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Microalgae as a Feedstock for Carbon Capture Technology

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Abstract: Microalgae have emerged as a promising feedstock for carbon capture technologies due to their exceptional CO_2 sequestration capacity and versatility in producing bioenergy and high-value bioproducts. This study aims to evaluate the potential and implementation of microalgae-based carbon capture and storage (CCS) systems as a strategy for mitigating climate change. A systematic literature review was conducted to assess microalgae cultivation techniques, carbon capture efficiencies, and subsequent conversion pathways such as biochar production, biofuel synthesis, and industrial carbon utilization. The analysis also focuses on key scalability parameters, including biomass productivity, nutrient demands, photobioreactor designs, and harvesting technologies. Performance evaluation revealed that the efficiency of CO_2 capture and sequestration by microalgae ranges between 40% and 93.7%, depending on species, cultivation conditions, and system configuration. These findings indicate that microalgae can be feasibly integrated into existing CCS infrastructures while requiring relatively low land and freshwater resources. Moreover, advancements in biorefinery processes have significantly improved the economic viability of microalgae-based carbon-negative technologies. Despite these advantages, several barriers to large-scale implementation persist, including high operational costs, energy-intensive processing steps, and regulatory uncertainties. In conclusion, microalgae represent a viable and sustainable option for carbon mitigation technologies. However, their success at scale will depend on continued interdisciplinary research, technological innovation, and the establishment of supportive regulatory and financial frameworks to ensure long-term cost-effectiveness and environmental impact reduction.

Keywords: Microalgae; carbon capture; climate change; microplastic; CO_2.

1. Introduction

Climate change has become a crucial global issue and a widely discussed topic, especially in recent decades, as the threat of global warming has intensified due to the increasing emission of greenhouse gases into the atmosphere. This condition has led to a rise in the global average temperature by approximately 0.6°C, while CO_2 concentrations are estimated to increase by 75% to 350% above pre-industrial levels in the 21st century. If CO_2 emissions are not reduced, global temperatures could rise between 1.4°C and 5.8°C by the year 2100. The impacts of climate change can pose serious challenges for the global population, particularly in developing countries, including rising sea levels, extreme weather events, flooding, loss of biodiversity, water resource shortages, and an increased risk of disease outbreaks. To address this issue, the Indonesian government has voluntarily committed to reducing national greenhouse gas emissions by 29% through independent efforts or up to 41% with international support by 2030, in accordance with the agreed-upon climate change convention [1].

The trend of carbon emissions in the atmosphere has steadily increased over the years to above 424.44 ppm, which is significantly higher than preindustrial levels. This rise in carbon emissions is primarily attributed to anthropogenic activities such as burning fossil fuels and deforestation. These increased carbon emissions have resulted in a significant impact on global temperatures and climate patterns. Conventional efforts to minimise carbon emissions, such as investing in renewable energy sources and implementing energy efficiency measures, have been effective in reducing greenhouse gas emissions. However, growing demand for industrial products and services has put additional pressure on resources and energy consumption, thus contributing to a rise in carbon emissions. This highlights the need for further sustainable practices and policies to address this issue, thus necessitating a shift towards more sustainable production and consumption patterns. The dependence on biobased and circular economy principles will lead to a reduction in carbon emissions because it promotes the use of renewable resources and minimises waste generation. This will ease the transition towards a more sustainable economic model, thus catalysing the achievement of long-term environmental goals and mitigating the impacts of climate change [2].

In light of the ongoing carbon emission challenges, attention has increasingly turned toward biological solutions such as microalgae, which offer a highly efficient and sustainable method of carbon sequestration. Among these methods, biological treatment using microalgae and nitrifying-denitrifying bacteria is considered the most efficient, cost-effective, and is gaining increasing global attention. Nitrogen removal using microalgae is more environmentally friendly compared to bacterial nitrification-denitrification, as over 70% of nitrogen is released as gases (N_2O or N_2) during bacterial activity. The emission of N_2O ranges from 2.1% to 10.4%, depending on the organic load, and has 297 times the global warming potential of CO_2 [3].

Microalgal resources have been utilised as a sustainable tool for carbon capture due to their ability to capture CO2 and produce biomass that is useful for bioprospecting. This is attributed to the fact that carbon captured remains locked within the biomass even after harvesting and processing, making it an effective long-term solution for reducing greenhouse gas emissions. The ability of microalgae to grow rapidly and produce large amounts of biomass and metabolites under optimised conditions increases their biotechnological applications in various industries, such as food, pharmaceuticals, cosmetics, and biofuels. The cultivation of microalgae also increases environmental sustainability through wastewater treatment and nutrient recycling [2]. Microalgae are phototrophic, unicellular microorganisms capable of utilizing sunlight and carbon dioxide to produce chemical energy while releasing oxygen. Their growth rate is significantly higher than that of other photosynthetic organisms, and they generate greater concentrations of industrially valuable biomolecules compared to higher plants. These microorganisms can survive in a wide range of harsh environmental conditions and can even be cultivated in wastewater in arid regions. Historically, the anthropogenic use of algal biomass dates back to around 1500 BCE, when it was incorporated into diets and medicinal practices. The first medicinal application of microalgae was developed approximately 2,000 years ago to treat famine-related diseases. Given the current global challenges in energy, the environment, and the economy, microalgal biomass biorefineries offer a promising solution to these crises [4]. Additionally, microalgae can produce high-value compounds beneficial to industries such as pharmaceuticals, biomedicine, cosmetics, chemicals, and nutraceuticals. For instance, various species of microalgae have been found to contain bioactive compounds with antioxidant, anticancer, and antimicrobial properties, including carotenoids, polysaccharides, lipids, phenolic compounds, vitamins, and peptides. Furthermore, microalgae are utilized in the production of biofuels such as biocrude oil, biodiesel, biogas, and hydrogen. Research has also explored their potential in bioplastic production as an alternative to petroleum-based polymers. Therefore, CO_2 capture systems utilizing microalgae could serve as economic drivers, enabling the commercialization of these products while simultaneously reducing excessive CO_2 levels in the atmosphere [5].

Carbon capture and sequestration technology has emerged as a crucial approach with the potential to sustainably address carbon emissions into the atmosphere. This technology involves capturing carbon and either storing it or utilizing it for other purposes. In recent years, two major carbon capture methods—physical and biological—have gained significant attention. Despite its potential, the physical method of carbon capture and sequestration has several drawbacks, including high operational costs due to its substantial energy consumption. In contrast, the biological method has proven to be a more cost-effective and environmentally friendly alternative. This approach utilizes green plants to convert carbon into energy necessary for their survival. Initially, terrestrial plants such as trees were primarily used for this process, but recent findings indicate that microalgae have a significantly greater potential for carbon capture and sequestration. Bhola reported that microalgae are 10 to 50 times more efficient at capturing carbon compared to terrestrial plants. Consequently, the use of microalgae presents advantages over other carbon capture technologies [6]. Beyond its role in reducing CO_2 emissions and mitigating global warming, microalgae-based carbon capture offers additional benefits. The harvested microalgae can serve as a valuable source of bioenergy, including biofuels and biogas. Furthermore, microalgae can produce various high-value compounds, making them an economic asset for commercialization. Cultivating and harvesting microalgae for carbon capture not only contributes to environmental sustainability but also provides economic opportunities through the commercialization of its derived products [7].

So far, research in this field has primarily focused on aspects such as efficiency, microalgae cultivation, and the cost implications of using microalgae for carbon-negative technology. However, aspects related to lifecycle assessments and techno-economic analysis have not been thoroughly examined. Therefore, this paper reviews the application of microalgae in carbon-negative technology, with a focus on performance evaluation, lifecycle and economic assessment, as well as the environmental impact and implications of utilizing microalgae for this purpose [6].

2. Research and Methodology

2.1 Materials

Microalgae are composed of eukaryotic cells, which include a cell wall, plasma membrane, cytoplasm, nucleus, and various organelles such as mitochondria, lysosomes, and the Golgi apparatus. Additionally, microalgae contain plastids-structures containing chlorophyll responsible for photosynthesis. However, different strains of microalgae possess varying combinations of chlorophyll molecules; some contain chlorophyll A, while others have a combination of A and B, or A and C [8].

Algae are among the most effective organisms for carbon sequestration and photosynthesis. They are categorized into macroalgae and microalgae, which differ in size and structure. Microalgae are primarily classified based on their environment and morphology. Depending on the conditions, they can be autotrophic, heterotrophic, or both. Autotrophic microalgae require salts, inorganic compounds, and an appropriate light source for growth, whereas heterotrophic microalgae depend on external organic molecules and nutrients for energy.

The classification of microalgae is mainly determined by their cellular structure, color, and life cycle. There are two prokaryotic and nine eukaryotic groups of microalgae. These organisms have great potential for producing value-added products and biofuels. Additionally, microalgae can naturally tolerate high CO_2 concentrations, making them suitable for capturing CO_2 emissions from power plant exhaust systems. It is also important to note that photosynthesis was the first biological process responsible for fixing the carbon we utilize today [6].

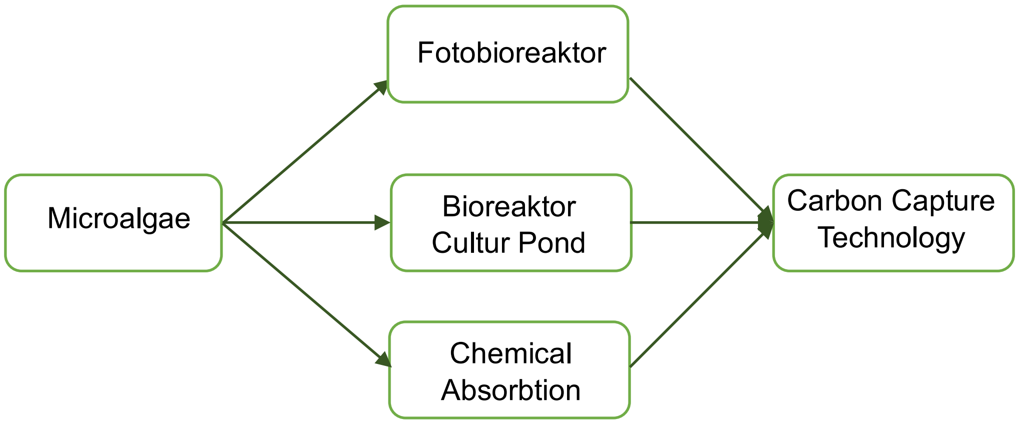

Figure 1. Carbon capture technology from microalgae

Most microalgal species grow best at a pH range between 7.0 and 8.4. Several key factors influence microalgal photosynthetic efficiency and CO_2 assimilation, including heat, light, and mass transfer of CO_2 and nutrients. In this respect, physico-chemical (e.g. pH, temperature, salinity, turbidity) and nutrient profiles of culture media, properties of flue gas (e.g. CO_2 concentration, temperature, toxic compounds), light wavelengths and penetration, bioreactor design, and selection of microalgae species significantly influence microalgal CO_2 biofixation [9].

Carbon Capture and Storage (CCS) is a technology designed to capture CO_2 emissions and prevent their release into the atmosphere. Since 2006, the United Nations Framework Convention on Climate Change (UNFCCC) has recommended CCS as one of the primary technological options for CO_2 mitigation. This technology can capture up to 90% of CO_2 emissions from power plants and industrial facilities. One promising carbon capture technology is the biological approach using microalgae cultures. The implementation of this technology requires integration with microalgae utilization methods to establish a sustainable and environmentally friendly system. A photobioreactor is a transparent reactor equipped with media supply and gas emission installations to cultivate microalgae and absorb CO_2. Photobioreactor technology has been shown to enhance microalgae productivity by two to five times compared to normal conditions. The growth rate of microalgae is influenced by the flow velocity of the culture medium. The CO_2 gas injection rate is a critical factor in determining the CO_2 absorption capacity of microalgae [10]. CO_2 capture using microalgae involves a wide range of simultaneous processes. The course starts with the transfer of CO_2 in a gaseous stream to the culture medium where microalgae grow, until CO_2 is fixed in the form of biomass. One of the main concerns associated with optimizing the carbon fixation efficiency is finding strains that favor CO_2 capture and a suitable cultivation system, considering configuration and operating conditions such as light availability, temperature, pH, and mixing [11].

Open-system microalgae cultivation is a method in which microalgae grow in natural outdoor environments, typically in water bodies such as ponds, rivers, and lakes. Over time, open-system cultivation has also been adapted for artificial ponds specifically designed for microalgae growth. In this system, CO_2 availability for microalgae is abundant, as it is directly sourced from the surrounding air. However, when microalgal biomass becomes dense, air penetration into the growth medium is hindered, necessitating the use of a submerged aerator to enhance CO_2 absorption. In contrast, closed-system microalgae cultivation relies on enclosed photobioreactors. This system was developed to address the limitations of open cultivation, particularly in minimizing contamination risks. Several types of closed photobioreactors have been employed for microalgae production, including tubular photobioreactors, flat-plate photobioreactors, and column photobioreactors. Each type offers distinct advantages in optimizing growth conditions, improving CO_2 absorption, and ensuring higher biomass productivity [12].

Many studies have explored various absorbents for CO_2 absorption. The selection of solvents, such as amine-based absorbents, carbonate salts, and ionic liquids, is one of the most crucial elements in reducing energy consumption in the CO_2 capture process using chemical absorption. In recent years, different solvents, including phase-change solvents and blended solvents, have been developed as potential candidates for CO_2 absorption. Therefore, it is essential to identify absorbents with high absorption capacity and low energy consumption to effectively remove CO_2 [13].

The raceway culture pond is equipped with paddles or propellers for mixing, an electric motor drive, CO_2 gas inlet pipes, and freshwater and nutrient supply pipes. The microalgae culture pond is made of stainless steel with a capacity of 1,000 liters, and the water depth can be adjusted to 20 cm, 15 cm, or 10 cm. In this experiment, a depth of 20 cm was selected. The pond is covered with a transparent plastic (mica) lid to minimize the risk of contamination of the microalgae culture. The water used in the system is freshwater. Microalgae are heterotrophic microorganisms that resemble plants, requiring light and CO_2 in addition to nutrients. The CO_2 supply is determined based on the concentration of gas obtained from the effluent section of a boiler chimney. The system for supplying CO_2 to the pond includes a gas reservoir made of plastic, where the CO_2 concentration is maintained at approximately 6%. Additional equipment includes gas piping from the plastic reservoir to the culture pond. A compressor is used to draw in CO_2 gas, while a gas release valve is installed at the effluent section to sample and measure the CO_2 concentration [14].

2.2 Methods

The method applied in this research is a literature study. Data was collected from various sources, including the internet, journals, and books. Internet sources used include Google Scholar, Google Books, and several website. The data obtained was then analyzed using a descriptive method, not only to present the information in detail, but also to provide a clear and easy-to-understand undestanding [15]. The method used in this research is an analytical research method with a qualitative approach. This method was chosen to facilitate the analysis of the main issues in the journal and to identify the relationships between various aspects or variables in the study [16].

3. Results and Discussion

3.1 Microalage in Climate Change Mitigation

Climate change poses a substantial hurdle, necessitating amplified efforts to limit greenhouse gas emissions originating from both biogenic and anthropogenic sources, with particular emphasis on carbon dioxide and methane. Viable strategies for mitigating carbon dioxide emissions encompass underground sequestration or utilization by photosynthetic plants. The following methods can be used to decrease the concentration of harmful gases in the atmosphere while simultaneously promoting ecosystem balance. However, it is important to ensure that these strategies are implemented responsibly to avoid potentially negative environmental impacts. Further research and development in this area could lead to more efficient and sustainable solutions to combat climate change. Microalgae have been extensively studied as a viable alternatives to geological storage for carbon dioxide sequestration technology [17].

Microalgae are ancient plant organisms with microscopic sizes ranging from 3 to 30 μm and are often referred to as phytoplankton. As microscopic organisms, microalgae are widely distributed and can be found in various environments exposed to sunlight. Their morphology and characteristics are highly diverse, allowing them to adapt to different ecological conditions [18].

Microalgae play a pivotal role in carbon sequestration, one of their primary functions. Microscopic organisms utilize photosynthesis to capture atmospheric CO_2 and convert it into biomass. This process serves a dual purpose: it helps combat climate change by reducing greenhouse gas concentrations and contributes to Goal 13: Climate Action. The resulting biomass can also be used to produce biofuels, providing an alternative renewable energy source that reduces reliance on fossil fuels. This review aims to fill a knowledge gap concerning the augmentation of microalgal cultivation for feed, food, bioenergy production, and wastewater treatment.It delves into the principles of the circular economy and the technical and economic challenges. Furthermore, it underscores the alignment of microalgal biotechnology with the United Nations SDGs. Addressing existing obstacles in the production of microalgae could enhance environmental health and reduce production costs [17].

Microalgae have garnered increasing attention due to their ability to absorb carbon dioxide efficiently through photosynthesis, making them a valuable resource in climate change mitigation strategies. Beyond their biological function, microalgae directly impact the reduction of greenhouse gases by capturing atmospheric CO_2 and converting it into biomass. This not only lowers the overall concentration of GHGs but also provides sustainable pathways for producing renewable energy and other bioproducts, positioning microalgae as a key player in addressing environmental challenges related to global warming.

To better understand the significance of microalgae in environmental applications, it is important to consider the broader context of climate change and the greenhouse effect. The greenhouse effect, which contributes to rising global temperatures, is primarily driven by greenhouse gas (GHG) emissions, with carbon dioxide (CO_2) being one of the most significant contributors. Mitigation strategies are essential to reduce GHG levels, and one promising approach involves carbon capture using algae. Algae are considered a key renewable biofuel source for the future and have the potential to play a significant role in mitigating the greenhouse effect. Through the natural process of photosynthesis, algae can effectively sequester CO_2, making them a highly promising tool for reducing greenhouse gas concentrations [19].

3.2 Microalgae as a Carbon Capture Technology

The technology used to reduce atmospheric CO_2 levels can generally be classified into two types: (1) technologies that remove existing CO_2 from the atmosphere and (2) technologies that prevent or reduce CO_2 emissions from industrial activities. These two types of technologies are collectively known as Carbon Capture, Utilization, and Storage (CCUS). Carbon capture refers to technologies that capture CO_2 from the exhaust gases of fossil fuel combustion, such as through chemical absorption or membrane technology. The captured CO_2 can either be utilized as an industrial raw material or stored underground to prevent additional emissions into the atmosphere. Carbon utilization involves the direct use of CO_2 without processing, such as in enhanced oil recovery (EOR), or its conversion into various chemicals, materials, or fuels. Carbon storage is the technology used to store CO_2 back into the Earth, for example, by injecting it into depleted oil reservoirs [13]..

Amidst a broad spectrum of renewable energy sources, microalgae stand out due to their unparalleled photosynthetic efficiency and rapid growth rate [20]. Microalgae, which are unicellular photosynthetic organisms, flourish in diverse environments and can endure varying parameters such as salinity, temperature, light intensity, and pH. The potential of microalgae to support the UN-SDGs and enhance climate resilience is gaining increased recognition. These versatile microorganisms offer innovative solutions across various sectors, making them invaluable in the fight against climate change and the promotion of sustainable development. Microalgae generate essential compounds, such as proteins, vitamins, polysaccharides, carbohydrates, lipids, antioxidants, and pigments [17].

Microalgae are photosynthetic organisms that absorb CO_2 and convert it into sugars as their primary energy source while releasing O_2 into the environment. Additionally, microalgae produce environmentally friendly hydrogen, particularly in the atmosphere, as part of greenhouse gas mitigation efforts. The reaction occurs aerobically, ensuring that no methane or other harmful gases are released into the environment. Microalgal biomass can be harvested and used as organic fertilizer [21]. Microalgae's composition, predominantly carbon by over half its dry weight, implicates that a ton of biomass produced within cultivation systems correlates to the sequestration of roughly 1.83 tons of CO_2. This sequestration coefficient can be validated through the molar conservation of carbon, further reinforcing its applicability across various cultivation methods [20].

Carbon dioxide fixation using microalgae represents a promising and viable approach for carbon capture and storage. This process relies on photosynthesis, enabling the conversion of water and CO_2 into organic compounds without requiring additional energy input or generating secondary pollution. Compared to conventional CCS techniques, microalgae-based CO_2 fixation offers several advantages, including a high photosynthetic rate (e.g., 6.9×10^4 cells/mL/h), fast growth rates ranging from 0.7 to 3.2 per day, strong environmental adaptability, and relatively low operational costs [8].

Let us now consider microalgae instead of terrestrial plants: the term “microalgae” usually refers to microorganisms, both prokaryotic and eukaryotic. Besides, we shall only consider photoautotrophic microalgae, performing photosynthesis in order to produce their own feed. For microalgae, the photosynthesis efficiency reaches 3–9%, even up to 20% according to certain authors depending on species. In this way, marine microorganisms realize half of the global CO_2 fixation, providing at the same time half of the oxygen, despite representing only 1% of global plant biomass [22]. Interestingly, biological capture and sequestration of carbon using microalgae have been recognized as one of the world’s most important and effective carbon sequestration methods. In the long run, bio-capture of carbon using microalgae has been deemed environmentally friendly, economically feasible, and a sustainable technology. Microalgae have the ability to fix carbon dioxide for 10-50 times more than other terrestrial plants [23]. Some microalgal–bacterial consortia demonstrate enhanced carbon fixing capabilities when bacterial components are involved in nitrogen-fixing, sulfur-oxidizing, or methanotrophic processes. This association potentially improves the overall carbon capture efficiency by utilizing inorganic nutrients fixed by the bacteria, which facilitates a multitude of metabolic pathways, including photosynthesis [24].

Many species of microalgae have the ability to capture carbon dioxide as its carbon source for the photosynthetic process. Previous study had shown the aqua water and seawater microalgae cultivation on the photobioreactor to capture carbon dioxide. CO_2 emissions has been reduced up to 78% by bio-scrubber technology using microalgae. Microalgae consumes 368 mg/L carbon dioxide as its carbon source for the metabolism every day. The growth of microalgae can be affected by several factors, such as composition of medium, culture conditions, and bioreactor type. Effect of culture salinity and CO_2 concentration effected to the growth rate of Chlorella vulgaris in the freshwater and tofu waste water. High concentration of carbon in the medium caused high lipid content of microalgae. The final product of CO_2 fixation of microalga is biomass, that can be used as food, pharmaceuticals, energy, and animal feed. This work aimed to cultivate many species of microalgae in the carbon dioxide incubator and study its CO_2 bio-fixation capability [25].

Furthermore, microalgae have the potential to recycle CO_2 into bioenergy through photosynthesis, thus, highlighting that bioconversion of CO_2 using microalgae is an environmentally friendly and sustainable method. Interestingly, bioconversion of CO_2 using microalgae has shown strong environmental flexibility. Its ability to tolerate and adapt to a variety of extreme environmental conditions enhances applicability. They do not occupy arable land, which makes them suitable for cultivation in coastal beaches, saline alkali lands, and deserts. Another noteworthy feature of microalgae is the capacity to convert flue gases into inorganic carbon sources from power plants and other industrial exhaust gas. Economic feasibility is another great advantage, as wastewater from industries, agricultural activities, and municipalities can be utilized as alternative nutrient sources to cultivate microalgae at a low cost. The simultaneous production of high added value products by microalgae is arguably the highest advantage in the biological utilization of microalgae. These high added value products can be used to prepare food, animal and aquaculture feed, cosmetics, pharmaceuticals, fertilizers, biologically active substances and biofuels such as biodiesel, biohydrogen, aviation oil, methane [23].

The growth of microalgae is also influenced by its physiological characteristics, which affect nutrient uptake and cultivation environment. Naturally, microalgae growing in open ponds can proliferate rapidly, covering the pond's surface. If the physiological traits of the microalgae are highly favorable, this condition can stimulate biomass production with high oil and starch content. However, certain physiological responses may prevent microalgae from surviving in such ponds. This may occur due to the high concentration of accumulated O_2 in the pond, which inhibits microalgal growth. Light saturation is another issue affecting microalgal physiology. Microalgae growing on the surface of the pond receive excessive sunlight, surpassing the amount required for photosynthesis. Therefore, recent research has focused on physiological and genetic modifications to reduce light-absorbing pigments in microalgae [12]. Research on microalgal species such as C. vulgaris, Chlorella sp., S. obliquus, Scenedesmus sp., and D. salina often focuses on their symbiotic relationships with bacteria to enhance CO_2 removal and biomass production. For instance, C. vulgaris has been extensively studied in conjunction with Bacillus and Pseudomonas, owing to their synergistic benefits. Zhou, recently explored the interaction between C. vulgaris and Bacillus subtilis and found that a 1:1 (algae:bacteria) co-culture ratio supplemented with antibiotics significantly increased the CO_2 removal rate to 119.90 mg $L^{-1}d^{-1}$ compared with that of C. vulgaris monoculture at 100.87 mg $L^{-1}d^{-1}$. Transcriptomic analysis further identified an enhancement in the Calvin cycle as the primary mechanism underlying this improvement. Choix, co-cultivated S. obliquus with Azospirillum brasilense under 35% CO_2, which resulted in a significant increase in CO_2 fixation rates [24]. This challenge holds significant economic and environmental benefits while also creating numerous job opportunities. Additionally, conducting a lifecycle assessment (LCA) of carbon capture by microalgae can offer scientists valuable insights into the amount of carbon that can be sequestered through this process. It also provides investors with an estimate of the financial return timeframe. These studies are essential to encouraging scientists and businesses to scale up direct air CO_2 capture using microalgae [7].

4. Conclusion

Microalgae present a promising solution in carbon capture technology due to their high CO_2 absorption efficiency and potential applications in bioenergy and value-added products. This study demonstrates that microalgae can be utilized in various climate change mitigation methods, including biochar production, biofuel synthesis, and direct carbon storage in industrial applications. Despite their high carbon sequestration capacity and compatibility with existing carbon capture systems, key challenges in implementation include high operational costs, energy-intensive processes, and regulatory barriers. Therefore, the development of more efficient technologies, interdisciplinary collaboration, and supportive policies are essential to enhancing the effectiveness and economic feasibility of microalgae-based systems. Therefore, to enhance the feasibility of microalgae-based carbon capture technologies, future efforts should focus on policy incentives for industry adoption, investment in genetic engineering to boost CO_2 uptake efficiency, and the development of cost-effective, large-scale photobioreactor systems. These measures will support commercialization and environmental integration.

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4. References

[1] A. P. Dilasari, H. N. Ani, and R. J. H. Rizka, "Analisis Best Practice Kebijakan Carbon Tax Dalam Mengatasi Eksternalitas Negatif Emisi Karbon Di Indonesia," *Owner*, vol. 7, no. 1, pp. 184–194, 2022, doi : https://doi.org/10.33395/owner.v7i1.1182.

[2] A. Y. Ugya, Y. Sheng, H. Chen, and Q. Wang, "Microalgal bioengineering: A futuristic tool for carbon capture," *Results Eng.*, vol. 24, p. 102990, 2024, doi: https://doi.org/10.1016/j.rineng.2024.102990.

[3] M. Mubashar *et al.*, "Carbon-negative and high-rate nutrient removal using mixotrophic microalgae," *Bioresour. Technol.*, vol. 340, 2021, doi: https://doi.org/10.1016/j.biortech.2021.125731.

[4] M. V. L. Chhandama, J. Ruatpuia, S. Ao, A. C. Chetia, K. B. Satyan, and S. L. Rokhum, "Microalgae as a sustainable feedstock for biodiesel and other production industries: Prospects and challenges," *Energy Nexus*, vol. 12, 2023, doi: https://doi.org/10.1016/j.nexus.2023.100255.

[5] A. M. Miranda, F. Hernandez-Tenorio, D. Ocampo, G. J. Vargas, and A. A. Sáez, "Trends on CO2 Capture with Microalgae: A Bibliometric Analysis," *Molecules*, vol. 27, no. 15, pp. 1–14, 2022, doi: https://doi.org/10.3390/molecules27154669.

[6] J. Ighalo *et al.*, "Progress in Microalgae Application for CO2 Sequestration," *Clean. Chem. Eng.*, vol. 3, p. 100044, 2022, doi: https://doi.org/10.1016/j.clce.2022.100044.

[7] A. Maghzian, A. Aslani, and R. Zahedi, "Review on the direct air CO2 capture by microalgae: Bibliographic mapping," *Energy Reports*, vol. 8, pp. 3337–3349, 2022, doi: https://doi.org/10.1016/j.egyr.2022.02.125.

[8] W. Klinthong, Y. H. Yang, C. H. Huang, and C. S. Tan, “A Review: Microalgae and their applications in CO2 capture and renewable energy,” *Aerosol Air Qual. Res.*, vol. 15, no. 2, pp. 712–742, 2015, doi: https://doi.org/10.4209/aaqr.2014.11.0299.

[9] E. Daneshvar, R. J. Wicker, P. L. Show, and A. Bhatnagar, “Biologically-mediated carbon capture and utilization by microalgae towards sustainable CO2 biofixation and biomass valorization – A review,” *Chem. Eng. J.*, vol. 427, 2022, doi: https://doi.org/10.1016/j.cej.2021.130884.

[10] R. R. Rusdiani, R. Boedisantoso, and M. Hanif, “Optimalisasi Teknologi Fotobioreaktor Mikroalga sebagai Dasar Perencanaan Strategi Mitigasi Gas CO2,” *J. Tek. ITS*, vol. 5, no. 2, pp. 188–192, 2016, doi: https://doi.org/10.12962/j23373539.v5i2.16942.

[11] P. Ruiz-Ruiz, A. Estrada, and M. Morales, *Carbon dioxide capture and utilization using microalgae*. 2020. doi: https://doi.org/10.1016/B978-0-12-818536-0.00008-7.

[12] S. O. Gultom, “Mikroalga: Sumber Energi Terbarukan Masa Depan,” *J. Kelaut. Indones. J. Mar. Sci. Technol.*, vol. 11, no. 1, p. 95, 2018, doi: https://doi.org/10.21107/jk.v11i1.3802.

[13] A. A. Isya, K. R. Arman, and J. Wintoko, “Mini-Review Teknologi Carbon Capture and Utilization (CCU) Berbasis Kombinasi Proses Kimia dan Bioproses,” *Equilib. J. Chem. Eng.*, vol. 4, no. 2, p. 71, 2021, doi: 10.20961/equilibrium.v4i2.47908.

[14] T. Handayani, A. Mulyanto, and N. Sopiah, “Penyerapan Emisi Co2 Oleh Mikroalga Euglena Sp Dengan Bioreaktor Kolam Kultur,” *J. Ecolab*, vol. 8, no. 1, pp. 1–10, 2014, doi: https://doi.org/10.20886/jklh.2014.8.1.1-10.

[15] S. Ainurrohmah and S. Sudarti, “Analisis Perubahan Iklim dan Global Warming yang Terjadi sebagai Fase Kritis,” *J. Phi J. Pendidik. Fis. dan Fis. Terap.*, vol. 8, no. 1, pp. 1–10, 2022.

[16] W. S. Sumadinata, “Climate Change As a Trigger of Global Security Issues,” *J. Multidisiplin Sahombu*, vol. 3, no. 01, pp. 69–76, 2023, doi: https://doi.org/10.58471/jms.v3i01.1745.

[17] A. Ahmad and S. S. Ashraf, “Harnessing microalgae: Innovations for achieving UN Sustainable Development Goals and climate resilience,” *J. Water Process Eng.*, vol. 68, no. September, p. 106506, 2024, doi: 10.1016/j.jwpe.2024.106506.

[18] F. Agustiyar, “Mikroalga: Bioenergi dan Lingkungan Berkelanjutan,” *Semin. Nas. TREnD*, no. 1, pp. 50–60, 2021.

[19] D. Wongsodiharjo and Y. Ismail Masjud, “Utlize microalgae in order to lowering green house emission by using carbon capture,” *Sustain. Urban Dev. Environ. Impact J.*, vol. 1, no. 1, pp. 1–10, 2024, doi: 10.61511/sudeij.v1i1.2024.632.

[20] M. Chen, Y. Chen, and Q. Zhang, “Assessing global carbon sequestration and bioenergy potential from microalgae cultivation on marginal lands leveraging machine learning,” *Sci. Total Environ.*, vol. 948, 2024, doi: https://doi.org/10.1016/j.scitotenv.2024.174462.

[21] A. Afriani and M. A. Nasution, “Pemanfaataan dan Aplikasi Mikroalga dalam Pengolahan Limbah Cair Pabrik Kelapa Sawit,” *Warta*, vol. 23, no. 3, pp. 99–106, 2018.

[22] C. Even, D. Hadroug, Y. Boumlaik, and G. Simon, “Microalgae-based Bioenergy with Carbon Capture and Storage quantified as a Negative Emissions Technology,” *Energy Nexus*, vol. 7, p. 100117, 2022, doi: https://doi.org/10.1016/j.nexus.2022.100117.

[23] H. Onyeaka, T. Miri, K. C. Obileke, A. Hart, C. Anumudu, and Z. T. Al-Sharify, "Minimizing carbon footprint via microalgae as a biological capture," *Carbon Capture Sci. Technol.*, vol. 1, 2021, doi: https://doi.org/10.1016/j.ccst.2021.100007.

[24] Z. He, J. Wang, and Y. Li, "Recent advances in microalgae-driven carbon capture, utilization, and storage: Strain engineering through adaptive laboratory evolution and microbiome optimization," *Green Carbon*, pp. 1–26, 2025, doi: https://doi.org/10.1016/j.greenca.2024.10.001.

[25] Widayat, M. Suzery, H. Satriadi, Wahyudi, and J. Philia, "Selection and Cultivation of Microalgae for CO2 Biofixation," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1053, no. 1, p. 012132, 2021, doi: https://doi.org/10.1088/1757-899x/1053/1/012132.