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The Role of Microalgae in Carbon Capture and Lipid Accumulation: A Mini Review

Eva Musifa, Sriwijaya University, Indonesia

ABSTRACT

The increasing concentration of carbon dioxide (CO_2) in the atmosphere is a major factor driving global climate change. Therefore, effective, sustainable, and environmentally friendly mitigation strategies are needed. Microalgae have emerged as a promising biological solution due to their high photosynthetic capacity to absorb CO_2 and convert it into biomass. This review article aims to examine the role of microalgae in carbon mitigation, focusing on the CO_2 absorption mechanism, the efficiency of the cultivation system, and its relationship to lipid production as a biofuel feedstock. Microalgae utilize the Carbon Concentrating Mechanism (CCM) to increase carbon fixation efficiency, even at low CO_2 concentrations. The absorbed carbon is then converted through the Calvin cycle into organic compounds that serve as precursors for lipid biosynthesis. Microalgae tend to increase lipid accumulation in the form of triacylglycerols (TAGs), which have the potential to be converted into biodiesel. In addition to contributing to carbon sequestration, microalgae also have economic value through the production of biofuels and other high-value compounds, thus supporting the concept of a circular economy. With the right technological development, microalgae have the potential to become an integrated solution for carbon mitigation and renewable energy supply in the future.

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CORRESPONDENCE AUTHOR

evamusifa@mipa.unsri.ac.id

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1. INTRODUCTION

The rise in global carbon dioxide (CO_2) emissions has become a major driver of the intensifying climate crisis. Based on the latest data through early 2026, atmospheric CO_2 concentrations continue to rise, with projections projected to reach an average of 429.4 ppm in 2026, exceeding the safe limit for limiting global warming to below 1.5°C (Nayak et al., 2022; Nogia et al., 2016; Office, 2026). Excess carbon dioxide amplifies the greenhouse effect, leading to rising global temperatures, changing climate patterns, and increasing the frequency of natural disasters such as floods and droughts. Furthermore, high CO_2 concentrations also impact marine ecosystems through ocean acidification, which can damage coral reefs and disrupt marine life (Sun, 2024) Therefore, efforts to reduce CO_2 emissions through the use of renewable energy, energy efficiency, and forest conservation are crucial for maintaining environmental balance and sustainability (Tripathi et al., 2023). Various technologies have been developed to reduce carbon emissions, including physical and chemical approaches to carbon capture and storage. However, these methods are generally expensive and have the potential to cause secondary environmental impacts. Therefore, alternative solutions that are more environmentally friendly, efficient, and sustainable are needed, one of which is the biological approach (Doney et al., 2020).

Microalgae are microscopic photosynthetic organisms with a high capacity to absorb CO_2 through photosynthesis (Khan et al., 2018). Compared to land plants, microalgae have a faster growth rate and higher carbon sequestration efficiency, giving them significant potential as carbon mitigation agents (Ezhumalai et al., 2024). Furthermore, microalgae can be cultivated using various systems such as open ponds and photobioreactors, and can utilize CO_2 waste directly from industrial emission sources at rates rangin from 1.8 to 2.0 CO_2 per kilogram of dry biomass produced (Sarwer et al., 2022). In addition to its role in carbon sequesration, microalgal biomass represents a valuable bioproduct that can be converted into a wide range of commercially relevant products, such as biofuels, animal feed, and high-value bioactive compounds (Siddiki et al., 2022). This makes microalgae a solution that not only contributes to carbon emission reduction but also supports the concept of a circular economy and sustainable development (Santos et al., 2025). Beyond their role in carbon sequestration, microalgae have attracted increasing attention because the captured carbon can be converted into valuable biochemical products, particularly lipids that serve as feedstock for biofuel production.

With these advantages, the use of microalgae as a biological solution for carbon mitigation is an important topic for further study, both in terms of efficiency, technological implementation, and potential for future development. In

addition to their role in carbon capture, microalgae are also known to accumulate high levels of lipids within their cells at around 20-70% of dry cell weight under optimized cultivation conditions (Onyeaka et al., 2021; J. Singh & Dhar, 2019). These lipids can be converted into biofuels such as biodiesel, opening up opportunities for integrating carbon mitigation and renewable energy production. The relationship between carbon capture and lipid production in microalgae lies in the utilization of absorbed carbon for biomass synthesis, including lipid compounds (Feng et al., 2024; Montoya-Vallejo et al., 2023). Under certain conditions, such as nutrient stress, microalgae tend to increase lipid accumulation as an energy storage mechanism (Musifa et al., 2023). Higher CO_2 uptake generally increases biomass production and provides more carbon resources for lipid synthesis. However, a trade-off often exists between rapid cell growth and lipid accumulation, requiring optimization of cultivation conditions.

The resulting microalgal biomass not only plays a role in carbon sequestration but also has economic value because it can be processed into various products (Sarwer et al., 2022). This makes microalgae a solution that not only contributes to carbon emission reduction but also supports the concept of a circular economy and sustainable development (Osman et al., 2023). Although numerous studies have investigated either CO_2 sequestration or lipid production in microalgae, these aspects are often discussed separately. Limited reviews comprehensively examine the interrelationship between carbon capture efficiency, cultivation conditions, and lipid accumulation across different microalgal species. Furthermore, recent advances in cultivation technologies and industrial-scale applications have not been fully integrated into a unified framework (Lim et al., 2024). Therefore, a comprehensive review is needed to synthesize current knowledge and identify future research directions for maximizing both carbon mitigation and biofuel production. Based on this potential, this review aims to critically evaluate the current state of knowledge regarding the use of microalgae as a biological strategy for carbon mitigation and sustainable biofuel production. Specifically, this review synthesizes recent findings on CO_2 sequestration mechanisms, cultivation technologies, environmental factors influencing lipid accumulation, and the challenges associated with large-scale implementation. By integrating these aspects, this review seeks to identify key research gaps and provide future perspectives for optimizing microalgae-based carbon capture and bioenergy systems.

2. METHODS

2.1 Research Design

The study used a modified systematic and narrative review methodology to identify and evaluate the role of carbon capture from microalgae and lipid accumulation. The method was used because it provides a structure and transparent framework for selection, assesment and synthesize of evidence from relevant literature (Musifa et al., 2025).

2.2 Inclusion and Exclusion

The inclusion criteria are articles published from 2015 to 2026, studies focused on carbon capture from microalgae, peer-reviewed articles and studies that used for type of mechanism of lipid accumulation. While, the exclusion criteria are articles not relevant to the topic of microalgae wastewater and incomplete articles.

2.3 Study Selection and Search Strategy

Initial selections was done by screening the title and abstracts of articles obtained from literatures searches. Articles thst met the inclusion criteria were then further evaluated by reading the full text. Literature searches were conducted in several scientific data bases, including PubMed, Scopus, Web of Science and Google Scholar. The keywords udes include “ microalga carbon capture”, “lipid accumulation of microalgae”. The search also included combination of the keywords using logical operators (AND, OR) to expand and refine the searching result.

2.4 Data Extraction and Analysis

Data extracted feom selected article include: the role of microalgae carbon capture and lipid accumulation. The extracted are arranged in tabular form to facilitate analysis. The extacted data were analyzed qualitatively to identify common patterns, successes and challenges in the use of microalgae carbon capture. In addition, eligible articles were analyzed descriptively to develop a comprehensive narrative on microalga carbon capture. The result review ill be synthesized to provide original insights into the type of mechanim pf lipid accumulation and carbon capture dor microalgae.

3. DISCUSSION

3.1 Microalgae as Carbon Capture Agents

Microalgae are single-celled photosynthetic organisms that live in water (both freshwater and marine). During photosynthesis, microalgae absorb CO_2 from the air or industrial exhaust gases and convert it into organic compounds

such as carbohydrates, proteins, pigments, and lipids within the microalgae biomass (U. B. Singh & Ahluwalia, 2012). Microalgae are being viewed as attractive photosynthetic "cell factories" capable of absorbing CO_2 while producing economically valuable biomass. Microalgae also have a fast growth rate, high efficiency (6-20%), and can fix 10-50 times more CO_2 per unit area than terrestrial plants (David et al., 2025).

Table 1: Carbon fixation through microalgae phosynthesis

Indikators	Reported Value	Source
Raceway ponds	20-50 g CO_2/m^2/day	(David et al., 2025)
Well-design photobioreactors (PBRs)	80-100 g CO_2/m^2/day	(Razzak et al., 2023)
System capture	efficiency 40-93.7% in various cultivation systems	(Cheng et al., 2025)
Landscale	13 million acres = 0.5 Gt CO_2/year (theoretical estimate)	(Tripathi et al., 2023)

The table above (Table 1) shows the capacity of microalgae to fix carbon through photosynthesis quantitatively at various scales. The conversion ratio of ±1.3-1.8 kg CO_2 per kg of biomass indicates high carbon assimilation efficiency, consistent with the carbon content of the microalgal biomass This is supported by the estimate that 100 tons of biomass can fix approximately 183 tons of CO_2, reflecting a proportional relationship between biomass accumulation and the amount of carbon fixed through metabolic mechanisms such as the Calvin cycle (Cheng et al., 2025). However, carbon capture efficiencies varying between 40-93.7% indicate that system performance is strongly influenced by cultivation type and operational conditions, with closed systems such as photobioreactors generally outperforming open ponds. On a broader scale, the estimated land requirement of 13 million acres to achieve a mitigation potential of 0.5 gigatons of CO_2 per year underscores the significant potential of microalgae in global emissions reduction, although this figure remains theoretical and depends on technological optimization as well as economic and environmental factors (Tripathi et al., 2023). Although the reported carbon fixation rates demonstrate the remarkable potential of microalgae for carbon capture, several limitations should be considered. Most reported values are obtained under controlled laboratory or pilot-scale conditions where light intensity, temperature, nutrient supply, and CO_2 concentration are optimized. In large-scale outdoor cultivation systems, environmental fluctuations, contamination risks, and self-shading effects can significantly reduce productivity. Moreover, the overall carbon mitigation potential must account for the energy requirements associated with mixing, aeration, harvesting, dewatering, and biomass processing (S. K. Singh et al., 2026). Therefore, the net carbon balance of microalgae-based carbon capture systems depends not only on biological fixation rates but also on process efficiency and lifecycle assessment.

3.2 CO_2 Capture Mechanism

Microalgae absorb CO_2 as the primary carbon source in photosynthesis and are estimated to contribute nearly half of total global photosynthesis. To overcome the limited solubility of CO_2 in water and the low affinity of the RuBisCO enzyme for CO_2, microalgae have developed an organized mechanism known as the Carbon Concentrating Mechanism (Burlacot et al., 2022). This process begins with the entry of inorganic carbon (Ci) in the form of CO_2 and HCO_3^-. CO_2 diffuses passively through the cell membrane, while HCO_3^- is actively transported against the concentration gradient, requiring energy. Microalgae are known to possess various Ci transport systems located in the plasma membrane, chloroplast sheath, and thylakoid membrane (Prasad et al., 2021). Furthermore, CCM functions to increase the internal concentration of HCO_3^- hundreds of times compared to the external environment, which is then converted to CO_2 around the RuBisCO_2 enzyme by carbonic anhydrase, thereby increasing the local CO_2 concentration and suppressing photorespiration (Fei et al., 2021). In green microalgae such as *Chlamydomonas reinhardtii*, this process is localized in specialized structures called pyrenoids, which are rich in RuBisCO_2 and associated with thylakoids (Caspari et al., 2017). Energetically, this mechanism is supported by the light reactions of photosynthesis through cyclic electron flow and oxygen photo reduction, which contribute to the formation of a proton gradient in the thylakoid lumen, as well as the supply of ATP from chloroplast-mitochondria interactions to support active Ci transport. Therefore, CCM allows microalgae to maintain high carbon fixation efficiency even in environmental conditions with low CO_2 concentrations. The CO_2 capture process in microalgae can be described in four sequential steps. First, inorganic carbon enters the cell either through passive diffusion of CO_2 or active transport of HCO_3^-. Second, the accumulated HCO_3^- is transported into the chloroplast where carbonic anhydrase catalyzes its conversion into CO_2. Third, CO_2 is concentrated within the pyrenoid surrounding RuBisCO, thereby increasing the efficiency of carbon fixation. Finally, the fixed carbon enters the Calvin-Benson cycle and is converted into carbohydrates that serve as precursors for cellular growth and lipid biosynthesis.

Table 2:. CO_2 Capture Pathways

Components/Pathways	Main Role in CO_2 Capture	Source
Passive CO_2 diffusion	Bseline entry of dissolved CO_2 into cells; can sustain fixation at air-level CO_2 in some models	(Beardall & Raven, 2020)
Actice HCO_3-/CO_2 transport	Energy-dependent Ci (CO_2 + HCO_3^-) uptake across plasma, chloroplast, and thylakoid membranes; builds intracellular Ci pool, core of CCM	(Burlacot et al., 2022)
Carbon anhydrase (CA)	Rapid $CO_2 \rightleftharpoons HCO_3^-$ interconversion; enables HCO_3^- accumulation and local CO_2 release near Rubisco	(Kupriyanova et al., 2023)
Pyrenoid (Rubisco-rich)	Microcompartment concentrating Rubisco and CA; local CO_2 "reaction chamber" for fixation	(Prasad et al., 2021)

Table 2 depicts the CO_2 capture and fixation in microalgae occurs through coordinated components and pathways to support photosynthetic efficiency. The process begins with passive diffusion of CO_2 into the cell as the initial step in the entry of inorganic carbon, which is then reinforced by the active transport system HCO_3^-/CO_2 to increase the intracellular concentration of Ci (inorganic carbon) as the basis of the Carbon Concentrating Mechanism. On the other sides, the enzyme carbonic anhydrase plays a role in rapidly catalyzing the interconversion of CO_2 and HCO_3^- around the enzyme RuBisCO (Spalding, 2008), thus ensuring high availability of CO_2 at the fixation site. In many microalgae, especially green algae, this process is localized in the pyrenoid, a RuBisCO-rich compartment that functions as a "reaction chamber" with a high CO_2 concentration (Y. Wang et al., 2015). The concentrated CO_2 is then fixed through the Calvin–Benson Cycle into organic compounds such as sugars. This entire process is supported by alternative energy supply pathways, such as cyclic electron flow (CEF) and oxygen photoreduction, which play a role in generating a proton gradient (ΔpH) and ATP to drive the CCM mechanism (Fei et al., 2021). By integrating these pathways, microalgae are able to maintain high efficiency in CO_2 capture and conversion, even in environmental conditions with limited carbon availability.

The efficiency of the CCM is strongly influenced by environmental conditions. Under low CO_2 concentrations, microalgae upregulate bicarbonate transporters and carbonic anhydrase activity to maintain sufficient carbon supply for photosynthesis. Light intensity also plays a crucial role because ATP and reducing power generated during the light reactions are required to support active Ci transport. Temperature affects enzyme activity and membrane transport processes, whereas nutrient availability, particularly nitrogen and phosphorus, influences the allocation of assimilated carbon toward growth or storage compounds. Consequently, the effectiveness of CO_2 capture is determined not only by cellular mechanisms but also by environmental regulation. Although CCM significantly enhances carbon fixation efficiency, maintaining active Ci transport requires substantial energy expenditure (Kupriyanova et al., 2023). Therefore, under certain conditions, the energetic cost of operating CCM may reduce overall biomass productivity. This trade-off between carbon acquisition and cellular energy demand remains an important consideration in the optimization of large-scale microalgae cultivation systems.

3.3 Lipid Accumulation on Microalgae

Microalgae convert CO_2 into lipid-rich biomass that can be utilized in various sectors, including food, healthcare, and biodiesel production. The types of lipids produced are highly diverse, but are generally dominated by triglycerides (TAGs), phospholipids, and glycolipids, which play a vital role in cell structure and as energy reserves. The accumulation of these lipids is strongly influenced by environmental conditions, such as nutrient limitations (especially nitrogen), light intensity, and other environmental stresses that can shift cellular metabolism from growth to energy storage in the form of lipids. Furthermore, the composition of the fatty acids produced, such as saturated and unsaturated fatty acids, determines the quality of microalgae as a raw material for biofuels and nutraceutical products. Therefore, the ability of microalgae to convert CO_2 into high-value lipids not only supports carbon sequestration through photosynthesis but also strengthens their potential as a sustainable raw material source in the bioenergy and bioproduct industries (Zienkiewicz et al., 2016).

Lipid accumulation in microalgae is commonly triggered by environmental stress conditions, particularly nitrogen limitation. Under nitrogen-replete conditions, photosynthetically fixed carbon is primarily directed toward protein synthesis and cell division. However, when nitrogen becomes limiting, protein synthesis decreases while photosynthesis may continue, leading to excess carbon and reducing equivalents within the cell. To prevent metabolic imbalance and oxidative damage, microalgae redirect carbon flux toward the synthesis of neutral lipids, especially triacylglycerols

(TAGs), which function as carbon and energy storage molecules. Similar responses can also be induced by phosphorus limitation, salinity stress, high light intensity, and temperature stress (Musifa et al., 2023).

Table 3: Main Microalgal Lipid Types and Functions

Lipid Groups	Example & Features	Main functions	Source
Triacylglycerols (TAG) / neutral lipids	20–50% DW typically; up to ≥80% in some strains; often C16–C18 FA rich	Energy reserve; main biodiesel feedstock via transesterification to FAME	(Ye et al., 2024)
Saturated & unsaturated fatty acids (C16-C18)	C16:O, C18:O, C18:1; essential for biodiesel quality	C16:O, C18:O, C18:1; essential for biodiesel quality	(Udayan et al., 2022)
PuFA omega-3	EPA, DHA, ALA, LA; for cardiovascular/brain health	EPA, DHA, ALA, LA; for cardiovascular/brain health	(Maltsev et al., 2021)
Polar lipids (phospholipid, glykolipid)	Structural membrane lipids organizing light-harvesting complexes	Maintain photosynthetic membranes; source of PUFAs that can be remodeled into TAG under stress	(Udayan et al., 2022)
Carotenoid (lutein, β-karoten, astaxanthin)	Strongly light-regulated; can reach 4–14% DW in some species	Pigments and antioxidants for food, cosmetics, and pharma	(Khan et al., 2018)

The lipid composition of microalgae reflects the diversity of biological functions and their potential applications in various industrial sectors. Neutral lipids, particularly triacylglycerols (TAGs), are the primary form of energy reserves accumulated under stress conditions and are the most relevant fraction as a biodiesel feedstock due to their high and easily converted fatty acid content. The dominant fatty acid profile is generally in the C16–C18 range, both saturated and unsaturated (e.g., C16:0, C18:0, and C18:1), which greatly determines the physicochemical properties of biodiesel such as oxidative stability and flash point ((Maltsev et al., 2021; Pal et al., 2011). Furthermore, microalgae also produce polyunsaturated fatty acids (PUFA), especially omega-3s such as EPA, DHA, ALA, and LA, which have high nutraceutical value because they play an important role in cardiovascular health and neurological function. Structurally, polar lipids such as phospholipids and glycolipids are the main components of cell membranes that maintain cellular integrity and function, including in transport and photosynthesis. Meanwhile, carotenoids such as lutein, β-carotene, and astaxanthin function as photosynthetic pigments and powerful antioxidants that protect cells from oxidative stress, and have high economic value in the food, pharmaceutical, and cosmetic industries (Cointet et al., 2019).

3.4 Metabolism Pathwys from CO_2 to Lipid

CO_2 fixed by microalgae through photosynthesis is then channeled through various metabolic pathways to form fatty acids and triacylglycerols (TAGs), the primary neutral lipids. The initial stage begins with CO_2 fixation through the Calvin Cycle, where CO_2 is catalyzed by the enzyme RuBisCO to form 3-phosphoglycerate (3-PGA), which is then reduced to glyceraldehyde-3-phosphate (G3P) in the chloroplast (Kayani et al., 2025). Lipid accumulation in microalgae is commonly triggered by environmental stress conditions, particularly nitrogen limitation. Under nitrogen-replete conditions, photosynthetically fixed carbon is primarily directed toward protein synthesis and cell division. However, when nitrogen becomes limiting, protein synthesis decreases while photosynthesis may continue, leading to excess carbon and reducing equivalents within the cell. To prevent metabolic imbalance and oxidative damage, microalgae redirect carbon flux toward the synthesis of neutral lipids, especially triacylglycerols (TAGs), which function as carbon and energy storage molecules. Similar responses can also be induced by phosphorus limitation, salinity stress, high light intensity, and temperature stress.

Lipid biosynthesis is regulated by several key enzymes. Acetyl-CoA carboxylase (ACCase) catalyzes the conversion of acetyl-CoA to malonyl-CoA and is generally considered a rate-limiting step in fatty acid synthesis. Other important enzymes include malic enzyme (ME), glucose-6-phosphate dehydrogenase (G6PDH), and fatty acid synthase (FAS), which provide reducing power and catalyze carbon chain elongation. Changes in environmental conditions can alter the expression and activity of these enzymes, thereby influencing lipid productivity.

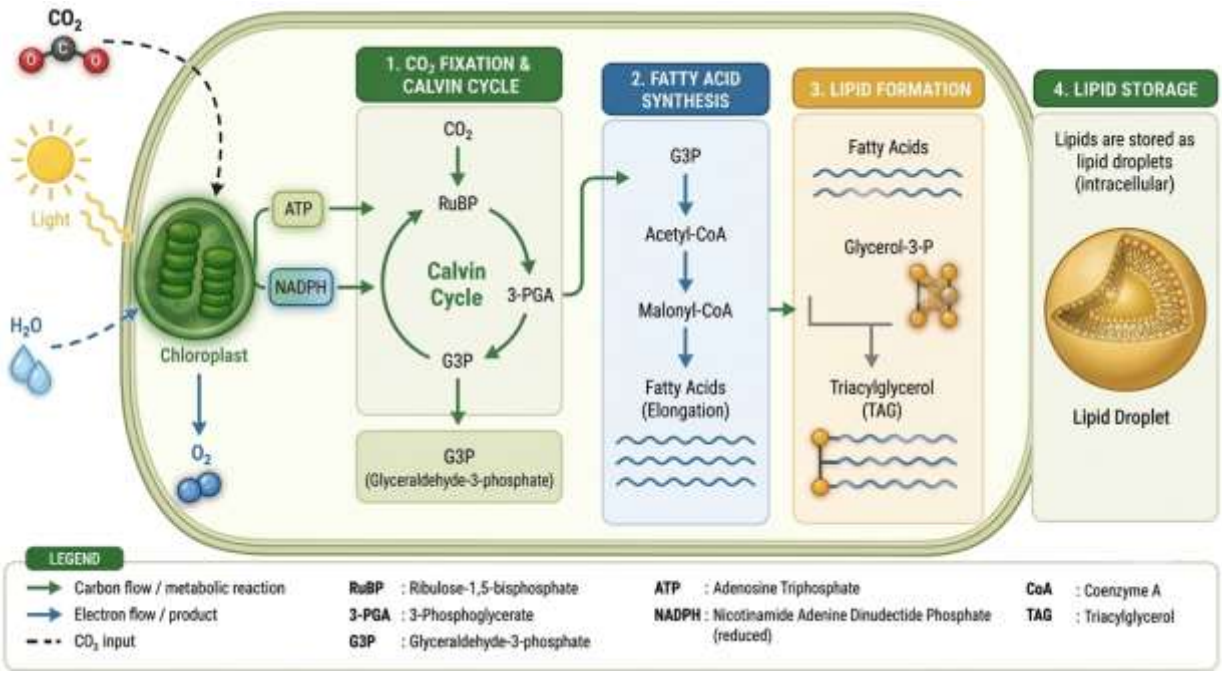

Figure 1: CO_2 fixation metabolism pathway

Figure 1 describes about CO_2 fixation metabolic pathway. This process is enhanced by the carbon concentration mechanism (CCM) and carbonic anhydrase activity, which increase the availability of CO_2 around RuBisCO, especially under low CO_2 conditions (Wei et al., 2019). G3P is then distributed to central metabolic pathways such as glycolysis (EMP) and the pentose phosphate pathway (PPP) to provide energy (ATP), reducing power (NADPH), and carbon precursors for lipid biosynthesis. In the next step, G3P is converted to pyruvate, which is then converted to acetyl-CoA in the chloroplasts through the catalysis of the pyruvate dehydrogenase complex. Acetyl-CoA is then carboxylated to malonyl-CoA by acetyl-CoA carboxylase, a committed step in fatty acid biosynthesis. The carbon chain elongation process then occurs through the fatty acid synthase (FAS) system with the assistance of acyl carrier protein (ACP), producing saturated and unsaturated fatty acids that can then be assembled into triacylglycerols, the primary form of energy storage in microalgae (Sun, 2024). At the industrial scale, microalgae cultivation is typically performed in open raceway ponds or closed photobioreactors supplied with concentrated CO_2 streams from industrial flue gases. Following cultivation, biomass undergoes harvesting, dewatering, lipid extraction, and conversion into biodiesel through transesterification. Integration of carbon capture with biofuel production offers a promising pathway toward a circular bioeconomy by simultaneously reducing CO_2 emissions and generating renewable products. However, challenges related to harvesting costs, energy consumption, and process scalability remain major barriers to commercial implementation.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

Microalgae are highly potential biological agents in mitigating carbon dioxide emissions due to their ability to efficiently absorb CO_2 through photosynthesis. Supported by the Carbon Concentrating Mechanism (CCM), microalgae are able to increase carbon concentration within their cells, thus optimizing carbon fixation, even in low CO_2 environments. The fixed carbon is then utilized in metabolic pathways to produce biomass rich in organic compounds, including lipids. Lipid accumulation, particularly triacylglycerols (TAGs), is crucial as it can be utilized as a feedstock for biodiesel. However, there is a trade-off between biomass growth and lipid production, influenced by environmental conditions such as nutrient availability, light intensity, and cultivation systems. This review highlights the strategic role of microalgae as a sustainable biological platform that simultaneously addresses two global challenges: carbon emission mitigation and renewable energy production. By integrating carbon sequestration with lipid-based biofuel generation, microalgae offer a promising pathway toward achieving climate change mitigation targets, supporting circular bioeconomy principles, and enhancing long-term environmental sustainability

4.2 Recommendation

Further research is recommended to optimize the cultivation conditions and production systems of microalgae, integrate them with industrial CO_2 emission sources, and develop engineering approaches and economic analyses to increase the efficiency of carbon capture and lipid production sustainably. Future studies should focus on the

development of advanced cultivation technologies, including high-efficiency photobioreactors and hybrid cultivation systems capable of enhancing CO_2 utilization and lipid productivity. Research on genetic engineering and metabolic pathway optimization is also needed to improve carbon fixation efficiency and lipid accumulation in promising microalgal strains. Furthermore, large-scale implementation studies integrating microalgae cultivation with industrial flue gas sources should be prioritized. Comprehensive techno-economic assessments and life cycle analyses are essential to evaluate commercial feasibility, environmental impacts, and long-term sustainability of microalgae-based carbon capture and biofuel production systems.

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