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Literature Review: Enhancing Technological Carbon Capture to Mitigate the Impact of Climate Change

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Abstract

The release of carbon dioxide is a significant factor contributing to the increase in global temperatures and the intensification of climate change. Efforts have been made to mitigate carbon dioxide emissions through the implementation of Carbon Capture technology, which encompasses various approaches such as Carbon Capture and Utilization (CCU), Carbon Capture and Storage/Sequestration (CCS), and Carbon Capture Utilization and Storage (CCUS). These approaches involve the utilization of physical methods such as absorption, gas separation, and pressure-temperature techniques, as well as chemical methods like the adsorption of amine compounds and membranes. Additionally, biological methods such as fixation are also employed in this endeavor. The operational framework of Carbon Capture technology encompasses three primary processes: pre-combustion, combustion, and oxy-combustion. The Carbon Capture technology employs microalgae cultivation as a biofixation method, demonstrating environmental sustainability and exhibiting considerable potential for future applications. This approach effectively captures substantial amounts of carbon dioxide while demanding minimal nutritional inputs. There are several advantages associated with the utilization of microalgae, including greater effectiveness in fixing CO_2 compared to plants, minimal presence of contaminants, and a reasonably straightforward operational framework. Undoubtedly, the utilization of technology is poised to escalate in the forthcoming years, given the prevailing climate change problem.

Keywords: *Carbon Capture and Storage, Low Carbon Society, Microalgae, Renewable Energy*

Introduction

The progression of time has led to a growing concern over the heightened vulnerability to climate change and the growth of environmental contamination. The global movement of individuals has experienced a notable surge, coinciding with the processes of modernization and globalization. The utilization of cars necessitates the use of fuel, namely fuel oil, resulting in the emission of significant amounts of carbon dioxide (CO_2) gas in comparison to other endeavors. Industrialization is accountable for around 30% of worldwide carbon dioxide (CO_2) emissions, which arise from chemical reactions involved in the production of metals like iron, steel, and chemicals. China and the United States are widely recognized as the two nations that exhibit the highest levels of carbon dioxide (CO_2) emissions. Based on the analysis conducted by the US Energy Information Administration in 2016, it is projected that carbon dioxide (CO_2) emissions will experience a notable escalation from 35.6 billion metric tons in the year 2020 to 43.2 billion metric tons by 2050. This anticipated rise in emissions is expected to contribute to the exacerbation of global warming. Therefore, it is imperative to mitigate the potential adverse effects of rising global temperatures by reducing carbon dioxide emissions.

The presence of air pollution in urban areas poses a significant risk to both the overall air quality and the well-being of the local population. As per the World Health Organization (WHO, 2021), the established thresholds for atmospheric particulate matter that can infiltrate bodily tissues, specifically PM 10 (with a diameter of 10 µg) and PM 2.5 (with a length of 2.5 µg), are below 45 µg/m3 and 15 µg/m3 on a daily basis, as well as 15 µg/m3 and five µg/m3 annually. Indonesia, being an archipelagic nation, exhibits a notable susceptibility to the ramifications of climate change. Since its ratification of the Kyoto Protocol in 1997, Indonesia has undertaken various initiatives aimed at mitigating national greenhouse gas (GHG) emissions. These efforts have primarily focused on sectors that are major contributors to emissions, including forestry, energy, transportation, industry, and waste management. Furthermore, it is widely acknowledged that fossil fuels will continue to serve as the predominant energy source for a minimum of the next five decades. It is important to note that the combustion of these energy resources results in the release of carbon dioxide (CO_2), which plays a substantial role in the phenomenon of global climate change. This phenomenon is characterized by an approximate average increase in global temperature of ± 1℃, as documented by Cuéllar-Franca and Azapagic in 2015. Indonesia's dedication to mitigating national greenhouse gas (GHG) emissions is reinforced by the enactment of Law Number 16 of 2016 and the submission of the Nationally Determined Contribution (NDC) document to the United Nations Framework Convention on Climate Change (UNFCCC). The commitment entails a carbon emission reduction target of 29% by 2030, which is derived from a business-as-usual scenario. Alternatively, with international assistance, the target can be increased to 41%. To effectively achieve this reduction, multiple sustainable strategies are required to support the mitigation of carbon dioxide emissions, which are the primary contributors to greenhouse gas emissions in the ozone layer.

One potential avenue for reducing greenhouse gas emissions is the use of mitigation technologies, such as carbon capture and storage (CCS) technology. In contrast to alternative mitigation technologies, such as low-carbon technology, which involves the selection of raw materials or energy sources to minimize carbon consumption and emissions, carbon capture and storage (CCS) technology operates by capturing carbon emissions generated from industrial processes and subsequently storing and repurposing them for other production processes. CCS technology encompasses various techniques, including physical methods such as absorption using pressured water, Rectisol, and Selexol. Additionally, chemical methods including chemical absorption and membranes, as well as biological methods utilizing microalgae growth, can also be employed in CCS. Subsequently, a range of carbon-capture methods were identified, including Carbon Capture and Utilization (CCU) and Carbon Capture Utilization and Storage (CCUS), which have been extensively implemented in the central region of Indonesia and initiated by the Ministry of Energy and Mineral Resources of the Republic of Indonesia. Furthermore, carbon capture technology has the capability to capture carbon dioxide from the atmosphere and convert it into a viable source of electricity, thereby serving as an environmentally sustainable energy solution.

Academic researchers have expressed interest in the advancement of microalgae culture as a means of environmentally sustainable carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) techniques. This technique primarily employs the capture and utilization of atmospheric carbon for the purpose of generating alternative energy sources and manufacturing valuable commodities. The rapid growth rate, remarkable resilience to harsh settings, and cost-effectiveness of microalgae culture have emerged as significant areas of interest among academics. Furthermore, it is worth noting that microalgae play a significant part in ecological processes by serving as essential agents in the reduction of carbon dioxide (CO_2). This is achieved by their ability to convert carbon into biomass via the process of photosynthesis, as highlighted by Li, Li, and Ho (2022). The objective of this literature study is to elucidate the diverse array of carbon capture technologies presently accessible for mitigating the phenomenon of global warming. This literature study aims to examine various tactics, schemes, working techniques, and the advancement of CCS (Carbon Capture and Storage) technology in mitigating the potential adverse impacts of certain GHG (Greenhouse gas) emissions.

Literature Review

Figure 1 illustrates the overall representation of CCS technology.

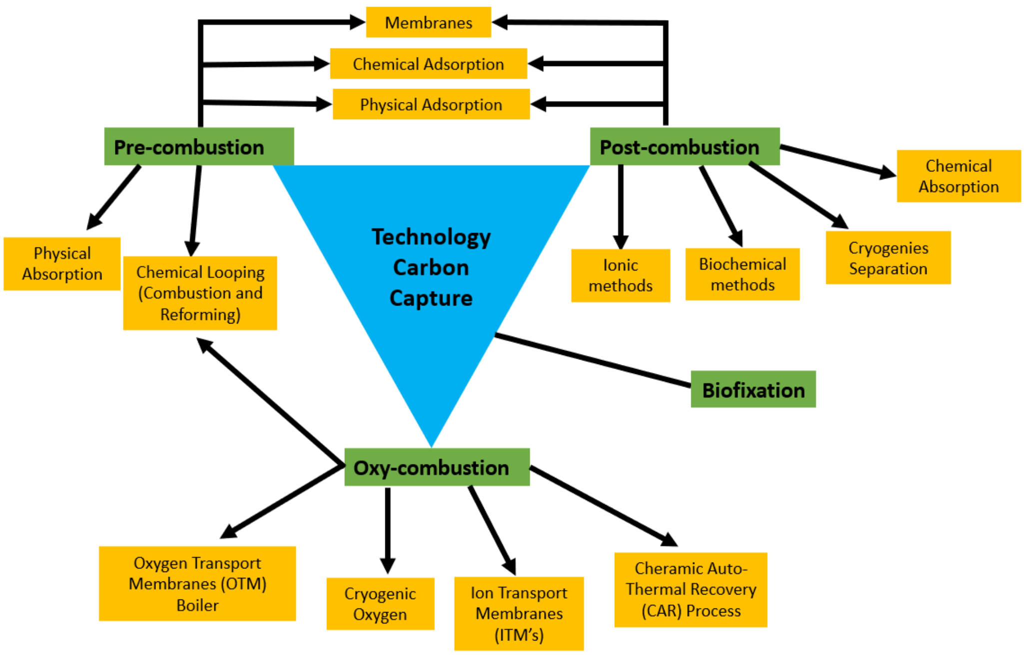

Figure 1 illustrates a range of carbon capture technologies.

The operational mechanisms of Carbon Capture (CC) technology encompass the capture of carbon dioxide (CO_2) emissions from industrial operations, subsequent conveyance and transportation of the captured CO_2 via pipelines or canals to designated storage facilities, and the subsequent injection of the CO_2 into subterranean rock formations to ensure enduring containment. Carbon dioxide (CO_2) storage sites encompass subterranean salt aquifers, oil and gas reservoirs, and coal seams that are at least 0.62 miles (1 km) deep. Additionally, saline/salt reservoirs situated on the seabed with a minimum depth of 1 mile (1.6 km) are also considered as potential CO_2 storage places. Additionally, there exist the designations CCS (Carbon Capture Storage) and CCUS

(Carbon Capture Utilization and Storage). The distinction lies in the fact that, in addition to being stored, carbon can be repurposed to facilitate production processes within specific sectors. For instance, in industries such as biofuel and oil, carbon is employed to enhance recovery. Enhanced Oil Recovery (EOR) is a technique employed for oil extraction, wherein a combination of carbon dioxide (CO_2) and water is utilized to facilitate the upward movement of oil within the well, while simultaneously sequestering the CO_2 underground. The emission reductions resulting from the utilization of CO_2 vary depending on the particular application and the presence of other fuels or materials that can replace CO_2.

According to the Global CCS Institute report of 2022, the current global count of CCS technology facilities stands at 194. Among them, 30 facilities are already operational, 11 are in the construction phase, while the other facilities are still in the developmental stage. Out of the entirety of the projects, 94 are located in the Americas, with 80 of them situated in the United States. In Europe, there are 73 projects, with 27 of them being located in the United Kingdom. Additionally, there are 21 projects in the Asia-Pacific region and 6 projects in the Middle East. These projects together possess a carbon capture capacity of 244 million tons per year, indicating a 44% increase in comparison to the previous year. Carbon capture and storage (CCS) technology, which focuses on sources that release carbon emissions, can be categorized into three primary methods: pre-combustion (often employed in industrial processes), oxy-combustion, and post-combustion (typically utilized in power plants). Additionally, a biological system including fixation through the employment of bacteria and/or animals is also employed. The pre-combustion method entails the gasification of the fuel and subsequent separation of carbon dioxide (CO_2), a process that incurs significant costs in order to enhance its efficacy. The oxy-combustion method involves the combustion of energy in an environment consisting predominantly of oxygen rather than regular air. This process yields a more concentrated stream of CO_2 emissions, facilitating their absorption with greater ease. Subsequently, a post-combustion methodology is employed wherein carbon dioxide (CO_2) is extracted from the exhaust generated during the combustion process. In addition to the process of microbial and organismal fixation with the purpose of utilizing carbon as an energy source. A comprehensive elucidation of the three approaches will be provided in the subsequent sections.

Pre-combustion

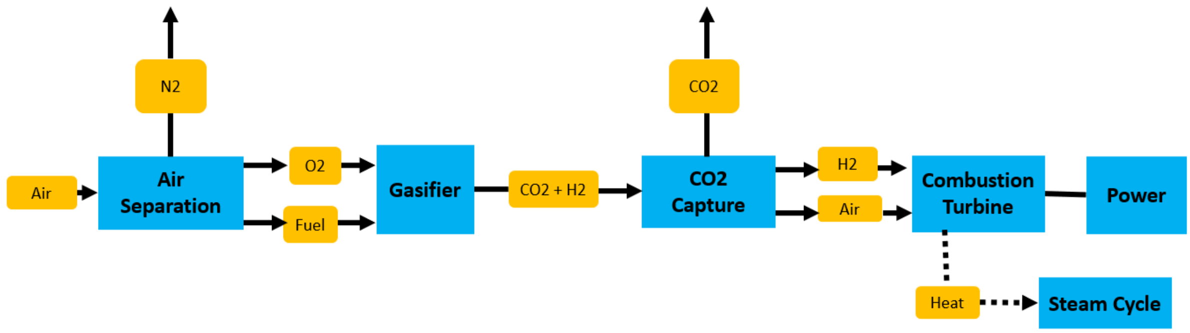

Figure 2 illustrates a carbon capture scheme employing the pre-combustion approach.

The present methodology involves the occurrence of a chemical reaction between a fuel source and either oxygen or air and steam, resulting primarily in the production of synthetic gas, commonly referred to as syngas or fuel gas. This syngas predominantly consists of carbon monoxide (CO) and hydrogen (H_2). Carbon monoxide (CO) undergoes a reaction with steam in the presence of a catalyst within a specialized reactor known as a shift converter. This reaction results in the formation of carbon dioxide (CO_2) and an increased yield of hydrogen gas (H_2). Subsequently, the carbon dioxide is eliminated through a process of physical or chemical adsorption, resulting in the production of a fuel stream rich in H_2. The application of this technological approach has the potential to be extended to newly constructed power plants. However, it is important to note that the technology is still in its early stages of development and has not yet achieved commercial maturity. Furthermore, the implementation of this technology necessitates substantial capital investment due to the extensive modifications that need to be made to the boiler and flue gas systems (Sreenivasulu, Gayatri, Sreedhar, & Raghavan, 2015).

Oxy-combustion

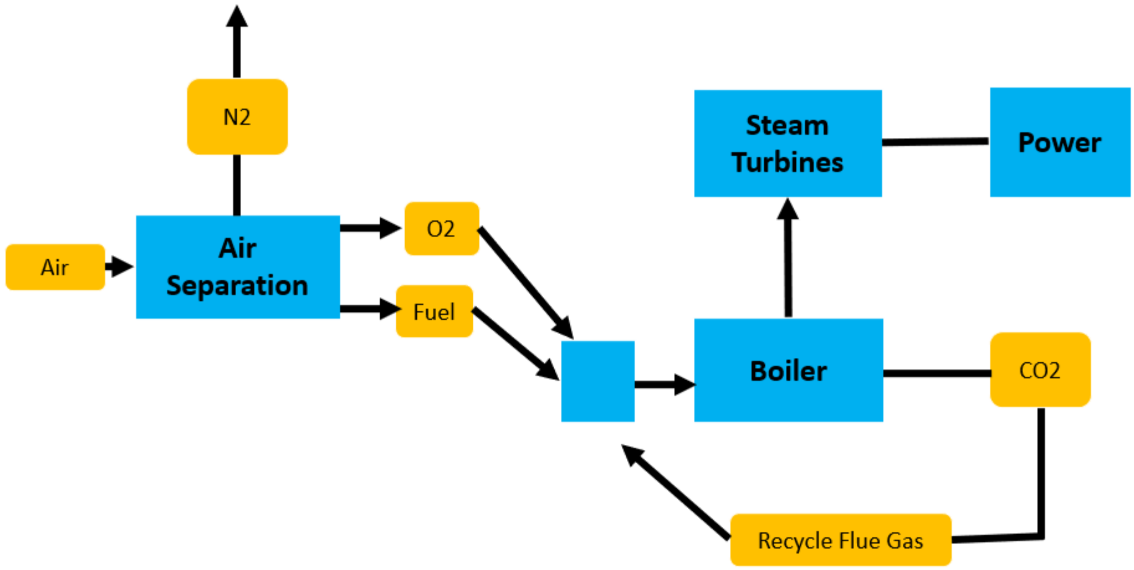

Figure 3. Oxy-Combustion Approach Carbon Capture Scheme

In this approach, the process involves the separation of oxygen from the surrounding air prior to the combustion process. Consequently, the fuel undergoes burning in an oxygen-enriched environment, which is further diluted with recycled exhaust gas, as opposed to pure oxygen. The presence of an oxygen-rich atmosphere devoid of nitrogen (N_2) leads to the production of exhaust gas primarily composed of carbon dioxide (CO_2) and water (H_2O), hence facilitating the purifying process of the concentrated CO_2 stream.

Post-combustion

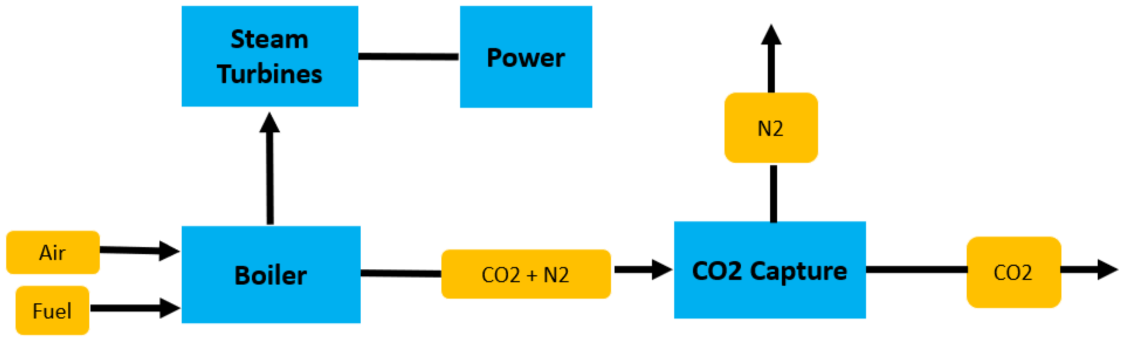

Figure 4. Scheme of Post-Combustion Approach Carbon Capture

In this approach, the process involves the separation of oxygen from the surrounding air prior to the combustion stage. Subsequently, the fuel undergoes combustion in an oxygen-enriched environment, which is further diluted with recycled exhaust gas, as opposed to pure oxygen. The environment, which is abundant in oxygen and lacks nitrogen (N_2), generates a flue gas at the end that is predominantly composed of carbon dioxide (CO_2) and water vapor (H_2O). As a consequence, this leads to a more concentrated stream of CO_2, facilitating the purification process. Furthermore, the separation of CO_2 from combustion flue gas in the context of coal, gas, and other fossil fuel-based thermal power generation can be achieved using several methods such as absorption, adsorption, membrane separation, and other retrofit alternatives (Sreenivasulu et al., 2015). The uptake choices of these products have just recently been established in the commercial sector. The concentration of CO_2 in the flue gas is relatively low, often ranging from 10% to 15%. As a result, the process of capturing and recovering CO_2 from flue gas requires significant investment in terms of both capital expenditures and energy consumption. In fact, the power plant operation necessitates an additional 25% to 30% of energy input to accommodate this CO_2 capture process.

Biofixation

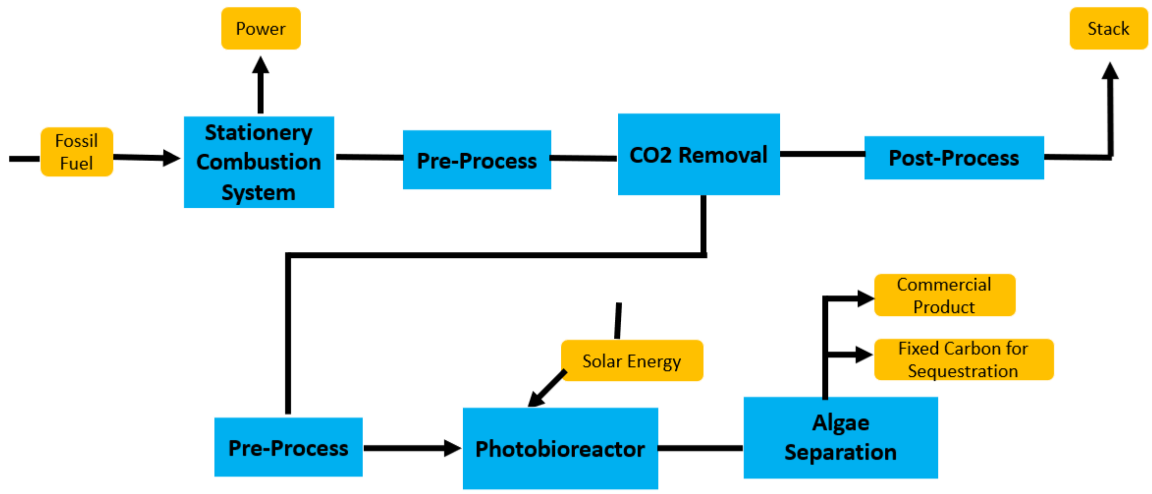

Figure 5. Carbon Capture Scheme with Biofixation Approach

The process of microbial biofixation involves the utilization of autotrophic bacteria, such as photoautotrophs and chemoautotrophs, to fix carbon dioxide (CO_2) for the purpose of cellular growth, hence mitigating carbon dioxide emissions. Broadly speaking, there exist two primary methods for microbial carbon dioxide (CO_2) sequestration: enhancing the biological productivity of autotrophic organisms within their native environment (such as marine fertilization), and cultivating autotrophic microorganisms in controlled systems (like microalgae farming) (Wang & Lan, 2010).

Furthermore, it has been demonstrated by Lam, Lee, and Mohamed (2012) that lipids derived from microalgae biomass possess the potential to be transformed into biodiesel, a sustainable fuel source that exhibits lower carbon dioxide emissions compared to conventional diesel fuel upon combustion.

Physical Carbon Capture Strategy

Several physical techniques are commonly employed in various applications. These techniques include physical adsorption methods, which utilize materials such as zeolite, alumina, and carbon, cryogenic technology, which involves cooling and condensing multigas components at different temperatures, and physical absorption methods, which rely on substances like Selexol, Rectisol, and Purisol (Ben-Mansour et al., 2016; Mondal et al., 2017). An alternative approach involves the utilization of hydrate-based separation, wherein the introduction of a gas stream at high pressure leads to the formation of hydrates that subsequently drive the CO_2 gas into the water phase. Subsequently, the hydrate is isolated through the liberation of carbon dioxide. The determination of the suitable technology for capturing CO_2 is heavily contingent upon the specific characteristics of the CO_2-emitting facility and the type of fuel employed (Zhang et al., 2018). The majority of carbon capture (CC) technologies are primarily suited for implementation in the oxy-combustion method from a physical standpoint.

Chemical Carbon Capture Strategy

A range of separation techniques can be employed, primarily utilizing pre-combustion and post-combustion methodologies. These include gas phase separation, solvent absorption (utilizing amines, potassium carbonate, ammonia, sodium hydroxide, etc.), sorbent adsorption (employing molecular sieves, molecular baskets, activated carbon, lithium components, etc.), as well as membrane-based and hybrid processes, such as chemical adsorption and membrane combinations. The primary techniques employed for this purpose include chemical loop combustion (CLC) and hydrate-based separations. CLC, or Chemical Looping Combustion, is commonly referred to as unmixed combustion due to the absence of direct contact between the fuel and air during the process. Metal oxides, including Fe2O3 (iron ore), NiO (nickel oxide), CuO (copper oxide), and Mn2O3 (manganese trioxide), serve as oxygen carriers that facilitate burning by providing oxygen. The aforementioned procedure involves the utilization of two distinct reactors, one dedicated to air and the other to fuel. An Oxygen carrier is employed to facilitate the circulation between these two reactors.

Membrane separations are typically conducted in a continuous manner, where the permeation process is driven by the pressure differential across the membrane (Al-Mamoori et al., 2017). The gas separation performance is significantly influenced by the membrane material, as well as its configuration, shape, composition, and operating circumstances. According to Sreenivasulu et al. (2015), the utilization of reusable metal oxides obtained from unutilized ore, industrial, or agriculture wastes in the CLC option is considered to be a much more sustainable alternative compared to the combustion of oxy-fuels.

Biological Carbon Capture Strategy

The process of Carbon Capture technology involves harnessing the photosynthetic activity of autotrophs for biological purposes. One such method involves the utilization of microalgae in the process of carbon dioxide fixation. Among the three different types of carbon capture technologies, one with significant promise is the utilization of carbon as a material for supporting production, known as CCU (Carbon Capture and Utilization). This approach involves recycling captured CO2 and utilizing it as a valuable resource for the manufacturing of emission-neutral or even value-added products (VAP). Furthermore, the utilization of microalgae's biologically mediated carbon capture and utilization (bio-CCU) methodology holds significant potential as a biotechnological approach for the substantial reduction of carbon emissions (Daneshvar et al., 2022). Various strategies can be employed to enhance the production of microalgae, such as the utilization of carbon capture techniques facilitated by mutagenesis, genetic engineering, and the application of nanomaterials. The application of UV, nuclear, and chemical mutagenesis techniques aims to enhance the capacity of microalgae to fixate CO_2 (carbon dioxide). According to a recent study by Li et al. (2022), the utilization of nanomaterials has been found to have a substantial impact on the relative electron transfer rate within photosynthetic system II, as well as the number of reactive oxygen species in microalgae. Consequently, this leads to an overall enhancement in photosynthetic activity, particularly in relation to carotenoid production. The selection of carbon capture and storage (CCS) technology utilizing microalgae has a direct impact on the biomass yield achieved, thus influencing the quantity of carbon sequestered. Furthermore, variations exist in the energy, fertilizer, water, and building material demands, which will ultimately impact the quantity of carbon utilized or emitted (Prayitno et al., 2021). In the context of Indonesia, the development of CCS (Carbon et al.) technology is now in progress, encompassing two primary types: photobioreactors (FBR) and open ponds (Prayitno et al., 2021). The selection of carbon capture and storage (CCS) technology utilizing microalgae has a direct impact on the biomass yield achieved, thus influencing the quantity of carbon sequestered.

The selection of microalgae culture as a carbon capture and storage (CCS) method is predicated upon its capacity to assimilate carbon dioxide (CO2) gas as a primary substrate for photosynthetic processes, subsequently transforming it into organic matter. The capacity to trap carbon emissions, particularly those released from industrial chimneys, is a notable advantage of microalgae in the context of large-scale carbon capture (Daneshvar et al., 2022; Olaizola & Bridges, 2004). Microalgae encompass both prokaryotic blue-green algae, specifically Cyanobacteria, and eukaryotic microalgae, which consist of green algae, red algae, and diatoms. Microorganisms exhibit superior performance compared to alternative raw materials due to their exceptional adaptability to harsh settings and their uncomplicated yet adaptable nutritional requirements. According to Singh and Dhar (2019), microalgae have a better efficiency in fixing CO_2 compared to terrestrial plants, owing to their simple cellular structure and rapid development. The process of prokaryotic photosynthesis emerged billions of years in the past, eventually leading to the development of eukaryotic photosynthesis. This transformative event played a crucial role in reshaping the Earth's atmosphere by actively devouring carbon dioxide (CO_2) and augmenting it with oxygen. The utilization of this heterogeneous assemblage of microorganisms has been employed for the purpose of transforming inorganic carbon (Ci) into organic carbonaceous substances through the process of photosynthesis. Eukaryotic green algae, diatoms, and euglenoids, along with prokaryotic cyanobacteria, commonly referred to as microalgae, engage in the process of carbon dioxide (CO_2) assimilation to produce a diverse range of biochemical compounds such as lipids, proteins, carbohydrates, pigments, and phenols (Daneshvar et al., 2022).

Microalgae have the ability to sequester carbon dioxide (CO_2) from different sources, including the atmosphere, industrial exhaust gases (such as exhaust and combustion gases), and fix it in the form of dissolved inorganic carbonates, such as sodium bicarbonate ($NaHCO_3$) and sodium carbonate (Na_2CO_3) (Wang & Lan, 2010). The process of carbon capture by microalgae culture can be effectively conducted inside their indigenous environments, including rivers, lakes, and seas, where the growth and development of microalgae are naturally supported. Enhancements to carbon capture methodologies involving microalgae within ecological settings, such as marine environments, can be optimized by marine fertilization techniques. This process entails augmenting aquatic nutrients while concurrently restricting iron nutrients (macronutrients), which have been seen to impede biomass productivity. Nevertheless, it remains imperative to address the issue of uncertainty pertaining to potential side effects that have the capacity to alter the ecological and biochemical characteristics of water (Amount & Bopp, 2006). In the context of microalgae cultivation, the utilization of controlled environments such as photobioreactors and open ponds, along with the addition of carbonate nutrients (specifically Na_2CO_3/Sodium Carbonate and $NaHCO_3$/Sodium Bicarbonate), has been demonstrated to enhance cellular proliferation. Furthermore, the biomass generated by the growth of microalgae has various potential applications, including its utilization as fertilizer, animal feed, health food, and conversion into biofuels. This comprehensive utilization of biomass facilitates the establishment of a full carbon cycle and enables the production of agrichar, which serves as a means of permanently sequestering CO_2 through biological processes. Therefore, the process of carbon dioxide (CO_2) fixation in photosynthesis demonstrates promising potential as a technology due to its inherent characteristics of energy efficiency, sustainability, and environmental friendliness.

The cellular absorption of carbon dioxide (CO_2) from the atmosphere entails the participation of the extracellular zinc metalloenzyme carbonic anhydrase (CA) and an active transport mechanism responsible for the uptake of supplementary nutrients, specifically carbonate. The carbonic anhydrase (CA) enzyme is classified as a metallo-enzyme due to its dependence on metal ions, namely zinc (Zn). It functions by promoting the fixation of carbon dioxide (CO_2) through the mechanism of nucleophilic attack, facilitated by hydroxide ions that are coordinated to the zinc atoms. This enzymatic process is significant in the context of carbon fixation, as it converts CO_2 into bicarbonate, which serves as a substrate for the enzyme RuBisCO. This information is supported by the findings of Mondal et al. (2017). Subsequently, the sequestration of carbon dioxide (CO_2) can occur in many forms such as lipids, carbohydrates, or proteins, contingent upon the specific species of microalgae. The process of extracting lipids from microalgae, which have assimilated CO_2, enables their utilization as biofuel, biodiesel, and bioethanol. The enzymatic catalysis of the chemical reaction facilitated by carbonic anhydrase can be represented by the following equation:

$CO_2 + H_2O \longrightarrow HCO_3^- + H^+$

Cyanobacteria and algae have evolved their own unique versions of photosynthetic carbon concentrating mechanisms (CCMs) in order to enhance the efficiency of capturing carbon dioxide (CO2) by Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), which is known for its inefficiency in this process. The essential involvement of carbonic anhydrase (CA), a metalloenzyme that contains zinc, has been found in the process of carbon concentration mechanism (CCM). CA facilitates the reversible hydration of carbon dioxide (CO2) to bicarbonate ions and protons, hence assisting in the fixation of atmospheric CO2 (Mondal et al., 2016). Various species of microalgae have been utilized in carbon capture technology, including Scenedesmus obliquus, Chlorella kessleri (Morais et al., 2007), Chlorella vulgaris, Dunaliella tertiolecta, Botryococcus braunii, Spirulina platensis (Sydney et al., 2010), Chlorocuccum littorale (Ota et al., 2009), Nannochloropsis oculata (Chiu et al., 2009), and Anabaena sp. CH1 (Chiang et al., 2011). The primary focus of these studies revolves around examining the impact of different concentrations of carbon dioxide (CO2) on the production of biomass. This methodology facilitates the establishment of a sustainable carbon cycle, as the microalgae effectively assimilate the carbon dioxide released during the combustion of biodiesel or bioethanol, thereby perpetually regulating the atmospheric carbon dioxide concentration. There are several notable benefits associated with the utilization of microalgae for carbon capture. These advantages include a heightened rate of photosynthesis, the implementation of a clean and cost-effective technology, as well as the generation of diverse high-value by-products. These by-products encompass biodiesel, pigments possessing medicinal properties, animal feed suitable for aquaculture, biomass, fertilizers, and various cosmetic products.

The prospective advancement of carbon capture technology in forthcoming years

One of the primary challenges encountered in the advancement of carbon capture technology on a large scale is the substantial financial burden associated with operational and maintenance expenses. While there is considerable variation in cost estimates, the primary expenses typically pertain to the equipment and energy consumption associated with the capture and compression stages. During the capture stage, the presence of CO_2 can lead to a decrease in the power and efficiency of industrial units, as well as an increase in their water consumption. According to Al-Mamoori et al. (2017), the financial viability of carbon capture projects may be compromised due to the increased expenses associated with these issues and others. One significant challenge encountered pertains to the substantial energy requirement associated with operating the system, particularly in relation to the utilization of electricity for pumps and the necessity for nutrient provision. To mitigate the energy demand, the design engineering of this technology necessitates attention, while the utilization of renewable energy resources is imperative for the reduction of carbon emissions. Nevertheless, it is imperative to conduct a comprehensive examination and analysis of the utilization of renewable energy in Indonesia, as its current implementation remains limited. This assessment is crucial in order to enhance the effectiveness and efficiency of carbon capture technology within the industrial sector.

In relation to financial considerations, the utilization of physical and chemical carbon capture technologies incurs higher costs compared to the biological approach. The cost-effectiveness of carbon utilization (CCUS) in the United States has been substantiated through research conducted by Daneshvar et al. (2022) and the National Energy Technology Laboratory (NTEL). This conclusion is based on the consideration of the global average price of carbon dioxide (CO_2), which stands at around \$62.65 per ton of CO_2. The proposed plan necessitates a substantial financial investment amounting to around \$8.20 trillion. However, it is important to note that this cost is partially mitigated by the advantages derived from existing carbon capture techniques, such as enhanced oil recovery. Consequently, the overall expenditure incurred by implementing this strategy until the year 2050 is estimated to be \$5.76 trillion. The achievement of this substantial expenditure is technically viable through the synergistic endeavors and cooperation among governmental entities, commercial enterprises, and local inhabitants. The potential for achieving significant reductions in carbon dioxide emissions within the commercial sector is contingent upon the implementation of cost-saving measures, such as the adoption of industrial bio-CCU. The use of microalgae fixation technology involves a collaborative effort with industrial carbon capture and utilization (CCU) technology, encompassing both physical and chemical processes. This collaboration aims to achieve energy utilization that is environmentally friendly, sustainable, and highly efficient, while minimizing carbon emissions.

The usage of microalgae for carbon dioxide (CO_2) fixation is a promising approach for both environmental conservation and resource exploitation. This technique can be integrated with wastewater and flue gas treatment, as well as biofuel production, resulting in significant economic advantages. Nevertheless, microalgae in industrial settings continue to face challenges, including suboptimal photosynthetic efficiency, substantial input expenses, and considerable capital requirements (G. et al., 2023). According to Wang and Lan (2010), the economic viability of a carbon dioxide (CO_2) fixation strategy for microalgae cultivation can be improved by using integrated approaches that involve the simultaneous mitigation of CO_2 emissions, the generation of high-value by-products, wastewater treatment, and waste usage. Furthermore, the implementation of carbon capture technology via microalgae cultivation necessitates additional advancements in the areas of design, raw materials, and industrial processes. To enhance the efficiency of the upstream process, various aspects require development. These include the careful selection of appropriate microalgae strains, the optimization of nutrient supply by exploring cost-effective and environmentally sustainable alternatives (e.g., utilizing organic wastewater), the refinement of culture operating conditions (e.g., light intensity, pH, and stirring), and the adoption of alternative energy sources that are environmentally friendly and renewable. Additionally, downstream processes, such as the implementation of effective harvesting techniques and the utilization of biomass, necessitate further exploration and refinement (Prayitno et al., 2021). Moreover, it is imperative to enhance biomass output from 20% to 60% in order to mitigate greenhouse gas (GHG) emissions per kilogram of biomass generated. This can be achieved by the careful selection of appropriate microalgae species and the development of a suitable technological framework tailored to the chosen microalgae type. Therefore, it is imperative for the advancement of carbon capture technology to prioritize the fundamental requirements of the environment, specifically the mitigation of greenhouse gas (GHG) emissions, in order to safeguard the well-being and safety of organisms, while also taking into account the economic dimension.

Conclusion

The rise in global temperature has a direct correlation with the concentration of carbon dioxide present in the Earth's atmosphere. The emission of CO_2 gas originates from the combustion of fossil fuels, which are commonly employed as an energy source across several industrial sectors. Regarding the mitigation of carbon dioxide in the atmosphere, significant emphasis has been placed on the development and implementation of carbon capture technology. This approach aims to curtail emissions by sequestering carbon dioxide within the Earth, so preventing its release into the atmosphere. The predominant method employed for carbon capture is known as CCS (Carbon et al.). This technology operates by capturing carbon dioxide (CO_2) and subsequently injecting it into depleted or nearly depleted underground rock formations found within oil and gas reservoirs. Additionally, there exists another approach called CCUS (Carbon et al.), which involves the recycling of CO_2 to facilitate various industrial processes, including those within the oil and biofuel sectors. The capture method can be classified into three categories: pre-combustion, oxy-combustion, and post-combustion. These categories employ various physical and chemical techniques. Furthermore, the implementation of microalgae cultivation as a technique of Carbon Capture and Storage (CCS) serves a crucial function in mitigating CO_2 (carbon dioxide) emissions through biological processes, including biofixation, so contributing to the preservation of the Earth's thermal equilibrium. The process of carbon capture by microalgae culture can be classified into two main categories: open systems, which involve the use of retention ponds, and closed systems, which encompass photobioreactors or FBRs. Furthermore, the fixation of microalgae can be enhanced through the regulation of many external parameters, including pH levels, irradiation intensity, nutrient availability, and temperature. The utilization of carbon capture technology in the future poses a significant challenge for academics in the development of highly efficient and cost-effective carbon capture technologies, which prioritize productivity, ease of maintenance, and operational expenses. Indonesia, situated in a tropical region characterized by rich microalgae biodiversity, possesses significant prospects for the advancement of this technology. Hence, it is anticipated that Indonesia would emerge as an engaged participant in the advancement of this technology, rather than solely serving as a recipient of similar innovations developed overseas.

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