_2 absorption and biomass productivity than traditional photobioreactors. The reduction of CO_2 in the atmosphere globally can be facilitated by successfully resolving key issues related to reactor optimization, CO_2 delivery, and strain performance of microalgae, complemented by genetic engineering and the application of carbonic anhydrase enzymatic solutions. For this reason, continuous research and innovation are critical to realizing the benefits of microalgae for climate change mitigation and as a potential green and renewable means of advancing to a sustainable future. This research project examines optimization methods for algal systems for effective direct air capture (DAC) from biological, technological, and economic perspectives.

1. INTRODUCTION

Anthropogenic activity has caused an accelerating rate of atmospheric carbon dioxide (CO_2) to increase. As a result, this new problem, and with it an associated level of urgency, has arisen as one of the three major international environmental issues facing humanity in our time. Since before the Industrial Revolution, atmospheric CO_2 concentrations had risen from about 280 ppm to more than 420 ppm, primarily from fossil combustion, industrialization, land use change and deforestation. Anthropogenic activities have therefore caused an unprecedented rate of increase in greenhouse gas concentrations, which have a major impact on global warming, climate change, ocean acidification and extreme weather events. This endangers ecosystems, biodiversity and food safety for both humans and animals and therefore threatens all aspects of human well-being (IPCC, 2023; Friedlingstein et al., 2023). To prevent a global rise in temperature of more than 1.5–2 °C above pre-industrial levels, the Intergovernmental Panel on Climate Change (IPCC) outlines a need for net-zero emissions by approximately mid-century along with the implementation of CDR technologies at a global scale (IPCC, 2023). The use of more conventional carbon capture and storage (CCS) technologies, including methods for capturing post-combustion, pre-combustion and oxy-fuel combustion gases, has demonstrated significant reductions of CO_2 emissions associated with industrial activities; however, the technologies can be energy-intensive and expensive to operate, they can also pose practical obstacles associated with long-term storage and infrastructure development (Fasihi et al., 2019). As a result of these challenges, the DAC process for removing CO_2 from ambient air at any location is receiving greater emphasis than earlier methods (National Academies of Sciences, Engineering, and Medicine, 2019). Despite demonstrating good carbon removal efficiencies, the commercial use of DAC technologies based on chemical sorbents and/or solid adsorbents is currently limited due to: (1) the large initial capital investment required; (2) the energy-intensive regeneration process; and (3) the environmental sustainability concerns related to those technologies (Shan et al., 2026; Fasihi et al., 2019). Within this context, biological carbon capture technologies that utilise microalgae have been identified as environmentally sustainable alternatives to existing DAC technologies that simultaneously sequester CO_2 from the atmosphere and produce a usable biomass (Dayanath et al., 2026). Microalgae are photosynthetic unicellular organisms with high photosynthetic efficiency and rapid growth rates that can successfully grow across a range of environmental conditions, making them potentially viable options for capturing carbon from the atmosphere (Ahmad et al., 2024; Cheah et al., 2015).

Microalgae achieve up to 10–50 times the photosynthetic efficiency of terrestrial plants and biomass productivity on a per unit area basis (Ali et al., 2024). Microalgae have carbon concentrating mechanisms (CCMs) that transport bicarbonate into their cell and then concentrate CO_2 around Rubisco (the enzyme responsible for fixing carbon), resulting in very efficient carbon fixation in low atmospheric CO_2 concentrations (Raven et al., 2017). Through photosynthesis, microalgae produce carbohydrates, lipids, proteins, and other bioactive products, which can be used to produce biofuels, biofertilizers, pharmaceuticals, nutraceuticals and animal feed; therefore, microalgae contribute to the establishment of a circular bio-economy (Thevarajah et al., 2025). Recent advances in reactor engineering, synthetic biology and process optimisation have increased the viability of using microalgae to directly capture CO_2 from the atmosphere (Wang et al., 2026). Various cultivation systems such as open raceway ponds, tubular photobioreactors, flat panel reactors, air-lift reactors and membrane photobioreactors have been examined for their ability to improve light utilisation, gas-liquid mass transfer and CO_2 fixation efficiency (Hashmi et al., 2025). Also, new methods that have been developed to help these systems overcome the limitations imposed on them due to difficulties posed by low levels of carbon dioxide (CO_2) present in the atmospheric environment and other difficulties associated with scaling up include hybrid DAC–microalgae systems, artificial intelligence (AI)–assisted cultivation, genome editing, and carbonic anhydrase engineering (Zainal et al., 2026). Unfortunately, although some things have changed since they were initially developed and tested, many technical and economic barriers are still impeding the success of microalgal DAC solutions to be implemented fully on an industrial mass scale. Therefore, there are still significant technical barriers to implementation, including low gas–liquid mass transfer rates, high harvesting costs, uncertainty of environmental conditions, biofouling, and difficulty in scaling up (Singh & Dhar, 2011; Cheah et al., 2015). In addition, the technical and economic viability and sustainability of life-cycle assessments of microalgae-based carbon capture technologies need further analysis to develop standards for the implementation of these technologies as part of the overall global carbon management strategy (Fasihi et al., 2019; Breyer et al., 2020).

Consequently, the reviewed recent literature highlights the production and design concepts related to optimized microalgal systems for direct air CO_2 capture. The recent literature cited has highlighted recent advances made in reactor technologies, carbon concentrating mechanisms, cultivation methods and other novel methods being applied to develop sustainable means of producing biomass and removing carbon dioxide from the environment. This literature also identifies the present and future challenges associated with scaling up microalgal DAC systems, opportunities and indicates their potential for assisting in the achievement of carbon neutrality and promoting a sustainable bioeconomy.

Table 1. Key Milestones in the Development of Microalgal Systems for Direct Air CO_2 Capture

Year	Development/Milestone	Significance	Reference
2007	Biodiesel and carbon capture potential of microalgae emphasized	Well-known microalgae as a promising carbon sequestration platform	Chisti, 2007
2008	CO_2 bio-mitigation using microalgae expansively reviewed	Established feasibility of biological carbon capture	Wang et al., 2008
2010	Large-scale microalgal cultivation and biofuel production emphasized	Extended industrial applications of microalgae	Brennan & Owende, 2010
2011	Comprehensive overview of carbon capture by microalgae	Identified major challenges and opportunities	Singh & Dhar, 2011
2015	Integration of microalgae with carbon capture and bioeconomy ideas	Promoted sustainable and circular approaches	Cheah et al., 2015
2019	Techno-economic assessment of DAC technologies	Evaluated feasibility of DAC integration	Fasihi et al., 2019
2023	Membrane Sparger design with Carbonic Anhydrase integration	Enhanced efficiency and scalability	Wang et al., 2025

1.1 Global Status of Atmospheric CO_2 and Climate Change

The levels of carbon dioxide (CO_2) in the atmosphere have reached levels that have never been seen before, primarily as a result of human activities such as fossil fuel burning, industrial activities, and changes in land use. In 2023, the global average CO_2 level in the atmosphere was 420ppm, which is almost 50% higher than what it was before the Industrial Revolution. This increase in atmospheric CO_2 has significantly contributed to global warming, raising sea levels, ocean acidification, and increasing extreme weather events. Current efforts to reduce greenhouse gas emissions alone will be insufficient to meet the goals outlined in the Paris Agreement. Therefore, large-scale deployment of carbon dioxide removal (CDR) technologies is required to meet these targets (IPCC, 2023; Friedlingstein et al., 2023).

1.2 Need for Direct Air Capture Technologies

Direct air capture (DAC) is a new technology that is being developed to eliminate CO_2 from the atmosphere directly, regardless of where it came from. Typical carbon-capturing methods will usually take a lot of carbon from an industrial source and separate the carbon from other gases using a chemical process. In contrast, DAC captures the carbon already in the atmosphere, which is distributed widely across the earth as a result of both past and present emissions (Dogoua and Moscona, 2026). Commercially developed DAC systems primarily utilize either liquid or solid sorbent materials to absorb CO_2. However, the high amount of energy required to regenerate, transport and store the carbon dioxide produced by these systems makes them difficult to be implemented on a large scale (Keith et al., 2018; Fasihi et al., 2019). As a result, there is a growing interest in finding sustainable, low-energy, biologically based methods of capturing CO_2.

1.3 Why Microalgae for Direct Air CO_2 Capture?

Microalgae are increasingly being considered for use in biological Direct Air Capture (DAC) because of their ability to grow quickly, high efficiency of photosynthesis and ability to use the CO_2 in the air as their primary carbon source. Microalgae have potentially 10-50 times the efficiency of photosynthesis of terrestrial plants and production of biomass per area (Seyyedattar & Zendehboudi 2026); Brennan and Owende, 2010). Many species of microalgae also contain efficient Carbon Concentrating Mechanisms (CCMs) which allow them to accumulate inorganic carbon and enhance carbon

(ISSN: 0973-7049(P))

The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES

21(3): S.I (3), 1483-1494, 2026

www.thebioscan.com

fixation at low levels of CO_2 in the air (Raven et al., 2017). In addition to being a source of carbon sequestration, microalgal biomass can be converted into biofuels, nutraceuticals, pharmaceuticals, pigments, and biofertilizers to increase the financial viability of carbon removal systems (Pittman et al., 2011).

1.4 Research Gaps and Scope of the Present Emerging Trends: While there have been major advancements in microalgal technologies for carbon capture, many challenges still exist. Most previous work has concentrated on carbon capture from flue gases rather than from the ambient air; also, the low carbon dioxide concentrations found in ambient air result in limitations related to gas transfer rates, reactor design and carbon use efficiency. In addition, very few comprehensive reviews exist that integrate the various advances in photobioreactor design and engineering, carbon concentration mechanisms, genetic engineering, artificial intelligence (AI)-assisted cultivation, and hybrid direct air capture (DAC) - microalgal systems. Thus, this current emerging trend is directed toward a critical evaluation of the design and optimisation strategies of microalgal systems for CO_2 capture from ambient air as well as a discussion of emerging technologies that will promote sustainable and economically viable means for carbon removal through the use of microalgae.

2. MICROALGAE AS BIOLOGICAL CO_2 CAPTURE SYSTEMS

Microalgae are micro-organisms that convert light energy into chemical energy via photosynthesis. Because of their high growth rates, efficiency in converting light to chemical energy via photosynthesis, and ability to use atmospheric carbon dioxide (CO_2) as a source of carbon, microalgae have become promising organisms for capturing CO_2 (Thanigaivel et al., 2022). Unlike traditional technologies for capturing CO_2 using chemical or physical methods, microalgae capture CO_2 and produce biomass using solar energy at atmospheric pressure (Esfandiari et al., 2026).

Microalgae can capture and accumulate carbon from the atmosphere through their efficient photosynthetic machinery and carbon-concentrating mechanisms (CCMs) as a result of their ability to photosynthesise in atmospheric levels of CO_2. They use photosynthesis to convert CO_2 from atmospheric air to carbohydrates, proteins, lipids, and other organic compounds that can be used for making biofuels, animal feeds, pharmaceutical products, pigments, and fertilisers (Hidalgo et al., 2026). Thus, microalgae have the potential to capture CO_2 and support the development of a circular bioeconomy. Despite these advantages,

several challenges hinder the commercialization of microalgal carbon capture systems (Rahman et al., 2024). The low concentration of atmospheric CO_2 (~420 ppm) limits gas-liquid mass transfer, while harvesting and downstream processing remain energy-intensive and costly. Moreover, large-scale cultivation requires optimized reactor designs, efficient light management, and robust strains capable of maintaining high productivity under fluctuating environmental conditions. Consequently, ongoing research is focused on developing genetically engineered strains, hybrid DAC–microalgae systems, and integrated biorefinery approaches to enhance the economic and environmental feasibility of microalgal carbon capture technologies (Khoshnevisan et al., 2022). There are numerous advantages of microalgae for carbon dioxide sequestration compared to terrestrial plants.

Microalgae have growth rates of 10-50 times faster than higher plants and have higher photosynthetic efficiencies when cultivated under controlled conditions. Microalgae can also be cultivated in freshwater, seawater, wastewater or on non-arable land, thus eliminating competition with food crops and relieving pressure on agricultural resources (Chong et al., 2022). Furthermore, microalgae can simultaneously utilise nutrients from wastewater, thereby aiding in nutrient removal and water purification, and improving the environmental sustainability of the cultivation process. (Chisti, 2007; Pittman et al., 2011)

Many factors influence the efficiency of microalgal CO_2 capture systems, such as light intensity, temperature, pH, nutrient availability, reactor configuration and mixing conditions. Closed Photobioreactors allow for greater control of the environmental conditions and greater carbon fixation efficiency than Open Raceway Ponds, although Closed Photobioreactors are more capital and operationally expensive (Alsalal et al., 2026). Recent developments in membrane photobioreactors, synthetic biology and cultivation strategies assisted by artificial intelligence have improved the efficiency of carbon utilisation and biomass productivity, making microalgae more attractive for a large-scale application of direct air capture (DAC) systems. (Cheah et al., 2015; Raven et al., 2017)

The major characteristics, advantages, limitations, and representative studies highlighting the role of microalgae as biological CO_2 capture systems are summarized in Table 2

Table 2. Microalgae as a Biological CO_2 Capture System: Characteristics, Advantages and Limitations

S. No.	Feature	Description	Significance for CO_2 Capture	Limitations	Representative Reference
1	High Photosynthetic Efficiency	Microalgae exhibit photosynthetic efficiencies higher than terrestrial plants and rapidly convert CO_2 into biomass.	Enables rapid atmospheric CO_2 fixation and biomass generation.	Efficiency decreases under light limitation and nutrient stress.	Chisti, 2007
2	Fast Growth Rate	Microalgae have doubling times ranging from hours to a few days.	Leads to high biomass productivity and enhanced carbon sequestration.	Requires continuous nutrient supply and controlled cultivation conditions.	Singh & Dhar, 2011
3	Carbon Concentrating Mechanisms (CCMs)	Specialized systems actively transport bicarbonate and concentrate CO_2 near Rubisco.	Improve carbon fixation efficiency even at low atmospheric CO_2 concentrations.	Genetic and physiological limitations under environmental stress.	Raven et al., 2017

(ISSN: 0973-7049(P))
The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(3): S.I (3), 1483-1494, 2026 www.thebioscan.com

4	Diverse Habitat Adaptability	Microalgae grow in freshwater, marine, wastewater, and extreme environments.	Facilitates cultivation in diverse climatic and geographical regions.	Species-specific environmental requirements.	Wang et al., 2008
5	Utilization of Waste Streams	Capable of using wastewater and industrial effluents as nutrient sources.	Reduces cultivation cost and provides simultaneous wastewater treatment.	Presence of toxic contaminants may inhibit growth.	Pittman et al., 2011
6	Production of Valuable Bioproducts	Biomass can be converted into biofuels, pigments, proteins, and biofertilizers.	Improves economic feasibility of carbon capture systems.	Downstream processing and harvesting are energy intensive.	Chisti, 2007
7	Environmental Sustainability	Cultivation requires less land compared to terrestrial crops and can be integrated with renewable energy systems.	Supports carbon-negative and circular bioeconomy approaches.	High water demand and scale-up challenges remain.	Cheah et al., 2015

By mapping keyword relationships, the Table 1 and figure 1 depicts how core areas of microalgae research have evolved, showcasing the movement of scientific interest toward emerging topics in recent years (2022–2025).

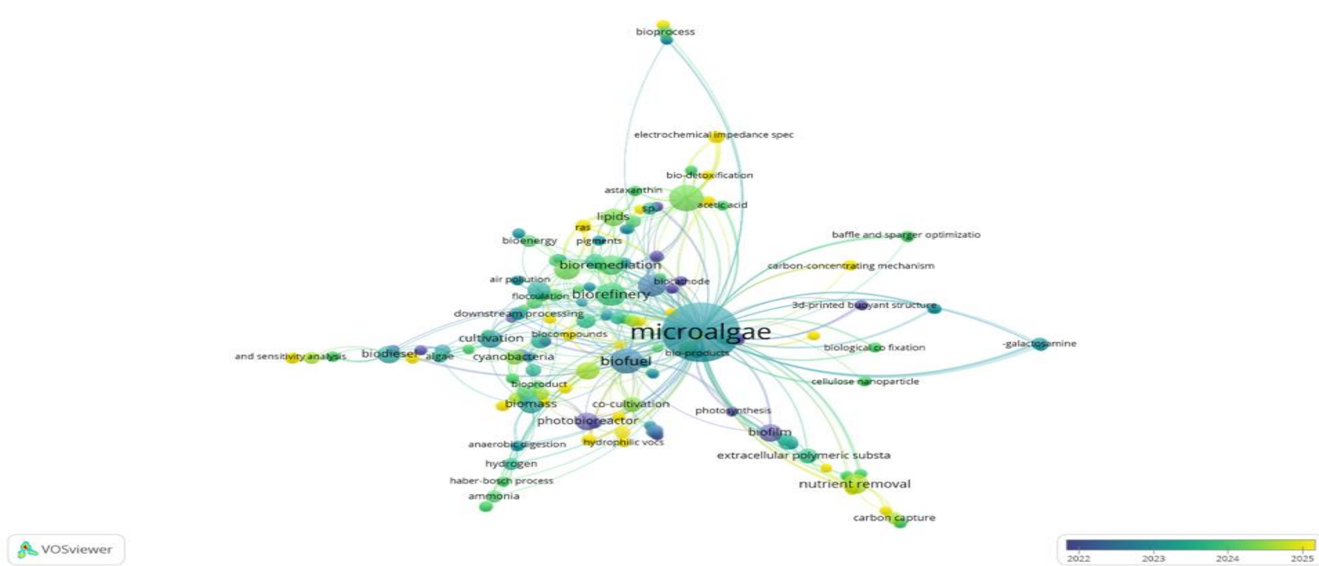

Figure 1. Overlay visualization of keyword co-occurrence network illustrating emerging research trends in microalgae research during 2022-2025.

Like to other photosynthetic organisms, algae use light energy to convert water (H_2O) and carbon dioxide (CO_2) into organic carbon (glucose) and oxygen (Zheng et al., 2021). Photosynthesis in macroalgae occurs in cells with pigments, while in microalgae, it takes place in chloroplasts. Microalgae photosynthesis involves two main processes: light-dependent and light-independent. In order to absorb light energy and yield the high-energy molecules ATP and NADPH, light-dependent processes take place in the thylakoids of chloroplasts (Alami et al., 2021). In turn, light-independent processes require ATP and NADPH. Light-independent reactions, occurring within the chloroplast stroma, facilitate the fixation of carbon dioxide (CO_2), which is then converted into organic compounds such as sugars, starches, and lipids (Daneshvar et al., 2022). Consequently, microalgae function as bio factories, leveraging their chloroplasts to harness light energy for photosynthesis and the conversion of carbon dioxide into organic chemicals. (Ganesan et al., 2022).

As a byproduct of converting CO_2 into organic carbon, algae release oxygen. The Calvin cycle fixes CO_2, which results in the synthesis of organic compounds. Calvin cycle products, mainly G3P, are building blocks for the production of vital macromolecules that are utilized in algal biomass, such as proteins, lipids, and carbohydrates (Shen, 2014).

In low CO_2 environments, algae can increase photosynthetic efficiency by concentrating CO_2 around the enzyme RuBisCO.

Specialized membrane proteins are used by algae to actively move CO_2 into their cells from the surrounding environment. By concentrating CO_2 close to RuBisCO, this method avoids its inefficiency when exposed to oxygen, which happens during photorespiration (Bercel & Kranz, 2019). Like in plants, RuBisCO fixes oxygen (O_2) instead of CO_2 during photorespiration in algae, which results in the loss of carbon and energy. Certain algae have mechanisms to lessen energy loss during photorespiration, which improves CO_2 fixation even further. By adjusting the CO_2 concentration, algae like Chlamydomonas reinhardtii reduce photorespiration through high-affinity CO_2 transportation and other modifications (Paul et al., 2021).

Bicarbonate ions ($HCO3^-$) are a common form of CO_2 in aquatic environments. Algae of various taxa have been shown to contain the enzyme carbonic anhydrase, which enables certain blue-green algae to convert bicarbonate into CO_2; thereby, allowing the algae to utilise the bicarbonate as an additional source of carbon dioxide for photosynthesis. According to Donat-P. Hader (2022) there are a number of microalgal species that have been found to have extraordinary efficacy in their ability to fix CO_2 making them good candidates for the direct capture of atmospheric CO_2. Many of these microalgal species; including, B. braunii, C. littorale, Chlorella sp., A. microscopica, Scenedesmus sp., E. gracilis, D. tertiolecta, N. oculata, C. reinhardtii, and Spirulina sp., are regularly used to reduce the amount of CO_2 released into the atmosphere (Li et al., 2022). The most frequently studied microalgal species, such as Chlorella, Spirulina, and Scenedesmus, consistently demonstrate their ability to grow rapidly and efficiently assimilate CO_2 (Prasad et al., 2024). Chlorella vulgaris is the most extensively studied and widely used microalgal species due to its high CO_2 uptake efficiency and versatility (Zhang et al., 2025). Because these species are highly productive in terms of photosynthetic production and can adapt to a variety of environmental conditions, they are effective at sequestering CO_2 from the atmosphere (Kumar et al., 2023). Due to their rapid growth rate and their ability to double their biomass quickly, microalgae have the potential to sequester a significant amount of CO_2 from the atmosphere (Pekkoh et al., 2024). Microalgae will flourish in environmentally stressful, CO_2-rich industrial conditions, as well as in all aquatic ecosystems, including fresh and marine ecosystems (Abdullah et al., 2024).

It is vital for microalgal strains chosen for direct air capture to have certain characteristics. This is because the amount of carbon dioxide present in ambient air is relatively low, approximately 0.04%, and also because ambient air contains other pollutants besides carbon dioxide (Liu et al., 2021). Tolerance to low levels of CO_2 and tolerance to pollutants, such as particulates and volatile organic compounds, are key factors in the resiliency of an algal strain to maintain its performance for CO_2 capture in real world atmospheric environments where temperature, humidity and pollutant levels can change frequently (Skifa et al., 2025).

3. DESIGN OF MICROALGAL CO_2 CAPTURE SYSTEMS

Microalgal systems (i.e., systems that cultivate microalgae) are an important design element for collecting carbon dioxide (CO_2) and have critical impacts on the rates of carbon fixed, the rates of biomass produced, and the cost-effectiveness of carbon removal methods (Hidalgo et al., 2026). Because the amount of CO_2 in the atmosphere is small (~420 parts per million by volume [ppmv]), an efficient reactor design is needed to maximise the gas–liquid mass transfer of CO_2, the light-use efficiency, nutrient distribution, and CO_2 assimilation. Microalgal culture systems can be categorised into three types: open systems, closed photobioreactors (PBRs), and hybrid systems (i.e., a combination). Each system type has unique benefits and drawbacks associated with it and contributes differently to the overall goal of CO_2 capture (Roy et al., 2026).

3.1. Open Raceway Pond Systems

The cultivation method that is oldest and most economically favorable for microalgal biomass is via open raceway pond. Open raceway ponds consist of shallow bodies of water that are kept in constant motion by paddle wheels which circulate the culture medium providing sufficient mixing of materials (Razzak et al., 2013). Their low investment cost (capital cost), their simple design, and their ease of operation have made them an attractive option for commercial-scale biomass production (Chisti et al., 2007). However, open raceway ponds have low CO_2 utilization efficiency due to poor gas/liquid mass transfer; contamination by unwanted microorganisms; evaporation losses; and the inability to maintain a stable and reliable set of environmental conditions. Due to these problems, open raceway ponds have not yet been successfully applied to direct air CO_2 capture (DAC) even though they have several distinct economic advantages (Yadav et al., 2020).

3.2. Tubular Photobioreactors (tPBRs)

A tubular photobioreactor (tPBR) is an enclosed photobioreactor system made up of transparent tubing oriented in a horizontal, vertical or helical manner. Tubular photobioreactors provide a greater surface area relative to volume, as well as increased light penetration and the ability to control environmental conditions than a pond culture (Chandola et al., 2026). The enclosed design reduces the chance of contamination and increases the efficiency of carbon utilization. Conversely, tPBR can also encounter difficulties in operation such as the accumulation of oxygen, fouling by living organisms, and high energy required for pumping fluids that increase costs associated with operation. Nevertheless, tPBR are currently one of the most commonly studied methods for carbon capture using microalgae. (Carvalho et al., 2006; Ugwu et al., 2008; Wang et al., 2008).

3.3. Flat-Panel Photobioreactors

Flat-panel photobioreactors contain narrow transparent panels that encourage maximum light exposure while reducing the shading effect from one panel to another. The high photosynthetic efficiencies and good mass transfer characteristics make flat-panel photobioreactors well suited for capturing atmospheric CO_2 (Soudagar et al., 2024). Due to their compact design, flat-panel photobioreactors are also well-suited for use in indoor and vertical cultivation systems. However, temperature control, difficulties in scaling up the system, and high construction costs are all hindrances to the commercial application of these types of reactors (Michael et al., 2026; Singh & Dhar, 2011).

3.4. Airlift Photobioreactors

Airlift photobioreactors utilise bubble-driven circulation of the culture medium instead of employing mechanical agitation. This bioreactor consists of a riser and a downcomer section, which creates natural circulation within the enclosed system by enhancing gas-liquid mass transfer and reducing shear stresses on microalgal cells (Shokravi et al., 2025). In addition, the unique design of an airlift photobioreactor makes it appropriate for direct air capture (DAC) applications as it creates greater atmospheric carbon dioxide (CO_2) dissolution rates at low energy consumption. The article reviews the advantages of an airlift's design and mixing characteristics as being part of the reason for their growing interest to be implemented at a large scale (Zou et al., 2025; Chisti et al., 2007).

3.5. Membrane Photobioreactors (MPBRs)

The use of membrane photobioreactors is a novel form of technology that combines the use of gas-permeable membranes with microalgal production systems (Wang et al., 2022). These membranes allow for controlled delivery of CO_2 and allow for improved efficiency of moving gas from one place to another and they also eliminate carbon losses associated with bubbling, which are generally associated with bubble sparging (Russell et al., 2025). Studies have shown that the use of membrane-based CO_2 delivery

(ISSN: 0973-7049(P))

The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(3): S.I (3), 1483-1494, 2026 www.thebioscan.com

increases the carbon utilization efficiency at low atmospheric CO_2 concentrations by a large margin. In addition, it has been proposed that carbonic-anhydrase coated membranes can be used to enhance the rate at which dissolved inorganic carbon species are converted to other forms and increase carbon fixation rates (Wang et al., 2025; Cheah et al., 2015).

3.6. Hybrid DAC-Microalgae Systems

Physicochemical direct air capture (DAC) technologies can be combined with biological carbon fixation to create hybrid systems, and utilizing atmospheric CO_2 in microalgal cultures requires the first step of concentrating CO_2 from the atmosphere using (1) either solid-state or liquid-state sorbents, (2) membranes or (3) moisture-swing adsorbents to provide atmospheric CO_2 for use within microalgal cultures. Combining these forms of capture eliminates mass-transfer limitations associated with capturing atmospheric CO_2 and maximizes productivity of biomass within microalgal cultures. Hybrid systems are now being seen as promising ways to achieve carbon negative, economically viable solutions for carbon removal from the environment (Fasihi et al., 2019; Keith et al., 2018).

Several variables affect which reactor design may be best suited for a given application, including (1) CO_2 source, (2) cultivation scale, (3) energy consumption, (4) biomass productivity (5) environmental conditions; and (6) techno-economic considerations. Future research efforts should focus on developing "smart", photobioreactor(s) containing sensors, AI-based process control and renewable energy integration for improved sustainability and scalability of microalgal systems engaged in direct air capture (DAC) (Breyer et al., 2020; Cheah et al., 2015).

Table 3. Comparison of Microalgal Cultivation Systems for Direct Air Capture (DAC)-Integrated Carbon Sequestration Applications

System Type	Design Features	Advantages	Limitations	Suitability for DAC	Representative Reference
Open Raceway Pond	Shallow open ponds with paddle wheel mixing	Low capital cost, simple operation, large-scale cultivation	Contamination, evaporation, poor CO_2 transfer	Low-Moderate	Chisti, 2007
Tubular Photobioreactor	Transparent tubes arranged horizontally/vertically	High surface area, good light utilization, contamination control	Oxygen accumulation, biofouling, high energy demand	High	Wang et al., 2008
Flat-Panel Photobioreactor	Flat transparent panels with narrow culture depth	High photosynthetic efficiency, efficient light utilization	High construction cost, temperature control issues	High	Singh & Dhar, 2011
Airlift Photobioreactor	Riser and downcomer sections with air circulation	Enhanced mass transfer, low shear stress, energy efficient	Limited scalability and design complexity	High	Chisti, 2007
Membrane Photobioreactor	Gas-permeable membranes integrated with cultivation chamber	Controlled CO_2 delivery, high carbon utilization efficiency	Membrane fouling and high capital cost	Very High	Cheah et al., 2015
Hybrid DAC-Microalgae System	Combination of DAC units and microalgal reactors	Overcomes low atmospheric CO_2 limitation, improves productivity	Complex integration and high initial cost	Very High	Fasihi et al., 2019

In order to maximise light availability, yet minimise shading effects, it is essential that photobioreactors be configured in a manner that provides maximum exposure of the photography reactors to light. There are two categories of photobioreactors, tubulars, and flat panels, which have high surface areas for the purpose of exposing the algae to high-intensity light (Yarkent et al., 2025). All algae must also be mixed properly in order for all cells to have equal access to CO_2 and nutrients (Samantaray et al., 2025). Bubble columns and airlift reactors are commonly used in microalgal reactors in order to maintain steady-state mixing of microalgal suspensions, as well as to facilitate gas exchange between liquid and gaseous phases, respectively (Yarkent et al., 2025).

In order to achieve maximum photosynthetic production, CO_2 must be supplied to the microalgal culture efficiently (Yahaya et al., 2024). The transfer of CO_2 from the surrounding gaseous phase to the microalgal culture should be one of the most important aspects of design. Two of the most common ways to enhance the mass transfer of CO_2 to microalgal cultures are through the use of gas diffusion membranes (GDMs) and microbubble systems (Zhang et al., 2025). Typical methods of contacting air to the microalgal culture medium include: direct bubbling of air into the culture medium to provide good gas-liquid contact between air and algal cells; membrane contactors, which allow the two phases to be separated while allowing CO_2 to diffuse across a gas diffusion membrane; and biofilm systems of microalgae growing on the surfaces of biofilms exposed to air (to promote maximum CO_2 exposure to algal cells (Li et al., 2025). The efficiency of each of these methods varies with regard to mass transfer efficiency, energy consumption, and operational complexity. Microalgal CO_2 capture systems may be synergistically combined with the biomass production for the generation of biofuels and valuable products like pigments, proteins, and antioxidants. This dual-purpose approach captures CO_2 while simultaneously providing an economic benefit through the production of biomass, which helps to create a sustainable system (Deepika, 2025). The design of these integrated systems must consider CO_2 capture efficiency and the optimal yield of biomass and quality of the product produced. Microalgae can contribute to carbon storage beyond the time they grow by converting carbon into biofuels/biomaterials or by creating biochar, etc. Algal biofuels may offer the potential for carbon sequestering efficiencies of as much as 1,500kg CO_2/hectare/year, which is significantly greater than most land-based biofuels (Li et al., 2025).

Microalgal CO_2 capture systems are available in various forms, including small modular units for localized air purification and large, industrial-sized units that are integrated into the infrastructure of power plants and cities.

As an example of the relationship between achievability of emissions reductions and cost of operation, small-scale systems provide many advantages including flexibility and quick response times; however, they have throughput limitations (Omokaro et al.,

(ISSN: 0973-7049(P))
The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(3): S.I (3), 1483-1494, 2026 www.thebioscan.com

2025). On the other hand, industrial-sized systems provide potential for overall carbon dioxide emissions sequestration but require significant capital investment and operational expertise. As such, deployment strategies must account for site-specific characteristics including climate conditions, land availability, and regulatory frameworks (Zainal et al.,2026).

4. OPTIMIZATION STRATEGIES FOR ENHANCED CO_2 CAPTURE

Microalgal systems that are designed for the direct capture and removal of atmospheric CO_2 require a multidisciplinary approach encompassing all of the following: selecting appropriate strains of microalgae for use in such systems; designing suitable reactors; identifying suitable ambient growing conditions; implementing a nutrient management strategy; and utilizing appropriate methods to deliver CO_2 to the growing microalgal culture. Genetic engineering advances, reactor optimization strategies, and integrated system designs must all be developed in order to improve the efficiency and scalability of microalgal systems (Abdul Kareem Joyia et al., 2024). By providing solutions to these challenges, microalgal systems could significantly mitigate climate change through the large-scale removal of CO_2 from the atmosphere. Ambient operational factors (e.g., light level, temperature, pH level, nutrient concentrations, and gas flow rates) can considerably impact how effectively microalgal systems capture, use, and store CO_2. Proper light levels are critical for ensuring adequate levels of photosynthesis while avoiding the occurrence of photoinhibition (Razzak et al., 2024). To support optimal growth and carbon fixation of the microalgal culture, temperature and pH levels must remain within ranges that are specific to the type of microalgae being cultivated. Nutrient availability (especially nitrogen and phosphorus) directly impacts the amount of biomass produced, while the gas flow rate determines how efficient the CO_2 mass transfer is. Consistent and precise modifications and controls applied to these ambient operational factors can increase overall CO_2 uptake for microalgal systems (Wang et al., 2026). Photosynthesis in microalgae is dependent on an adequate level of light; however, too much light causes photoinhibition resulting in lower growth and CO_2 uptake. To achieve maximum growth and CO_2 capture, studies indicate that optimal light intensity is critical. For instance, high levels of light can induce oxidative stress while low levels of light can impair the rate of photosynthesis (Yahaya et al., 2024). The photoperiod or duration of light also contributes to algal growth, as excessive or insufficient light cycles can negatively affect this. Therefore, optimizing photoperiods for different microalgal strains improves CO_2 capture by optimally balancing energy absorption and metabolic processes (Wang et al., 2026). Temperature affects the solubility of CO_2 in water and the activity of enzymes, which is why the optimal temperature range for most species of microalgae is between 20°C and 30°C; any temperature change outside of this range will negatively affect growth and photosynthesis. The pH of the growth medium directly impacts the availability of dissolved CO_2 for microalgae to use to photosynthesize. Therefore, maintaining pH between 6.5 and 7.5 during the growth of microalgae allows for the solubility of CO_2, which is crucial to photosynthesis; if pH increases to above this range, the CO_2 will convert into bicarbonate (HCO_3^-), which will make it difficult for microalgae to access CO_2 (Liu et al., 2021). Many nutrients, including vitamins, trace metals, phosphorus and nitrogen, are essential for microalgal growth. Nutrient availability will determine the efficiency of CO_2 sequestration and production of algal biomass (Chowdhury et al., 2026). Microalgae will change their metabolic pathways to produce more lipids for biofuels when nutrients are low. However, this may limit total growth and biomass yield and subsequently limit CO_2 capture by microalgae (Rawat et al., 2013). Inherent genetic and metabolic characteristics are the two primary factors influencing the efficiency of microalgal CO_2 capture. Photosynthetic efficiency, the efficiency with which light energy is converted to chemical energy, is critical in determining the efficiency of microalgae for CO_2 capture (Mohapatra et al., 2022). Furthermore, many microalgal species utilize carbon concentrating mechanisms (CCMs) which improve internal CO_2 levels and increase the efficiency of carbon fixation when atmospheric CO_2 concentrations are low (Kolachalama et al., 2025).

Recent advances in metabolic and genetic engineering have made it possible to engineer microalgal strains for improved CO_2 capture using several methods: enhancing CCM expression, overexpressing key enzymes from the Calvin Cycle, and enhancing the ability of microalgal strains to resist oxidative stress resulting from high rates of photosynthesis (Zhang et al., 2025).

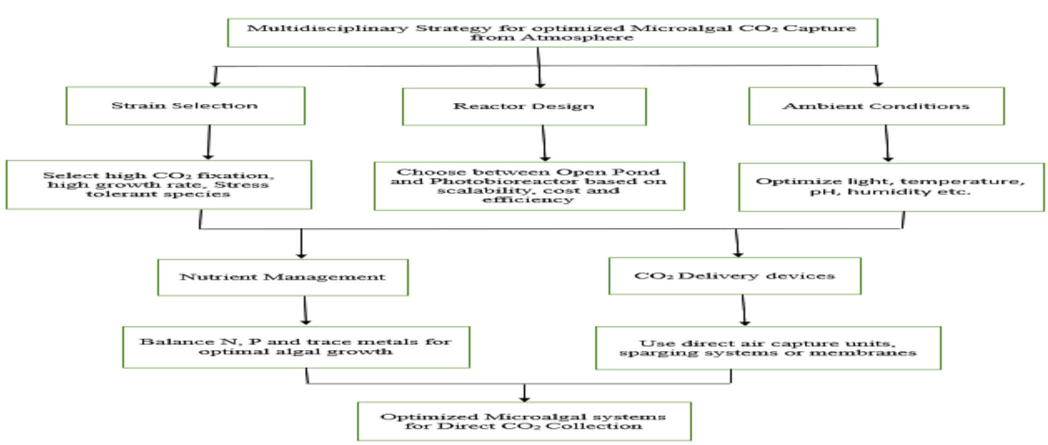

Figure 2: Multidisciplinary strategy for optimized microalgal CO_2 capture from the atmosphere.

The purpose of these modifications is to improve biomass production and carbon fixation rates of bio-classifying methods under widely varying conditions typically associated with atmospheric carbon capture. Advanced sensor implementation along with real-time monitoring capabilities can provide the ability to control and adjust crop growing conditions as required to optimize the efficiency of CO_2 capture. Utilizing a feedback control system with dissolved oxygen levels, pH and concentration of CO_2 will help stabilize and increase the amount of organic biomass generated (Yahaya et al., 2024). By automating the operation of

(ISSN: 0973-7049(P))

The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES

21(3): S.I (3), 1483-1494, 2026

www.thebioscan.com

these bioprodcts, there will be reduced need for human labour and therefore far greater potential scalability for microalgal DAC systems to be commercially realised. In addition, microalgal based DAC systems can complement and enhance other traditional chemical and physical forms of capturing carbon dioxide (Eldiehy et al., 2022). For instance, in order to improve both the overall efficiency of capturing CO_2 and making the conversion processes more versatile, hybrid DAC systems could incorporate membrane separation, adsorbents or solvent-based capture either downstream or alongside microalgal cultivation (Vatanpour et al., 2024). By utilising the strengths of each of these different technologies, integrating them together could result in a more efficient and cost-effective way of capturing CO_2.

5. CHALLENGES AND LIMITATION

Although it is usually known that microalgae can reduce CO_2 in atmosphere, the carbon sequestration process is reliant on on a number of other conditions. Algal systems, in particular microalgae, have been suggested as a feasible technique for Direct Air Capture (DAC) of CO_2 from the atmosphere. For these technologies to be practical for large-scale carbon capture, a number of obstacles need to be removed (Bajpai et al., 2022). The obstacles related with algae-based carbon capture systems include poor carbon di oxide concentration efficiency, scaling up algal systems, harvesting and biomass processing, water and fertilizer requirements, technoeconomic viability and light limitation. One of the primary challenges in direct air CO_2 capture using microalgae is the extremely low concentration of CO_2 in ambient air (~0.04%), which limits the rate of diffusion into the culture medium. This creates mass transfer limitations that reduce overall carbon fixation efficiency (Kumar et al., 2023). For the best growth, microalgae need a steady and enough supply of CO_2. The effectiveness of carbon sequestration can be impacted by variations in CO_2 levels in natural settings (Yan et al., 2024). Microalgae are being researched as a means to capture carbon dioxide (CO_2) on a large scale, but transferring this technology from the laboratory to the field remains a challenge (Handayani et al., 2026). Key parameters affecting the scalability of microalgal-based CO_2 capture include the availability of sunlight, water, and nutrients, as well as the presence of appropriate land or water resources (Biswas et al., 2025). However, the most obstructive challenge facing the large-scale use of microalgae for CO_2 capture is the energy and cost associated with efficiently separating the vast quantities of freshwater and seawater from microalgal biomass (Elsafi et al., 2025). Through the use of various mitigation strategies - including increasing airflow rates, incorporation of membrane contactors, and maximising the surface area of the gas-liquid interface - it is possible to enhance the transfer of CO_2 to microalgal cultures (Torres et al. 2015). Once harvested from the cultivation unit, microalgae must be transformed or processed to arrive at a stable end product for long-term carbon storage, which introduces additional technical challenges (Daneshvar et al., 2022). Microalgae are also susceptible to contamination from invasive species and/or other anti-microbial organisms that compete with microalgae for nutrients or otherwise affect the performance of the CO_2 capture system both in open(agriculture-style) and semi-open (caged, coloured) cultivation setups. Containment of single species (monoculture) becomes very difficult; therefore, management strategies for controlling contamination, such as sterilization, selectivity in the growth conditions and the use of very robust strains, are of paramount importance to the continued reliability of the microalgal CO_2 capture system (Hossain et al., 2019). Microalgae CO_2 Capture Systems: Energy inputs necessary for maintaining suitable performance measures, such as those for photobioreactor production e.g., lighting, mixing and CO_2 delivery, are all major determinants of microalgal CO_2 Capture System Economies of Scale (Alsalal et al., 2025). Building and operating photobioreactors alsoontribute to overall expense; these factors lead to many challenges toward large-scale commercialization of the technology. (Thevarajah et al., 2025). The results from economic analyses show an explicit need for significant cost reduction through new technologies and the integration of microalgal biomass production into the economy (i.e., biomass valorization) to ensure successful commercialization of the technology. Sustainability assessments, which include lifecycle assessment (LCA), are required to accurately estimate the net environmental benefits of microalgae CO_2 Capture Systems. Factors including energy inputs, water use, nutrient supply and waste management also affect the carbon footprint of a photobioreactor production system. Current studies indicate that if photobioreactor production systems are powered by nonrenewable energy sources, the lifecycle GHG emissions of the system may offset any GHG removal from the atmosphere. Therefore, system design must be based upon a holistic approach (Irfeey et al., 2025).

6. CASE STUDIES AND RECENT ADVANCES

Recently, several pilot projects for carbon dioxide capture using microalgae have been completed. The results of these pilots will demonstrate whether carbon dioxide can be captured in larger quantities, as well as the problems associated with scaling up to a commercial operation (Ramanna et al., 2025). These pilots tend to be focused on optimizing the operational parameters within a real-world environment, as well as integrating pathways for valorising the biomass produced by microalgae reviewed approximately 10 pilot deployments of microalgal CO_2 capture systems located in urban and industrial settings and provided useful information on the performance of these systems, including the performance of various designs; maintenance issues that arise; and cost implications (Chandola et al., 2026).

Additionally, innovations in materials science and reactor engineering have improved the efficiency of microalgal CO_2 capture. Novel light-diffusing polymers and transparent coatings have been developed to increase the light penetration and distribution within the photobioreactors (McLaughlin et al., 2023). As such, these innovations have had a direct and positive effect on the amount of photosynthesis that is occurring within the photobioreactors. Further, advancements in the geometry and modularity of photobioreactor designs will also improve the ability to exchange gases between the microalgae and the atmosphere, increasing both the efficiency of CO_2 capture as well as the ability of these systems to be scaled up in size (Khor et al., 2023).

Integrating Artificial Intelligence (AI) and Machine Learning (ML) into microalgae cultivation systems presents many opportunities to optimize the CO_2 capture process (Razzak et al., 2023). For example, predictive modelling and optimization algorithms applied to large data sets from the sensor networks allow for the dynamic adjustment of parameters that will maximize the system's operational efficiency throughout its lifetime (Dadsena et al., 2026). In this manner, improved control of the processing parameters will lead to reduced energy consumption; thus, accelerating the rate of adaptation of the system to changing environmental conditions (Gill et al., 2025).

7. FUTURE PROSPECTS AND RESEARCH DIRECTION

Innovations in the field of synthetic biology provide new opportunities to design, develop and commercialise microalgae that offer enhanced capabilities to fix carbon and tolerate stress. Nanomaterials can further enhance the delivery of CO_2 and the harvesting of light through modification of the surfaces of reactors and properties of the culture medium (Okeke et al., 2022). Combined biological (microalgae) and synthetic (bio-hybrid) systems are also an exciting means of developing highly efficient and durable platforms for CO_2 capture (Irfan et al., 2025). Even given the substantial advances made within laboratories in the development of microalgal CO_2 capture systems, there are many barriers to scaling these to commercial applications due to the relative high costs, complexities of the processes and operational stability (Komkhum et al., 2026). To bridge the gap from lab to market, interdisciplinary research collaboration, pilot demonstrations, cost-effective materials development and the development of automation technologies are critical (Yeassin et al., 2025). In order to fully realise microalgae-based Direct Air Capture (DAC) systems, it is critical that we address the challenges facing their successful deployment. Additional policy measures such as supportive regulations, government incentives and carbon pricing structures will also play a vital role in ensuring microalgae technology is rapidly adopted for CO_2 capture. Other policies supporting renewable energy development, green technology investments and microalgae capture in carbon markets will create an environment conducive to commercialisation of these technologies (Hanson et al., 2025).

8. CONCLUSION

The purpose of this study is to evaluate the advancements made in creating and refining microalgae-based systems for capturing CO_2 from ambient air, which is the key to an extensive report (Vaziri et al., 2024). Important findings include the relevance of identifying suitable microalgae species to use that are intended to exhibit quality traits and phenotypes in combination with the improvements in PBR [photobioreactor] designs to the importance of appropriately identifying and optimizing all variable operational parameters for maximizing carbon fixation (Cheng et al., 2024). While low ambient CO_2 levels and high costs of production continue to present barriers, the combination and synergistic qualities of utilizing animal genetic engineering to increase efficiency and reproducibility, investing in mechanizing the entire process, and marrying the microalgae to external resources through hybrid systems are likely to reveal new methods of improving CO_2 capture. As microalgal CO_2 sequestration progresses, advancements will likely continue to be made through a combination of innovative and multidisciplined approaches (e.g., biotechnology, different materials of science, artificial intelligence via machine learning, and regulatory support), demonstrating new scalable methods of being able to effectively implement CO_2 capture from the ambient environment (Yang et al., 2025). To realise these systems, containing biological carbon capture, to their fullest potential for assisting climate change mitigation, ongoing research and development will be important considering the existence of regulatory mechanisms that are willing to support continued development.

REFERENCES

- Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., et al. (2023). *Global carbon budget 2023*. **Earth System Science Data, 15**, 5301–5369. https://doi.org/10.5194/essd-15-5301-2023
- Fasihi, M., Efimova, O., & Breyer, C. (2019). *Techno-economic assessment of CO_2 direct air capture plants*. **Journal of Cleaner Production, 224**, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086
- Shan, S., Lv, H., Li, J., Lai, D., Held, C., & Yu, G. (2026). Direct air capture: Advances in materials, processes, and engineering. *Molecular Chemistry & Engineering*, *2*(2), 100040. https://doi.org/10.1016/J.MOCHEM.2026.100040
- Dayanath, W. M. S., Ilankoon, I. M. S. K., Syed Ali, S. A., Chong, M. N., & Foo, S. C. (2026). Microalgae-based direct air capture systems for carbon dioxide emission reductions in developing megacities: A techno-economic and policy analysis. *Journal of Environmental Chemical Engineering*, *14*(3), 122763. https://doi.org/10.1016/J.JECE.2026.122763
- Cheah, W. Y., Show, P. L., Chang, J. S., Ling, T. C., & Juan, J. C. (2015). Biosequestration of atmospheric CO2 and flue gas-containing CO2 by microalgae. *Bioresource Technology*, *184*, 190–201. https://doi.org/10.1016/J.BIORTECH.2014.11.026
- Ahmad, A., & Ashraf, S. S. (2024). Harnessing microalgae: Innovations for achieving UN Sustainable Development Goals and climate resilience. *Journal of Water Process Engineering*, *68*, 106506. https://doi.org/10.1016/J.JWPE.2024.106506
- Raven, J. A., Beardall, J., & Sánchez-Baracaldo, P. (2017). *The possible evolution and future of CO_2-concentrating mechanisms*. **Journal of Experimental Botany, 68**(14), 3701–3716. https://doi.org/10.1093/jxb/erx110
- Thevarajah, B., Nimarshana, P. H. V., Sandeepa, G. D. S., Vivekanand, V., & Ariyadasa, T. U. (2025). Transformation of residual biomass into biofuels at commercial microalgae facilities: A perspective on sustainable energy recovery. *Journal of Environmental Chemical Engineering*, *13*(5), 117551. https://doi.org/10.1016/J.JECE.2025.117551
- Wang, R. L., Li, M. J., & Tao, W. Q. (2026). Advanced technology and applications of small-scale, modular, and distributed biomass direct air capture systems. *Applied Energy*, *406*, 127242. https://doi.org/10.1016/J.APENERGY.2025.127242
- Hashmi, Z., idriss, I. M., Zaini, J., Abu Bakar, M. S., & Bilad, M. R. (2025). Advancements in photobioreactor systems: Optimizing operations for enhanced microalgal growth and bioremediation. *Algal Research*, *91*, 104282. https://doi.org/10.1016/J.ALGAL.2025.104282
- Zainal, B. S., Fattah, I. M. R., Ong, H. C., Muraza, O., Osman, N., & Mahlia, T. M. I. (2026). Recent advancements and assessment of carbon capture technologies for climate crisis mitigation. *Chemical Engineering Journal*, *536*, 175776. https://doi.org/10.1016/J.CEJ.2026.175776
- Singh, J., & Dhar, D. W. (2011). *Microalgae as second generation biofuel: A review*. **Agronomy for Sustainable Development, 31**(4), 605–629. https://doi.org/10.1007/s13593-011-0018-0
- Breyer, C., Fasihi, M., & Aghahosseini, A. (2020). *Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: A new type of energy system sector coupling*. **Energy & Environmental Science, 13**(3), 303–315. https://doi.org/10.1039/c9ee03682a
- Behera, D., Fathima, J., Saady, N. M. C., Zendehboudi, S., Albayati, T. M., Al-nayili, A., Chatterjee, P., Ponnusami, V., Peach, B., & Espinoza, J. E. R. (2026). Sustainable agriculture through environmental adaptation engineering for waste management. *Green Technologies and Sustainability*, *4*(1), 100242. https://doi.org/10.1016/J.GRETS.2025.100242
- Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, *25*(3), 294–306. https://doi.org/10.1016/J.BIOTECHADV.2007.02.001
- Wang, B., Li, Y., Wu, N., & Lan, C. Q. (2008). CO_2 bio-mitigation using microalgae. *Applied Microbiology and Biotechnology, 79*(5), 707–718. https://doi.org/10.1007/s00253-008-1518-y
- Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*, *14*(2), 557–577. https://doi.org/10.1016/J.RSER.2009.10.009
- Wang, R. L., Li, M. J., Martin, G. J. O., & Kentish, S. E. (2025). Enhancing direct air carbon capture into microalgae: A membrane sparger design with carbonic anhydrase integration. *Algal Research*, *85*, 103875. https://doi.org/10.1016/J.ALGAL.2024.103875
- IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (H. Lee & J. Romero, Eds.). Intergovernmental Panel on Climate Change. https://doi.org/10.59327/IPCC/AR6-9789291691647
- *The economics of climate innovation: technology, climate policy, and the clean energy transition*. (2026). *2*, 221–383. https://doi.org/10.1016/BS.HESECC.2026.02.003
- Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). *A process for capturing CO_2 from the atmosphere*. **Joule, 2**(8), 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006
- Seyyedattar, M., & Zendehboudi, S. (2026). Carbon capture and storage: A comprehensive review on current trends, techniques, and future prospects in North America. *Fuel*, *407*, 137276. https://doi.org/10.1016/J.FUEL.2025.137276

- Pittman, J. K., Dean, A. P., & Osundeko, O. (2011). The potential of sustainable algal biofuel production using wastewater resources.

  Bioresource Technology, *102*(1), 17–25. https://doi.org/10.1016/J.BIORTECH.2010.06.035
- Thanigaivel, S., Vickram, S., Manikandan, S., Deena, S. R., Subbaiya, R., Karmegam, N., Govarthanan, M., & Kim, W. (2022). Sustainability and carbon neutralization trends in microalgae bioenergy production from wastewater treatment: A review. *Bioresource Technology*, *364*, 128057. https://doi.org/10.1016/J.BIORTECH.2022.128057
- Esfandiari, M., Zare, S., Habibi, T., & Mirfendereski, S. M. (2026). Experimental carbon dioxide biofixation and biomass production by microalgae. *Cleaner Chemical Engineering*, *13*, 100218. https://doi.org/10.1016/j.clce.2026.100218.
- Hidalgo, D., Martín-Marroquín, J. M., Garrote, L., & Corona, F. (2026). Microalgal cultivation systems for wastewater treatment and carbon sequestration. *Sustainable Production of Microalgae Biomass as a Biodiesel Feedstock*, 153–202. https://doi.org/10.1016/B978-0-443-29269-9.00012-5
- Rahman, A., Fares, A., Veettil, A. V., Mohtar, R., & Awal, R. (2025). A critical review of the microalgae and cyanobacteria-based biofertilizers: An insight into the cost effectiveness of different algae cultivation strategies. *Environmental Technology & Innovation*, *40*, 104480. https://doi.org/10.1016/j.eti.2025.104480
- Khoshnevisan, B., He, L., Xu, M., Valverde-Pérez, B., Sillman, J., Mitraka, G. C., Kougias, P. G., Zhang, Y., Yan, S., Ji, L., Carbajales-Dale, M., Elyasi, S. N., Marami, H., Tsapekos, P., Liu, H., & Angelidaki, I. (2022). From renewable energy to sustainable protein sources: Advancement, challenges, and future roadmaps. *Renewable and Sustainable Energy Reviews*, *157*, 112041. https://doi.org/10.1016/J.RSER.2021.112041
- Chong, C. C., Cheng, Y. W., Ishak, S., Lam, M. K., Lim, J. W., Tan, I. S., Show, P. L., & Lee, K. T. (2022). Anaerobic digestate as a low-cost nutrient source for sustainable microalgae cultivation: A way forward through waste valorization approach. *Science of The Total Environment*, *803*, 150070. https://doi.org/10.1016/J.SCITOTENV.2021.150070
- Alsalal, A. M., Almomani, F., & Alkanaimsh, S. (2025). Harnessing microalgae for a synergistic approach to CO2capture, wastewater treatment, and biodiesel production: A review. *Journal of Environmental Chemical Engineering*, *13*(5), 117465. https://doi.org/10.1016/J.JECE.2025.117465
- Zheng-qi Hou, Ming-yu Luo, Yi-ting Yang, Ji-cheng Zhou, Li-cheng Liu, Jin-jun Cai, Algae-based carbons: Design, preparation and recent advances in their use in energy storage, catalysis and adsorption, New Carbon Materials, Volume 36, Issue 2, 2021, Pages 278-303, ISSN 1872-5805, https://doi.org/10.1016/S1872-5805(21)60020-3.
- Alami, A. H., Alasad, S., Ali, M., & Alshamsi, M. (2021). Investigating algae for CO2 capture and accumulation and simultaneous production of biomass for biodiesel production. *Science of The Total Environment*, *759*, 143529. https://doi.org/10.1016/J.SCITOTENV.2020.143529
- Ashok Ganesan, Prachi Nawkarkar, Shashi Kumar, Chapter 17 - Algal biodiesel: technology, hurdles, and future directions, Editor(s): Sanjay Sahay,Handbook of Biofuels, Academic Press, 2022, Pages 331-351, ISBN 9780128228104, https://doi.org/10.1016/B978-0-12-822810-4.00017-8.
- Shen, Y. (n.d.). *Carbon Dioxide Bio-fixation and Wastewater Treatment via Algae Photochemical Synthesis for Biofuels Production 2*. Retrieved www.rsc.org/advances
- Bercel, T. L., & Kranz, S. A. (2019). Insights into carbon acquisition and photosynthesis in Karenia brevis under a range of CO2 concentrations. *Progress in Oceanography*, *172*, 65–76. https://doi.org/10.1016/J.POCEAN.2019.01.011
- Swastik Paul, Souhardya Bera, Rishav Dasgupta, Shibsankar Mondal, Subhasis Roy, Review on the recent structural advances in open and closed systems for carbon capture through algae, Energy Nexus, Volume 4, 2021, 100032, ISSN 2772-4271, https://doi.org/10.1016/j.nexus.2021.100032
- Li, S., Li, X., & Ho, S. H. (2022). Microalgae as a solution of third world energy crisis for biofuels production from wastewater toward carbon neutrality: An updated review. *Chemosphere*, *291*. https://doi.org/10.1016/j.chemosphere.2021.132863
- Prasad R, Gupta SK, Shabnam N, Oliveira CYB, Nema AK, Ansari FA, Bux F. Role of Microalgae in Global CO_2 Sequestration: Physiological Mechanism, Recent Development, Challenges, and Future Prospective, Sustainability, 2021; 13(23):13061. https://doi.org/10.3390/su132313061
- Kumar, P., Arora, K., Chanana, I., Kulshreshtha, S., Thakur, V., & Choi, K. Y. (2023). Comparative study on conventional and microalgae-based air purifiers: Paving the way for sustainable green spaces. *Journal of Environmental Chemical Engineering*, *11*(6), 111046. https://doi.org/10.1016/J.JECE.2023.111046
- Pekkoh, J., Ruangrit, K., Aurepatipan, N., Duangjana, K., Sensupa, S., Pumas, C., Chaichana, C., Pathom-aree, W., Kato, Y., & Srinuanpan, S. (2024). CO2 to green fuel converter: Photoautotrophic-cultivation of microalgae and its lipids conversion to biodiesel. *Renewable Energy*, *222*, 119919. https://doi.org/10.1016/J.RENENE.2023.119919
- Abdullah, M., Ali, Z., Yasin, M. T., Amanat, K., Sarwar, F., Khan, J., & Ahmad, K. (2024). Advancements in sustainable production of biofuel by microalgae: Recent insights and future directions. *Environmental Research*, *262*, 119902. https://doi.org/10.1016/J.ENVRES.2024.119902
- Shan Liu, Leipeng Cao, Fuqing Xu, Liangcheng Yang, Yebo Li, Okopi Solomon Inalegwu, Chapter Five - Integration of algae cultivation to anaerobic digestion for biofuel and bioenergy production, Editor(s): Yebo Li, Wenguang Zhou, Advances in Bioenergy, Elsevier, Volume 6, Issue 1, 2021, Pages 199-300, ISSN 2468-0125, ISBN 9780128240281, https://doi.org/10.1016/bs.aibe.2021.06.002.
- Skifa, I., Chauchat, N., Cocquet, P.-H., & Guer, Y. le. (2025). Microalgae cultivation in raceway ponds: Advances, challenges, and hydrodynamic considerations. *EFB Bioeconomy Journal*, *5*, 100073. https://doi.org/10.1016/J.BIOECO.2024.100073
- Roy, G., Gautam, M. K., Bobde, K., Mondal, D., & Mondal, S. (2026). A conceptual framework for algal-based membrane bioreactors (AMBR) in the removal of pharmaceutical micropollutants from wastewater. *Cleaner Water*, *6*, 100263. https://doi.org/10.1016/J.CLWAT.2026.100263
- Razzak, S. A., Hossain, M. M., Lucky, R. A., Bassi, A. S., & de Lasa, H. (2013). Integrated CO2 capture, wastewater treatment and biofuel production by microalgae culturing—A review. *Renewable and Sustainable Energy Reviews*, *27*, 622–653. https://doi.org/10.1016/J.RSER.2013.05.063
- Yadav, G., Dubey, B. K., & Sen, R. (2020). A comparative life cycle assessment of microalgae production by CO2 sequestration from flue gas in outdoor raceway ponds under batch and semi-continuous regime. *Journal of Cleaner Production*, *258*, 120703. https://doi.org/10.1016/J.JCLEPRO.2020.120703
- Carvalho, A. P., Meireles, L. A., & Malcata, F. X. (2006). *Microalgal reactors: A review of enclosed system designs and performances*. **Biotechnology Progress, 22**(6), 1490–1506. https://doi.org/10.1021/bp060065r
- Ugwu, C. U., Aoyagi, H., & Uchiyama, H. (2008). *Photobioreactors for mass cultivation of algae*. **Bioresource Technology, 99**(10), 4021–4028. https://doi.org/10.1016/j.biortech.2007.01.046
- Chandola, G., Muthuraj, M., Mandal, S., Vismaya, P. S., & Bhunia, B. (2026). Engineering advances in tubular photobioreactors for microalgae cultivation: Design, scale-up, optimization, and operational challenges. *Renewable and Sustainable Energy Reviews*, *231*, 116776. https://doi.org/10.1016/J.RSER.2026.116776
- Soudagar, M. E. M., Kiong, T. S., Jathar, L., Nik Ghazali, N. N., Ramesh, S., Awasarmol, U., & Ong, H. C. (2024). Perspectives on cultivation and harvesting technologies of microalgae, towards environmental sustainability and life cycle analysis. *Chemosphere*,

353, 141540. https://doi.org/10.1016/J.CHEMOSPHERE.2024.141540

- Michael, M., Vanness, V., Henry, H., Tjandra, T. M., Kristian, K., Nasution, J. A., Masytha, M., Sidabutar, R., Trisakti, B., Irvan, I., Dalimunthe, N. F., al Fath, M. T., Nabilah, Y., Kobayashi, T., Daimon, H., & Takriff, M. S. (2026). Microalgae for sustainable biodiesel and omega-3: A comprehensive review of production, processing, and implementation. *Renewable and Sustainable Energy Reviews*, *226*, 116327. https://doi.org/10.1016/J.RSER.2025.116327
- Shokravi, Z., & Mehravar, N. (2025). Optimization of photobioreactor and open pond systems for sustainable microalgal biomass production: Challenges, solutions, and scalability. *Microalgal Biofuels: Sustainable Production, Conversion, and Life Cycle Assessment*, 45–62. https://doi.org/10.1016/B978-0-443-24110-9.00003-7
- Zou, C., Zhang, C., Cheng, J., Lyu, W., Jin, X., Gao, M., Wu, S., Yu, H., Yu, H., Yang, Z., Sang, G., Zhang, L., Liu, H., & Wang, K. (2025). Advances, challenges, and prospects of carbon dioxide capture, utilization, and storage technologies for carbon neutrality. *Petroleum Exploration and Development*, *52*(6), 1664–1684. https://doi.org/10.1016/S1876-3804(26)60669-6
- Wang, R. L., Li, M. J., Li, D., & Yang, Y. W. (2022). The synergy of light/fluid flow and membrane modification of a novel membrane microalgal photobioreactor for direct air carbon capture. *Applied Energy*, *328*, 120133. https://doi.org/10.1016/J.APENERGY.2022.120133
- Russell, C., Krishnamoorthy, A., & Rodriguez, C. (2025). Algae Production Technologies. *Comprehensive Green Materials*, 24–51. https://doi.org/10.1016/B978-0-443-15738-7.00075-1
- Cagla Yarkent, Ceren Gürlek Kliber, Cecilia Faraloni, Graziella Chini Zittelli, Eleftherios Touloupakis, Isabela Calegari Moia, Giuseppe Torzillo, Jiří Masojídek, Karolína Štěrbová, Kumar Saurav, Suphi S. Oncel, Chapter 2 - State-of-the-art: microalgae production systems and microalgae applications, Editor(s): José Carlos Magalhães Pires, Ana Filipa Cruz Esteves, Eva Margarida de Azevedo Campos Salgado, In Woodhead Series Advances in Pollution Research, Advances in Sustainable Applications of Microalgae Elsevier Science Ltd, 2025, Pages 37-70, ISBN 9780443221279, https://doi.org/10.1016/B978-0-443-22127-9.00002-0.
- Shilalipi Samantaray, Shankha Koley, Baishnab C. Tripathy, Nirupama Mallick, Contiguous supplementation of bicarbonate and carbon dioxide to improve carbon utilization efficiency and biodiesel production from a single-cell alga Chlamydomonas reinhardtii, Renewable Energy, Volume 245, 2025, 122779, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2025.122779.
- Emmanuel Yahaya, Wan Sieng Yeo, Jobrun Nandong, Process modeling and 3-stage photobioreactor design for algae cultivation and CO2 capture: A case study using palm oil mill effluent, Biochemical Engineering Journal, Volume 212, 2024,109532, ISSN 1369-703X, https://doi.org/10.1016/j.bej.2024.109532.
- Zhang, X., Wang, W., Gu, X., Ji, J., & Hua, W. (2025). Advance in storage and utilization of CO2 for CCUS. *Journal of Environmental Chemical Engineering*, *13*(6), 120446. https://doi.org/10.1016/J.JECE.2025.120446
- Li, F., Li, W., Huang, W., Jin, H., Cheng, C., & Xue, C. (2025). Metal-organic frameworks (MOFs) for enhanced biological CO2 fixation: Advances and applications in enzyme catalysis and living cell applications. *Biotechnology Advances*, *83*, 108632. https://doi.org/10.1016/J.BIOTECHADV.2025.108632
- Deepika, C. (2025). Advancing sustainability: Microalgae biofuels in the circular bioeconomy. *Microalgal Biofuels: Sustainable Production, Conversion, and Life Cycle Assessment*, 505–549. https://doi.org/10.1016/B978-0-443-24110-9.00023-2
- Omokaro, G. O., Nafula, Z. S., Iloabuchi, N. E., Chikukula, A. A., Osayogie, O. G., & Nnoli, E. C. (2025). Microalgae as biofactories for sustainable applications: Advancing carbon sequestration, bioenergy, and environmental remediation. *Sustainable Chemistry for Climate Action*, *7*, 100098. https://doi.org/10.1016/J.SCCA.2025.100098
- Abdul Kareem Joyia, M., Ahmad, M., Chen, Y. F., Mustaqeem, M., Ali, A., Abbas, A., & Ashraf Gondal, M. (2024). Trends and advances in sustainable bioethanol production technologies from first to fourth generation: A critical review. *Energy Conversion and Management*, *321*, 119037. https://doi.org/10.1016/J.ENCONMAN.2024.119037
- Abdur Razzak, S., Bahar, K., Islam, K. M. O., Haniffa, A. K., Faruque, M. O., Hossain, S. M. Z., & Hossain, M. M. (2024). Microalgae cultivation in photobioreactors: sustainable solutions for a greener future. *Green Chemical Engineering*, *5*(4), 418–439. https://doi.org/10.1016/J.GCE.2023.10.004
- Wang, R. L., Li, M. J., & Tao, W. Q. (2026). Advanced technology and applications of small-scale, modular, and distributed biomass direct air capture systems. *Applied Energy*, *406*, 127242. https://doi.org/10.1016/J.APENERGY.2025.127242
- Chowdhury, M., Dhar, H., Debi, D., Dutta, E., Hossain, S., Acharjee, S., Ayoun, M. A., Mustaquim, Md. S., Nur, S., Minhaz, T. M., & Khatoon, H. (2026). Evaluation of carbon dioxide biosequestration capacity, biomass productivity, and biochemical composition of Gonyostomum sp. in total dissolved CO2 levels. *Results in Chemistry*, *26*, 103304. https://doi.org/10.1016/J.RECHEM.2026.103304
- Rawat, R. Ranjith Kumar, T. Mutanda, F. Bux, Biodiesel from microalgae: A critical evaluation from laboratory to large scale production, Applied Energy, Volume 103, 2013, Pages 444-467, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2012.10.004.
- Mohapatra, R. K., Padhi, D., Sen, R., & Nayak, M. (2022). Bio-inspired CO2 capture and utilization by microalgae for bioenergy feedstock production: A greener approach for environmental protection. *Bioresource Technology Reports*, *19*, 101116. https://doi.org/10.1016/J.BITEB.2022.101116
- Kolachalama, D., & Krishnamoorthy, S. (2025). Harnessing microalgae for biodesalination and CO2 sequestration toward integrated water-carbon solutions. *Journal of Environmental Chemical Engineering*, *13*(6), 120214. https://doi.org/10.1016/J.JECE.2025.120214
- Eldiehy, K. S. H., Bardhan, P., Borah, D., Gohain, M., Ahmad Rather, M., Deka, D., & Mandal, M. (2022). A comprehensive review on microalgal biomass production and processing for biodiesel production. *Fuel*, *324*, 124773. https://doi.org/10.1016/J.FUEL.2022.124773
- Vatanpour, V., Salimi Khaligh, S., Sertgumec, S., Ceylan-Perver, G., Yuksekdag, A., Yavuzturk Gul, B., Altinbas, M., & Koyuncu, I. (2024). A review on algal biomass dewatering and recovery of microalgal-based valuable products with different membrane technologies. *Journal of Environmental Management*, *371*, 123182. https://doi.org/10.1016/J.JENVMAN.2024.123182
- Sushant Bajpai, Nehil Shreyash, Sukriti Singh, Amir Rauf Memon, Muskan Sonker, Saurabh Kr Tiwary, Susham Biswas, Opportunities, challenges and the way ahead for carbon capture, utilization and sequestration (CCUS) by the hydrocarbon industry: Towards a sustainable future, Energy Reports, Volume 8, 2022, Pages 15595-15616, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2022.11.023.
- Luming Yan, Shengyuan Xue, Jianbin Cha, Xin Wen, Bukai Wang, Jingqi Shi, Panyu Li, Yongkui Zhang, Tonghui Xie, Effect of excess CO2 on semi-continuous microalgae systems: Carbon biofixation, Environmental Technology & Innovation, Volume 35, 2024, 103645, ISSN 2352-1864, https://doi.org/10.1016/j.eti.2024.103645
- Handayani, T., Prasetiyadi, P., Sitomurni, A. I., Rifai, A., Nuha, N., Barkah, A., Pinardi, D., Sahwan, F. L., Wahyono, S., Suryanto, F., Suprapto, S., Diyono, D., Rochman, F. F., Susanto, J. P., Hanif, M., Sudinda, T. W., & Tjokrokusumo, D. (2026). Integrated carbon dioxide capture and nutrient removal from food waste digestate: A microalgae-assisted process in a smart photobioreactor for enhanced environmental performance. *Biomass and Bioenergy*, *211*, 109202. https://doi.org/10.1016/J.BIOMBIOE.2026.109202
- Biswas, S., Muruganandam, L., & Ganesh Moorthy, I. (2025). Innovations and strategies for sustainable wastewater-integrated microalgal biodiesel production. *Current Research in Biotechnology*, *10*, 100335. https://doi.org/10.1016/J.CRBIOT.2025.100335

(ISSN: 0973-7049(P))

The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
21(3): S.I (3), 1483-1494, 2026
www.thebioscan.com

- Elsafi, M., Ho, Y. C., Beh, H. G., Thant, M. M. M., & Hassaballa, A. (2025). Reviewing microalgae research for carbon sequestration and biochar production to reduce carbon footprints and achieve carbon neutrality. In M. H. Hasan, H. Mohamad, S. J. Abdulkadir, & N. Shafiq (Eds.), *Proceedings of the International Conference on Smart Cities—Volume 1* (Lecture Notes in Civil Engineering, Vol. 667). Springer, Singapore. https://doi.org/10.1007/978-981-96-7818-1_36
- Torres, L., Hernández-Hernández, C. J., Saucedo-Lucero, J. O., Aizpuru, A., & Arriaga, S. (2025). CO2 capture and production of biomolecules in a microalgal airlift photobioreactor operated under different hydrodynamic conditions and in presence or in absence of a static magnetic field. *Chemical Engineering Journal*, *524*, 169697. https://doi.org/10.1016/J.CEJ.2025.169697
- Daneshvar, E., Wicker, R. J., Show, P. L., & Bhatnagar, A. (2022). Biologically-mediated carbon capture and utilization by microalgae towards sustainable CO2 biofixation and biomass valorization – A review. *Chemical Engineering Journal*, *427*, 130884. https://doi.org/10.1016/J.CEJ.2021.130884
- Hossain, N., & Mahlia, T. M. I. (2019). Progress in physicochemical parameters of microalgae cultivation for biofuel production. In *Critical Reviews in Biotechnology* (Vol. 39, Issue 6, pp. 835–859). Taylor and Francis Ltd. https://doi.org/10.1080/07388551.2019.1624945
- Irfeey, A. M. M., Rifnas, L. M., & Siriwardana, A. J. M. C. M. (2025). Climate change mitigation potential of algae biofuels. *Microalgal Biofuels: Sustainable Production, Conversion, and Life Cycle Assessment*, 415–438. https://doi.org/10.1016/B978-0-443-24110-9.00019-0
- Ramanna, L., Ansari, F. A., Rawat, I., & Bux, F. (2025). Microalgae-driven carbon sequestration and bio-fertiliser: Steps towards a sustainable future. *Chemical Engineering Journal*, *519*, 164892. https://doi.org/10.1016/J.CEJ.2025.164892
- McLaughlin, H., Littlefield, A. A., Menefee, M., Kinzer, A., Hull, T., Sovacool, B. K., Bazilian, M. D., Kim, J., & Griffiths, S. (2023). Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world. *Renewable and Sustainable Energy Reviews*, *177*, 113215. https://doi.org/10.1016/J.RSER.2023.113215
- Khor, W. H., Kang, H. S., Lim, J. W., Iwamoto, K., Tang, C. H. H., Goh, P. S., Quen, L. K., Shaharuddin, N. M. R. bin, & Lai, N. Y. G. (2022). Microalgae cultivation in offshore floating photobioreactor: State-of-the-art, opportunities and challenges. *Aquacultural Engineering*, *98*, 102269. https://doi.org/10.1016/J.AQUAENG.2022.102269
- Dadsena, L., Maharana, T., & Jujjavarapu, S. E. (2026). Enhancing durability and stability of microbial fuel cells through nanomaterial engineering and artificial intelligence optimization. *Fuel*, *418*, 138686. https://doi.org/10.1016/J.FUEL.2026.138686
- Gill, J. M., Hussain, S. M., Ali, S., Zahoor, A. F., Alasmari, A., Munir, M., Naeem, E., Amjad, M., Yousaf, Z., & Faisal, M. (2025). Optimizing aquaculture sustainability: Microalgae-based co-culture systems for aquaculture wastewater treatment and pollution reduction. *Algal Research*, *92*, 104430. https://doi.org/10.1016/J.ALGAL.2025.104430
- Okeke, E. S., Ejeromedoghene, O., Okoye, C. O., Ezeorba, T. P. C., Nyaruaba, R., Ikechukwu, C. K., Oladipo, A., & Orege, J. I. (2022). Microalgae biorefinery: An integrated route for the sustainable production of high-value-added products. *Energy Conversion and Management: X*, *16*, 100323. https://doi.org/10.1016/J.ECMX.2022.100323
- Irfan, F., Tasnim, N., Razzak, S. A., & Uddin, S. (2025). Advances in capturing carbon and producing bioplastics through the microalgal approach towards a sustainable future: A review. *Journal of Cleaner Production*, *486*, 144576. https://doi.org/10.1016/J.JCLEPRO.2024.144576
- Komkhum, T., Winterburn, J., Wongsirichot, P., Janpum, C., & In-na, P. (2026). Microalgal photobioreactors as living air purifiers for better
- indoor carbon dioxide quality control. *Biomass and Bioenergy*, *211*, 109178. https://doi.org/10.1016/J.BIOMBIOE.2026.109178
- Yeassin, R., Rashid Adnan, M. M., Ahmed Chowdhury, M. M., Mia, A., Jawad Chowdhury Enan, M. A., & Fuad, M. H. (2025). A comprehensive review of biomass and biofuels and their progress
- using digital technologies. *Energy Conversion and Management: X*, *28*, 101254. https://doi.org/10.1016/J.ECMX.2025.101254
- Vaziri, P., Reza Rasaei, M., Seyfoori, S., Zamani, S., Mahmoodi, M., & Sedaee, B. (2024). Advancing carbon capture technologies in CCS: A comprehensive review of pre-combustion processes. *Gas Science and Engineering*, *131*, 205481. https://doi.org/10.1016/J.JGSCE.2024.205481
- Jun Cheng, Yun Huang, Jia Feng, Jing Sun, Junhu Zhou, Kefa Cen, Improving CO2 fixation efficiency by optimizing Chlorella PY-ZU1 culture conditions in sequential bioreactors, Bioresource Technology, Volume 144, 2013, Pages 321-327, ISSN 0960-8524, https://doi.org/10.1016/j.biortech.2013.06.122.
- Yafan Yang, Duxue Wang, Shengpeng He, et al. (2025). *Microscopic-scale modeling of CO_2 sequestration and enhanced oil recovery: Methods, mechanisms, and challenges*. *Computational Energy Science, 2*(1), 10–19. https://doi.org/10.46690/compes.2025.01.03