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Application of Carbon Capture and Utilization (CCU) in Oil and Gas Industry to Produce Microalgae-Based Biofuels with Solvent-Captured Method

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Abstract
The production process in the oil and gas industry, which is a major demand, still plays a huge role in carbon emissions, especially in the refining process. The energy and industrial sectors are responsible for more than 75% of these global CO_2 emissions. This condition is an important issue regarding the effort to reduce climate change due to these emissions by implementing CCU. This article aims to examine methods of carbon capture with chemical absorption by solvents and to compose a model diagram of carbon utilization with microalgae. An extensive literature search was conducted in accordance with the scoping review methodology and the PEO framework. Our search criteria were limited to article research within the last 5 years (2017–2021). Themes found from this review included the CCU method in general, carbon capture by solvent method, type of solvent used, advantages and disadvantages, and utilization of carbon in the gas and oil industries. CCU is a model that can be offered as an alternative to reduce CO_2 emissions produced by industry. The scoping review result shows the best method for carbon capture is with monoethanolamine (MEA) solvent. The flue gas from post-combustion streams into the absorption column and the solvent is added. The carbon-rich solvent is regenerated by heat to produce a clean solvent to be reused in the capture cycle. Carbon that has been absorbed by the MEA in the form of gas will be channeled through pipes to the microalgae industry as utilization of captured carbon and then converted to biofuels. It was discovered that MEA is a cost-effective solvent, efficiently captures carbon, and can be used repeatedly. However, the amine emissions from MEA are considered hazardous. The conclusion is that MEA solvent has advantages and disadvantages. Further optimization research is needed to determine the preeminent capture and separation process. Thus, it is necessary to determine the best conditions for the use of captured carbon by microalgae.

Keywords:
CCU, solvent, biofuels, microalgae

1. Introduction

World carbon dioxide emissions continue to increase amid the development of human (industrial) activities. In general, carbon gas emissions usually focus specifically on carbon dioxide gas. Carbon dioxide emissions are emissions stemming from the burning of fossil fuels and the manufacture of cement. These include carbon dioxide produced during the consumption of solid, liquid, and gas fuels and gas flaring (Eurostat, n.d.). Carbon dioxide (CO_2), one of the main greenhouse gases (GHG), is mainly produced during fossil fuel combustion, which generally takes place to produce energy.

The energy industry stands as the biggest source of human-caused GHG emissions, with a total of 76.6% globally (Ge et al., 2020). Transportation, electricity and heat, manufacturing and construction, building, fugitive emissions, and other fuel combustion are included in the energy sector. Most of the CO_2 emissions, primarily products from the combustion of fossil fuels, come from a few countries. China, the United States, and the European Union are the three largest emitters (C2ES, 2021). China continues adding and rapidly contributing to the increase of CO_2 emissions, with 12,000 million tons in 2020 (C2ES, 2021). The United States went from 7,000 million tons in 2000 and going stable around (relatively decreasing) the number until 2020, while the European Union started from around 4,000 to around 3,000 in 2020 (C2ES, 2021).

Carbon Brief explains the greatest emissions come from countries with large geography. These countries, such as the United States, Russia, and China, cut down the forests to open up land for agriculture and fuels (Hausfather & Friedlingsten, 2022). Indonesia is included in the top ten countries contributing to cumulative carbon emissions after the United States, China, Russia, and Brazil, with 14.6% of emissions coming from fossil fuels (Mutia, 2022).

Carbon emissions affect the environment, economy, health, and other sectors. Excess carbon trapped in the atmosphere increases the average atmospheric temperature and leads to global warming (Ali et al., 2020). The layer prevents the earth from cooling and eventually affects environmental conditions, weather patterns, sea levels, and food and water supplies (Ali et al., 2020). Emissions contributed by China and the United States are responsible for a global income loss of over USD 1.8 trillion each for 25 years starting in 1990 (Hirsch, 2022). High concentrations of CO_2 inhaled by humans can directly harm the human respiratory system (Sechzer et al., 1960). The indirect impact of CO_2 emissions on public health is through climate change (Dong et al., 2021).

To reduce carbon gas emissions and achieve net zero emission targets, various ways are carried out, including the development of industries that contribute the most to the world's carbon gas emissions. The development of technology in the petroleum and gas industry is able to create an industry that has low carbon gas emissions, and it can be recycled into renewable energy. This creates a more environmentally friendly fossil fuel industry.

Carbon capture, utilization, and storage (CCUS) is a development in technologies of the fuel and gas industry that play a diverse role in meeting global energy and climate goals (IEA, 2021). CCUS is a set of technologies that is able to capture and utilize effectively the high concentration of CO_2 emitted by industrial activities (METI, n.d.). CCUS is the process of capturing CO_2 emitted from fossil power generation and industrial processes for reuse or storage (UNECE, 2021).

CCUS technology can be designed in such a way as needed and innovated so as to produce low carbon gas emissions. Carbon dioxide from the oil and gas industry can be captured in a variety of ways, including with liquid solvents. Instead of carbon storage in the ground, it is more beneficial for the production of valuable products such as biofuels (Cao et al., 2020). Carbon capture and utilization (CCU) is selected at this path. CCU has advantages in permanent carbon storage in that CCS has no risk of leakage and enables conversion into valuable products (Mikkelsen et al., 2010). This study aims to conduct a scoping review of journals that discuss CCU with the solvent method so that a superior solvent method is obtained to be used. Furthermore, the results of the scoping review were developed for modeling CCU results in the microalgae-based petroleum industry.

2. Methods

This study is designed to compile relevant contributions from previous studies and to analyze the result in relation to carbon capture and utilization using a solvent method and also the utilization of captured carbon for reuse purposes as biofuels. An extensive literature search was conducted in accordance with the scoping review methodology and the PEO framework. This study first conducts literature research on carbon capture and utilization and biofuels. Three online databases are selected as sources of the literature study: ScienceDirect, Springer, and Google Scholar. Only original articles (primary resource) considered in this study as other forms of publication, such as books, review articles, conference proceedings, etc., are excluded. The literature study is also restricted to articles published around 2017–2021 to present a relatively new study.

The keywords search applied in this study were ('carbon emission') AND ('CCU') AND ('solvent') AND ('biofuels'). The first round resulted in 280 articles. Excluded by the year of publication, 2017–2021, resulted in 81 articles. Further results are described in Figure 1.

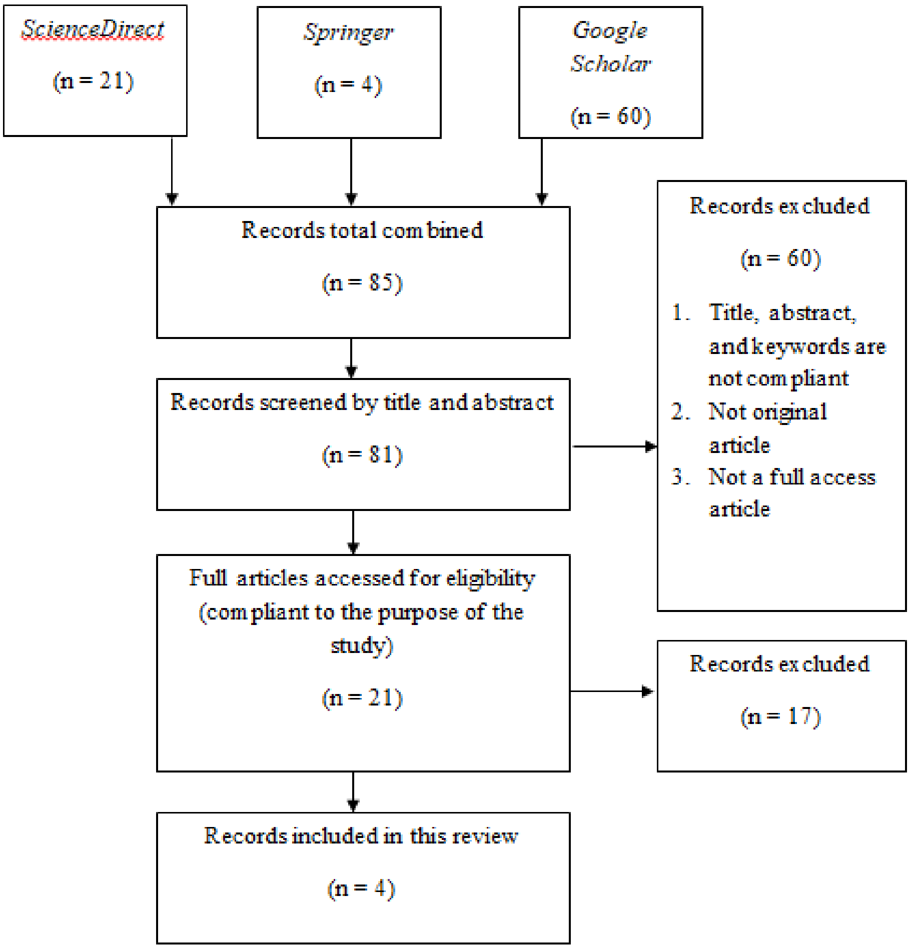

Figure 1. PRISMA-ScR flow diagram for guideline inclusion.

3. Result and Discussion

The table below summarizes the content analysis of the articles included in this study. Articles focus on topics on how carbon capture using solvent and the utilization of carbon captured for biofuels.

Table 1. Summary of selected articles.

No	Reference	Findings
1.	Carbon capture on micro gas turbine cycles: Assessment of the performance on dry and wet operations	Exhaust gasses from micro gas turbines can be captured with the chemical absorption method using MEA (monoethanolamine). CO_2-rich gasses are passed on the MEA stream and will be absorbed. MEA was then conducted for desorption or regeneration for retrieving and will be used to capture the CO_2 again (Giorgetti et al., 2017).

2.	Carbon recycling – An immense resource and key to a smart climate engineering: A survey of technologies, cost and impurity impact	The application of CCU is considered more promising than CCS in terms of fuel manufacturing, biofuels, and mineralization. Besides that, the influence of contaminants also plays a significant role in effectiveness and cost. However, solvent capture is slightly explained (Wang et al., 2020a).
3.	CO_2 capture and inorganic carbon assimilation of gaseous fermentation effluents using *parachlorella kessleri* microalgae	CO_2 capture methods simulated at laboratory scale and pilot study using NaOH solvent. CO_2 mixed in the solvent is used as a carbon source for microalgae that can be utilized for biofuel production. This study also concludes that carbon concentration can affect the growth of microalgae. Therefore, it is necessary to optimize the high growth conditions (Beigbeder et al., 2021).
4.	Upstream and downstream processing of microalgal biogas: Emissions, energy and economic performances under carbon taxation	Solvent monoethanolamine can absorb CO_2 after combustion in the formation of bioelectricity with enhanced oil recovery (EOR) technology, but the application of this method requires a high temperature for solvent regeneration (Brigagão et al., 2019).

Based on the results of the analysis from the articles that had been carried out (Table 1), it was found that carbon dioxide capture with solvent can be done and is commonly used. A commonly used solvent, based on the findings (Table 1), is monoethanolamine (MEA). It also explains the use of MEA solvents with various technological designs that have been carried out in previous studies so as to produce effective use of MEA solvents. There are also advantages and disadvantages of using this MEA solvent. Furthermore, the results of carbon capture can be utilized to form biofuels. The findings (Table 1 number 3) show that the biofuel processing technology related to carbon capture results is to use microalgae. Implementation of CCU has several alternatives and aims of utilization. Those utilizations such as chemical conversion, mineralization, electrocatalysis, and bio-utilization (Wang et al., 2020b). Chemical conversion is a pathway of using carbon to convert into synthetic gas. It has been commonly used to produce fuels (i.e., methanol, ethanol, hydrocarbons, and other synthesis gases) (White et al., 2015). Mineralization is the process of reacting carbon with mineral resources or industrial wastes containing metal ions to produce carbonates. Ca and Mg are the most abundant alkaline earth metals to react with CO_2 in the mineralization process (Yan et al., 2010). Meanwhile, electrocatalysis is a process in which CO_2 obtains electrons from the electrocatalyst surface and undergoes a reduction reaction. This method also obtains the final product in the form of synthetic gas, which can be used to produce fuels (Schneider et al., 2012). Bio-utilization is a method that requires harvesting producer (plant) or product, such as using algae to produce biofuels (as carbon sequestration) (Montana-Hoyos & Fiorentino, 2016). Microalgae is commonly used in bio-utilization. Microalgae cells can naturally situate carbon dioxide both in its gaseous form and as soluble carbonates, with CO_2 fixation efficiency 10–50 times more effective than terrestrial plants (Singh & Dhar, 2019). In biological immobilization, microalgae use sunlight to fix CO_2 through photosynthesis, which can be further converted into biofuels (Razzak et al., 2017). From several topics presented in the CCU method, this article is only focused on bio-utilization with microalgae.

Before further discussion of carbon utilization by microalgae, it is necessary to consider the selected method to capture carbon. This work mainly focuses on solvent methods, especially chemical absorption. Chemical absorption is the most recognizable method of CO_2 capture via post-combustion (Singh & Dhar, 2019). It depends on the reaction between carbon dioxide and a chemical solvent. Based on the scoping review results, several discussions were obtained regarding solvent-based carbon capture methods. The solvent consists of MEA (amine-based solvent), chilled ammonia process (CAP), and amino acid-based solvent. A comparison of each solvent is available in Table 2. MEA is the most extensively used amine solvents in large-scale industries (Mostafavi et al., 2021). It is an organic substance used for its ability to create strong bonds with CO_2, suitable for low partial pressures of CO_2 in the flue gas, high CO_2-capture capacity, and fast reaction kinetics (Budzianowski, 2017). MEA shows a good absorption and desorption rate. Using 30% of MEA is effective as carbon sequestration. Moreover, this concentration level is used as a reference in the development of new solvents (Budzianowski, 2017). Due to its good carbon capture ability, choosing MEA for chemical absorption in post-combustion capture of CO_2 is the most practicable and commercial technology. However, MEA still has some challenges. The solvent desorption process requires a high energy consumption for solvent regeneration. Solvent losses may occur due to evaporation and chemical degradation, leading to reduced absorption capacity. In addition, MEA has high corrosivity and toxicity (Chao et al., 2021). Therefore, innovation is needed to overcome these problems and challenges.

Ammonia (NH_3) is another absorbent considered for CO_2 capture applications in the industrial sector. Ammonia is not a degradable substance, does not react with oxygen alone, and is not degraded in an oxidizing environment compared to other amines. Its cost production is relatively cheaper than other amines. Although ammonia is normally a vapor, its high solubility makes aqueous ammonia a potential solvent for capturing carbon (Hanak et al., 2015). The chilled ammonia process (CAP) is an ammonia-based carbon capture method that uses an aqueous solution of ammonia in chilled conditions. This method uses both heating and cooling systems. The same principle as MEA, CAP also requires absorption and desorption processes. The difference is that the CAP temperature operated for carbon trapping is less than 20 ℃. It becomes important to maintain the exhaust gas temperature low before entering the absorber column. In addition, the formation of solid ammonium bicarbonate deposits in vapor streams leads to pipeline blockages (Sutter et al., 2016).

Another alternative solvent for CO_2 capture being investigated is amino acid salts. This method is superior in low environmental impact, low regeneration energy, and non-toxic (Lin et al., 2022). The most commonly used amino acids are in the form of sodium and potassium salts such as potassium glycinate, sodium taurate, and others (Chen et al., 2020). However, this method is still under development. There are several challenges to optimizing this method for carbon capture. Amino acid salt still has a relatively lower carbon-capture capacity than MEA (Lin et al., 2022). Precipitation also occurs when high concentrations of amino acids interact with large CO_2 loading. Thus reducing the entrapment capacity (Chen et al., 2020).

Table 2. Comparison of solvent for chemical absorption (Amara, 2020; Lin et al., 2022; Madejski et al., 2022).

Parameters	MEA	CAP	Amino acid-based
carbon capture efficiency	95%	90%	50-70%
absorption rate	high	medium	low
regeneration energy	high	low	low
complexity	corrosive, toxicity, and degradation problems	maintenance chilled condition and sedimentation	precipitation and degradation problems
state	widely used in plant scale	on pilot scale	in developing

Based on the discussion that has been shown regarding the solvent, the potential solvent suited for carbon capturing in the oil and gas industry is MEA. The primary reason is the high rate of absorption and desorption process. This property is very suitable for capturing a lot of carbon waste in post-combustion, especially exhaust gas from refinery plants (Carbon Clean, 2022). This method has also been widely used in various industries on a plant scale, thus ensuring its validity (Budzianowski, 2017).

However, we still have to pay attention to the disadvantages of this solvent, such as high energy for regeneration, which results in increased expenditure of funds as well. For that problem, an option of utilizing captured carbon can be diverted to make valuable products. One of the many utilizations is using microalgae as a carbon modifier (Razzak et al., 2017). Carbon captured by MEA is channeled through the pipeline to the algae industry. A study of carbon capture design was conducted by Lin et al. (2022) and Madjeski et al. (2022), and based on that, an inventive carbon capture scheme was created. This scheme is shown in Figure 2. Regenerated solvent and flue gas flowed into the absorber column. In this process, there is an interaction of solvent and carbon that will produce a CO_2-rich solvent. The CO_2-rich solvent is pumped to the heat exchanger and then to the regeneration or stripper tank. After separation, the regenerated solvent is thrown back into the absorber column. The high-purity CO_2 steam is then piped to the microalgae industry for utilization.

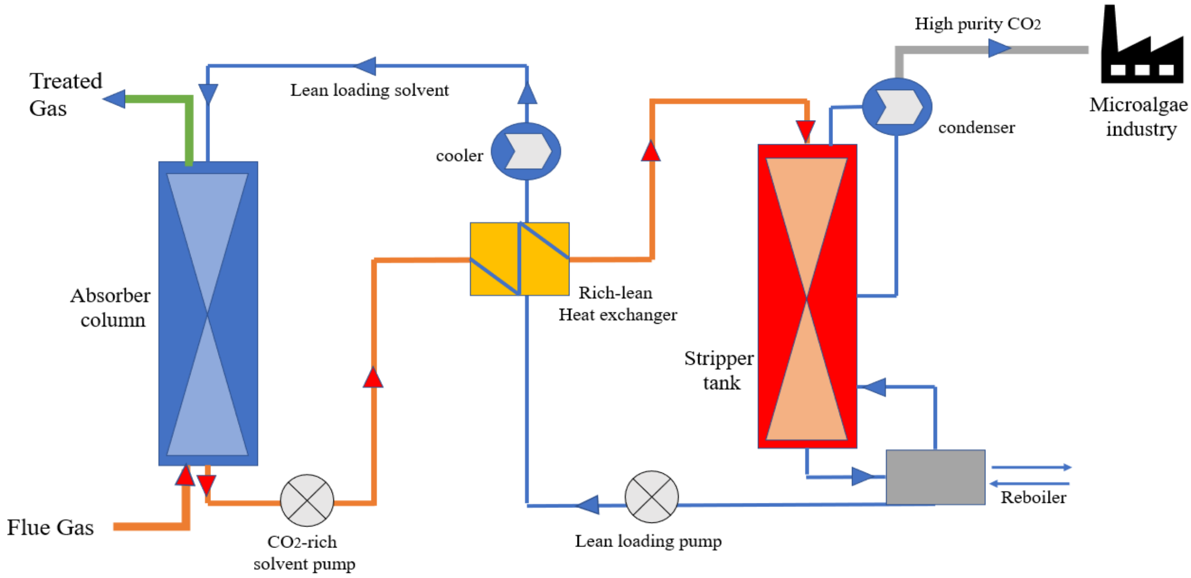

Figure 2. The scheme of carbon capture and utilization.

The captured carbon is not immediately exposed to algae. Optimization of photobioreactor conditions is needed, especially when high-purity CO_2 is added to the growth medium. Microalgae productivity increases with increasing carbon content, but decreases can occur with carbon exceeding 20v/v% (Farelly et al., 2013). Suggested CO_2 content of 5–10% is the best for algae growth and productivity (Razzak et al., 2017). pH level also has a particular effect on the rate of microalgae growth. The optimum condition for algae growth is at a pH of 7–8, and it is rarely found microalgae growing at a pH below 4 or above 9 (Matsumoto et al., 1997). Therefore, it is necessary to regulate the addition of captured carbon in the medium. CO_2 concentration is adjusted to the best conditions required for algae to be used efficiently. Thus, the productivity of metabolites used in biofuel production can be increased. Temperature is another important factor. In general, mesophilic microalgae grow optimally in the temperature range of 15 °C to 45 °C and with adequate light sources (Razzak et al., 2017). Once all the required conditions are met, efficient microalgae production will be achieved.

Different types of microalgae have different carbon capture efficiency. Many microalgae have been reported to have high efficiency in producing biofuels. Chlorella vulgaris has been studied to have a biofuel conversion yield of up to 90% by pre-treatment of H_2SO_4 extraction at 121 ^oC and fermentation (de Farias Silva et al., 2018). Nannochloropsis salina was reported to produce 0.56 L/g biogas at 35 ^oC extraction conditions (Zhao et al., 2014). Besides that, there are still types of microalgae that have been reported that are capable of converting CO_2 emissions into biofuels with fairly high efficiency (Choi et al., 2019). Microalgae is capable of converting hydrocarbons and carbon monoxide into energy fuels and removing SO_x (Huang & Tan, 2014). Microalgae can also be further processed to produce fuels such as biodiesel (via transesterification), bioethanol and biobutanol (via fermentation), and fuel gas (via gasification) (Nigam & Singh, 2011). However, the use of microalgae in producing biofuels is still not economically profitable. The main reasons are:

1. Microalgae have low growth progress in winter and at night (Farelly et al., 2013). In addition, high capital costs are needed to build a photobioreactor.
2. In the biofuel production process, the extraction and transesterification of algal cell lipids is an energy-intensive process. The presence of water content and a hard lipid cell wall adds to the burden of extraction.

Therefore, further research is needed that focuses on economic analysis in the algae industry for biofuel production. The main focus is to reduce microalgae production costs, media maintenance, and the extraction process, which generally costs a lot. With this step, it is hoped that greenhouse gas emissions produced by the oil and gas industry can be reduced and even used to make useful products. Considering this, the CCU method has a high potential to be used as an effort to reduce CO_2 pollution in a sustainable and long-term manner.

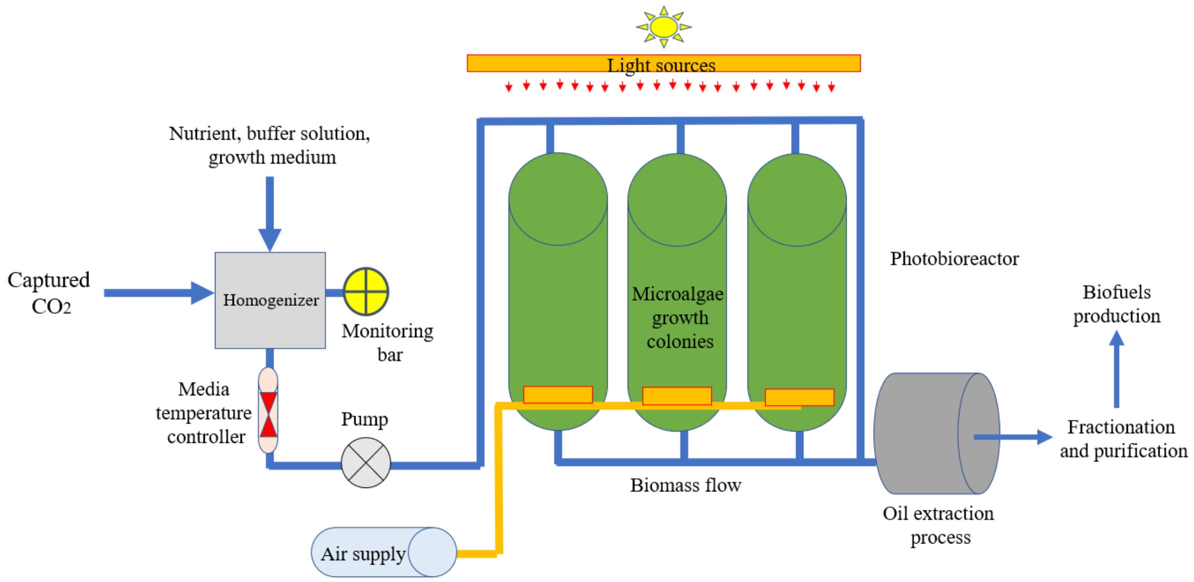

Figure 3. Carbon utilization by microalgae.

4. Conclusion

The solvent method provides good potential as a reproducible carbon capture and is promising for application in the oil and gas industry. MEA is widely applied in post-combustion and mainly has an advantage in its carbon-captured capacity. However, a challenge encountered in the solvent method of carbon capture is energy efficiency. Further research is needed to develop energy-efficient solvent regeneration methods. At the same time, optimization of carbon utilization by microalgae can also be carried out. Thus, biological products as materials for the synthesis of biofuels can be increased. From this review, it can be concluded the step of implementing CCU to make biofuel from microalgae is possible and has the potential to be realized.

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