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Comprehensive Review of Carbon Capture Technologies for Climate Change Mitigation

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Abstract

The emissions of carbon dioxide (CO_2) significantly contribute to the rise in global temperatures and the exacerbation of climate change. Various initiatives have been undertaken to reduce CO_2 emissions, notably through the adoption of carbon capture technologies. These technologies include Carbon Capture and Utilization (CCU), Carbon Capture and Storage (CCS), and the integrated approach of Carbon Capture, Utilization, and Storage (CCUS). Our study aims to elucidate the operational principles of CCU, highlight the benefits of carbon capture, and provide recent updates on the application of CCU and CCS in daily contexts. Utilizing a qualitative descriptive methodology through a literature review, we examine the primary sources related to CCU and CCS from various databases such as Scopus, Springer, Taylor & Francis, and Google Scholar, covering the period from 2014 to 2024. As a novelty, our review covers physical techniques like absorption, gas or membrane separation, and pressure-temperature manipulation, alongside chemical methods such as the adsorption of amine compounds. Furthermore, biological techniques, including fixation, are also utilized. The operational framework of carbon capture technology is structured around three main processes: pre-combustion, post-combustion, and oxy-combustion. Notably, carbon capture technology incorporates the cultivation of microalgae as a fixation strategy, which promotes not only environmental sustainability but also shows significant promise for future applications. This method effectively sequesters large quantities of CO_2 while requiring minimal nutritional resources. The advantages of utilizing microalgae include enhanced efficiency in CO_2 fixation compared to terrestrial plants, reduced contamination, and a relatively simple operational structure. It is evident that the adoption of carbon capture technology is expected to increase in the coming years, particularly in light of the ongoing challenges posed by climate change. Prospective advancements in carbon capture technology are then discussed based on the review result. Thus, our literature review contributes to promoting the broader implementation of carbon capture technologies.

Keywords:
carbon capture and storage, carbon capture and utilization, carbon capture technology, literature review

1. Introduction

Over time, concerns about increased vulnerability to climate change and escalating environmental pollution have intensified. Simultaneously, global migration has surged in tandem with modernization and globalization trends. The reliance on automobiles necessitates fuel consumption, particularly fuel oil, which leads to substantial carbon dioxide (CO_2) emissions. Industrial processes contribute approximately 30% of global CO_2 emissions, primarily due to chemical reactions in the production of metals such as iron and steel and various chemicals. China and the United States are prominently identified as the leading countries in terms of CO_2 emissions. According to the US Energy Information Administration, in 2016, CO_2 emissions are projected to rise significantly from 35.6 billion metric tons in 2020 to 43.2 billion metric tons by 2050. The presence of air pollution in urban areas poses a significant risk to both overall air quality and the well-being of the local population. Various anthropogenic activities, such as fossil fuel combustion, deforestation, agricultural production, mining, and livestock farming, trigger an increase in greenhouse gas emissions that worsen air quality. According to the 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.

Climate change, primarily caused by increased CO_2 emissions in the atmosphere, is currently the main driver of global warming and the greenhouse effect, posing a serious threat to the well-being of planet Earth and its inhabitants. Indonesia, being an archipelagic nation, is notably susceptible to the impacts of climate change. Since ratifying the Kyoto Protocol in 1997, Indonesia has undertaken various initiatives to mitigate national greenhouse gas (GHG) emissions. These efforts have focused on major contributing sectors, including forestry, energy, transportation, industry, and waste management. Furthermore, it is widely acknowledged that fossil fuels will remain the predominant energy source for at least the next five decades. The combustion of these energy resources results in the release of CO_2. This phenomenon is characterized by an average global temperature increase of approximately 1 °C (Cuéllar-Franca & Azapagic, 2015).

Indonesia's commitment to mitigating national 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 GHG emission reduction target of 29% by 2030, based on a business-as-usual scenario. In the most recent Enhanced Nationally Determined Contribution (ENDC) document, Indonesia's GHG emission reduction target with its own capabilities has increased to 31.89%, and the target with international support has increased to 43.2% (PPID KLHK RI, 2022). The increase in the target is driven by recent national climate change policies, which encompass various sectoral strategies. These include the Forestry and Other Land Use (FOLU) Net Sink 2030 initiative, the promotion of electric vehicle usage, the 40% biodiesel mix (B40) policy, enhanced efforts in waste management such as utilizing Wastewater Treatment Plant (WWTP) sludge, and elevated objectives within the agricultural and industrial sectors.

One promising strategy for mitigating GHG emissions involves carbon capture and storage (CCS) systems. Unlike other mitigation approaches, CCS specifically targets the capture of carbon emissions produced during industrial activities. This captured carbon can then be stored or repurposed for various production applications. CCS encompasses a variety of techniques, including physical methods (e.g., absorption through pressurized water), chemical methods (e.g., chemical absorption, chemical looping, and Direct Air Capture (DAC)), and biological approaches leveraging the growth of microalgae. A diverse array of carbon capture strategies has emerged, notably Carbon Capture Utilization (CCU) and Carbon Capture Utilization and Storage (CCUS), which have seen significant implementation in central Indonesia. Among the three different types of carbon capture technologies, a promising approach is the utilization of carbon for supporting production, known as CCU. This approach involves recycling captured CO_2 and using it as a valuable resource for manufacturing emission-neutral or value-added products. Moreover, carbon capture technology possesses the potential to extract CO_2 from the atmosphere and transform it into a sustainable source of electricity, thus contributing to environmentally friendly energy solutions.

Studies reviewing CCUS technology are abundant, but studies simultaneously reviewing physical, chemical, and biological strategies for CCUS are still limited. For example, Bashir et al. (2024) reviewed several CO_2 geo-storage techniques as well as physical and chemical processes (e.g., adsorption, mineral trapping, and capillary). Meanwhile, Liu et al. (2024) provided an overview of the physical and chemical properties of red mud that can absorb large amounts of CO_2. Madejski et al. (2022) updated CO_2 capture technologies, including pre-combustion capture and post-combustion capture methods (e.g., physical separation and chemical absorption). Allangawi et al. (2023) compared physical and chemical sorbents for carbon capture technologies, concluding that amine-based sorbents are superior materials for carbon capture. Additionally, Hanson, Nwakile, and Hammed (2024) reviewed chemical and biological strategies for carbon utilization methods.

Moreover, CCUS review studies in the Indonesian context are still limited to an overview of CCS status from the perspectives of potentials, barriers, regulations, and financing options (Best et al., 2011). Thus, we aim to fill this literature gap by exploring various strategies, frameworks, operational methodologies, benefits, and advancements associated with CCS technology in addressing the potential negative effects of specific GHG emissions. Our literature review aims to clarify the various carbon capture technologies currently available to address the challenges posed by global warming. The effectiveness of carbon capture technology in reducing carbon emissions remains ambiguous, as neither its percentage contribution nor the actual emissions reduction has been conclusively established. This uncertainty stems from the limited scope of its implementation and the fact that carbon capture technology is primarily in an experimental phase. Furthermore, we will investigate the roles of CCU and CCS as strategies to alleviate the annual risks associated with global warming in diverse global regions. As a contribution, we expect that our literature review will encourage wider adoption of carbon capture technologies.

2. Methods and Materials

This research employs a literature review methodology, collecting reference sources from nationally and internationally accredited scientific journals, conference proceedings, e-books, and relevant websites. The focus is on material related to the development of carbon capture technology. The literature sources, particularly scientific articles and journals, are accessed through various databases, including BASE, Science Direct, Taylor and Francis, Springer Nature, and Neliti, covering the period from 2014 to 2024. Keywords used for the research include "carbon capture technology", "carbon capture and storage," and "carbon capture utilization".

3. Results and Discussions

3.1 Carbon Capture Technology

Carbon capture technologies employ various methods to isolate CO_2 from emissions generated by industrial activities and energy production. These technologies are typically classified into three primary categories: CCS, CCUS, and CCU. Each category features unique mechanisms and applications that play a significant role in mitigating CO_2 emissions. The principal distinction among these technologies lies in their approaches to the storage, transportation, and utilization of CO_2. CCS involves capturing CO_2 emissions from industrial sources, transporting the captured gas through pipelines or canals to specific storage sites, and injecting the CO_2 into underground geological formations for long-term sequestration. Potential storage locations include subterranean salt aquifers, depleted oil and gas fields, unmineable coal seams, basalt formations, and organic-rich shales.

The distinction between CCU and CCUS lies in the additional capability of reusing captured carbon to enhance production processes in specific industries. For instance, sectors such as biofuels and oil utilize carbon to improve recovery rates. The CO_2 Enhanced Oil Recovery (EOR) is a well-established method that involves injecting CO_2 into oil reservoirs to augment oil extraction while concurrently sequestering CO_2. This approach has garnered interest as a dual-purpose strategy that not only boosts oil recovery but also mitigates climate change by lowering greenhouse gas emissions. The extent of emission reductions achieved through the application of CO_2 depends on the specific context and the availability of alternative fuels or materials that can substitute for CO_2.

Figure 1 illustrates the stages of carbon capture technology and its methodologies. CCS technology targets sources of carbon emissions and can be classified into three main techniques: pre-combustion, oxy-combustion, and post-combustion. The pre-combustion method is frequently applied in industrial settings, oxy-combustion is characterized by combustion in an oxygen-rich environment, and post-combustion is predominantly used in power generation facilities. Additionally, biological systems that utilize bacteria and/or animals for carbon fixation are part of this technology.

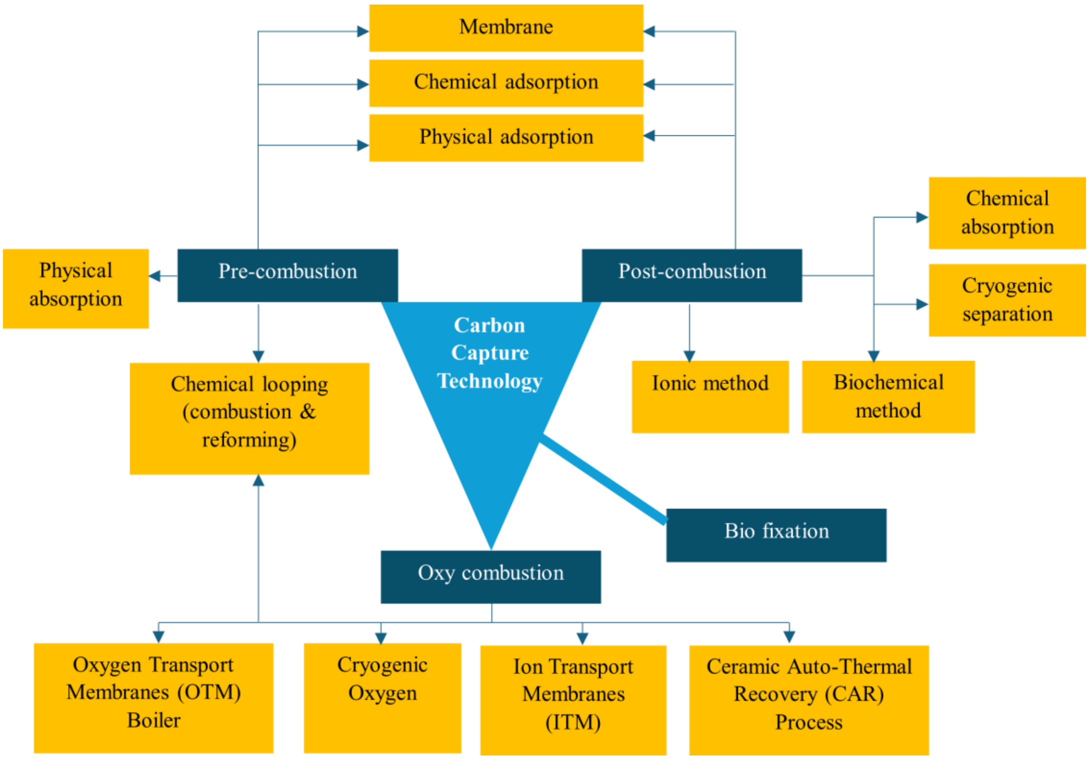

Figure 1. Types of carbon capture technologies (Zhang et al., 2018).

Understanding the interplay between these methods is crucial for effectively reducing CO_2 emissions, as each technique possesses distinct features, benefits, and applications. The pre-combustion approach involves the gasification of fuel followed by the separation of CO_2. While this process can be costly, it enhances overall efficiency. Oxy-combustion produces a concentrated CO_2 stream by burning fuel in an oxygen-dominant atmosphere, simplifying the capture process. Lastly, the post-combustion technique focuses on extracting CO_2 from the flue gases produced during combustion. The role of microbial and organismal fixation in utilizing carbon as an energy source will be discussed in detail in the following sections.

3.1.1 Pre-combustion

Pre-combustion carbon capture, as shown in Figure 2, is a promising approach for reducing GHG emissions from fossil fuel combustion. It involves the removal of CO_2 from fossil fuels or biomass before combustion occurs so it can enhance efficiency and facilitate cleaner energy production. This method typically takes place in Integrated Gasification Combined Cycle (IGCC) plants, where fuels are gasified to produce syngas—a mixture of hydrogen, carbon monoxide, and CO_2. It involves a chemical reaction between a fuel source and either oxygen or air combined with steam, leading to the production of synthetic gas, commonly known as syngas or fuel gas. This syngas is primarily composed of carbon monoxide (CO) and hydrogen (H_2). In a specialized reactor known as a shift converter, the CO reacts with steam in the presence of a catalyst, resulting in CO_2 production and an enhanced yield of H_2 gas. The CO_2 is then removed through physical or chemical adsorption processes, yielding an H_2-rich fuel stream.

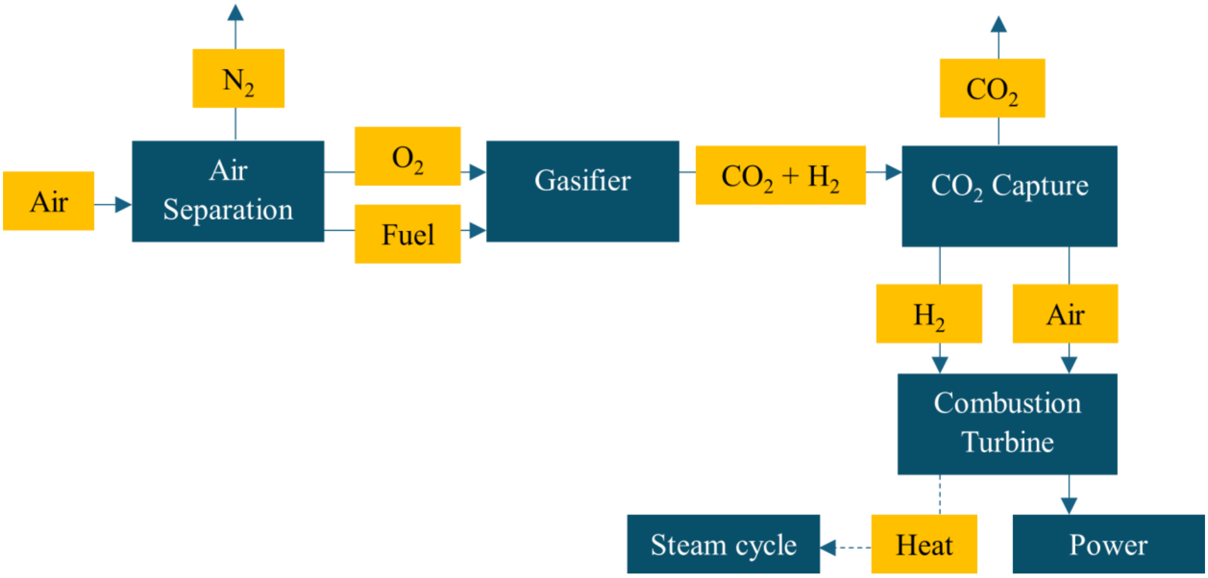

Figure 2. A carbon capture scheme employing the pre-combustion approach (Zhang et al., 2018).

This technological approach holds promise for application in newly constructed power plants. This approach is advantageous because it allows for a more efficient capture process and can produce H2 as a clean fuel source. However, it is crucial to recognize that the technology is still in the nascent stages of development and has yet to reach commercial viability. Additionally, the deployment of this technology requires significant capital investment and infrastructure due to the extensive alterations needed for the boiler and flue gas systems (Al-Mamoori et al., 2017; Sreenivasulu et al., 2015). Despite challenges related to capital costs and system complexity, ongoing advancements in gasification and solvent technologies continue to improve the viability of pre-combustion carbon capture in the transition towards a low-carbon future.

3.1.2 Oxy-combustion

The oxy-combustion process, depicted in Figure 3, involves the separation of oxygen from the surrounding air before the combustion process. Consequently, the fuel burns in an oxygen-enriched environment that is further diluted with recycled exhaust gas rather than pure oxygen. This oxygen-rich atmosphere, devoid of nitrogen (N_2), results in exhaust gas primarily composed of CO_2 and water (H_2O), thereby facilitating the purification of the concentrated CO_2 stream.

Thus, oxy-combustion can achieve higher capture efficiencies compared to post-combustion methods. By enhancing CO_2 concentration in flue gases and minimizing NO_x emissions, this technology offers an effective solution for industries seeking to lower their carbon footprint while maintaining energy production. However, it requires significant energy for air separation and incurs higher operational costs due to the need for pure oxygen. The challenges associated with this method include high energy consumption, operational complexity, and cost considerations (Rubin et al., 2012). As research progresses and challenges are addressed, oxy-combustion could play a crucial role in global decarbonization efforts.

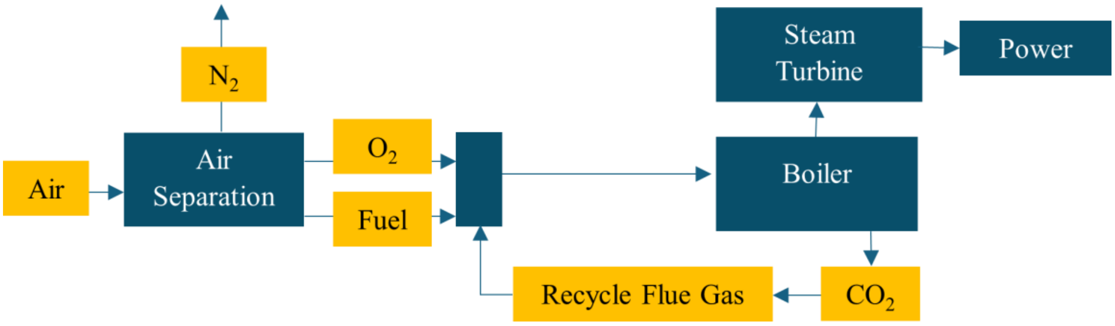

Figure 3. Carbon capture scheme with oxy-combustion approach (Zhang et al., 2018).

3.1.3 Post-combustion

Post-combustion carbon capture in Figure 4 represents a vital technology in the fight against climate change by enabling significant reductions in CO_2 emissions from existing power plants and industrial sources. 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 through several methods, such as absorption, adsorption, membrane separation, and other retrofit alternatives (Sreenivasulu et al., 2015). The uptake of these products has 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, capturing and recovering CO_2 from flue gas requires significant investment in both capital expenditures and energy consumption. In fact, power plant operations necessitate an additional 25% to 30% of energy input to accommodate this CO_2 capture process. While it faces challenges related to energy consumption and solvent management, ongoing research and technological advancements continue to enhance its viability and effectiveness. Post-combustion carbon capture will likely play an essential role in achieving substantial emission reductions across various sectors.

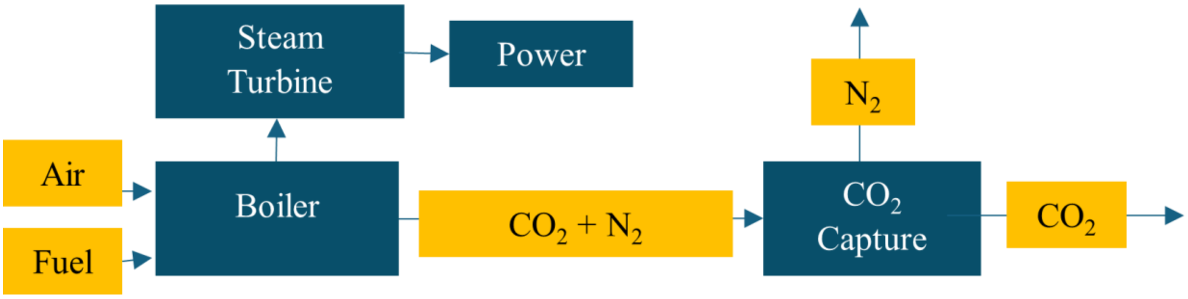

Figure 4. Carbon capture scheme using post-combustion approach (Zhang et al., 2018).

3.1.4 Biofixation

Biofixation carbon capture, as shown in Figure 5, utilizes biological systems, particularly microalgae, to capture and convert CO_2 into organic biomass. Additionally, lipids derived from microalgae biomass can be transformed into biodiesel, a sustainable fuel source with lower CO_2 emissions compared to conventional diesel upon combustion (Lam, Lee, and Mohamed, 2012). This method leverages the natural photosynthetic capabilities of microalgae, making it an innovative and sustainable approach to carbon management. Microbial biofixation involves using autotrophic bacteria, such as photoautotrophs and chemoautotrophs, to fix CO_2 for cellular growth, thereby mitigating CO_2 emissions. Two primary methods for microbial CO_2 sequestration are (i) enhancing the biological productivity of autotrophic organisms in their native environment (e.g., marine fertilization); and (ii) cultivating autotrophic microorganisms in controlled systems (e.g., microalgae farming) (Wang & Lan, 2010).

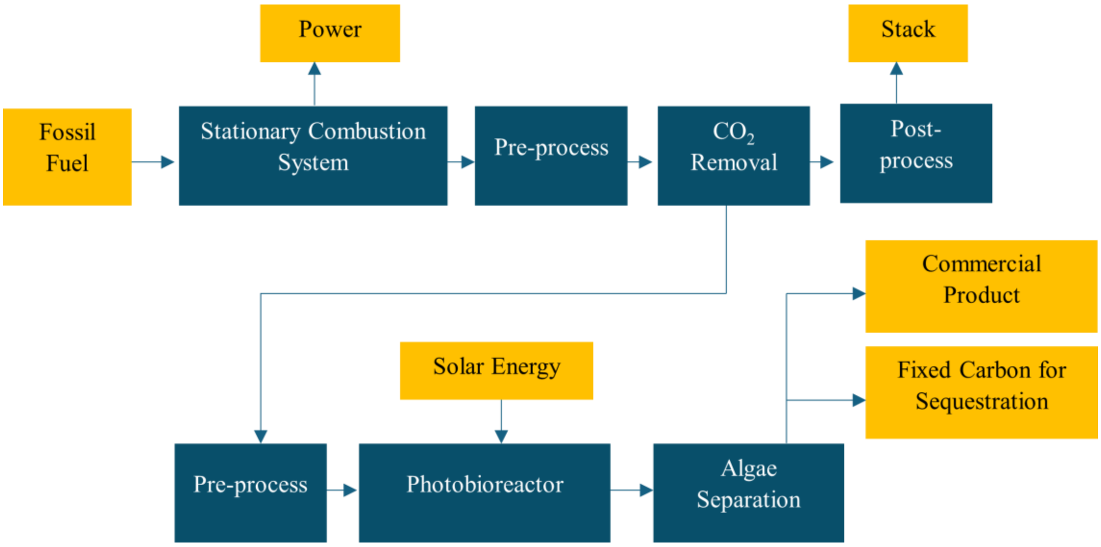

Figure 5. Carbon capture scheme with biofixation approach (Daneshvar et al., 2022; Wang & Lan, 2010; Zhao et al., 2018).

Thus, microalgae culture is a promising carbon capture technology that utilizes natural processes to mitigate greenhouse gas emissions. While challenges related to scalability and cost-effectiveness exist, continuous research and technological advancements enhance the viability of this method. With ongoing research and technological advancements, microalgae have the potential to significantly contribute to global carbon neutrality efforts while providing valuable resources through biomass utilization.

3.2 Physical Carbon Capture Strategy

Several physical techniques are commonly employed for various applications in CO_2 capture. These include physical adsorption methods, cryogenic technology, and physical absorption methods (Ben-Mansour et al., 2016; Mondal et al., 2017). Physical adsorption methods utilize materials such as zeolite, alumina, and carbon. Cryogenic technology involves cooling and condensing multigas components at different temperatures. Physical absorption methods rely on substances like Selexol, Rectisol, and Purisol. An alternative approach involves hydrate-based separation, where introducing a gas stream at high pressure forms hydrates that drive CO_2 gas into the water phase. The hydrate is then isolated by liberating CO_2. The suitable technology for capturing CO_2 depends heavily on the specific characteristics of the CO_2-emitting facility and the type of fuel employed (Zhang et al., 2018). Most carbon capture technologies are primarily suited for implementation in the oxy-combustion method from a physical standpoint.

3.3 Chemical Carbon Capture Strategy

A range of separation techniques can be employed, primarily using pre-combustion and post-combustion methodologies. These include gas phase separation, solvent absorption, sorbent adsorption, and membrane-based hybrid processes. The primary techniques used for this purpose include chemical loop combustion (CLC) and hydrate-based separations. CLC, commonly referred to as unmixed combustion, involves the absence of direct contact between the fuel and air during the process. Metal oxides, including iron ore (Fe_2O_3), nickel oxide (NiO), copper oxide (CuO), and manganese trioxide (Mn_2O_3), act as oxygen carriers that facilitate combustion by providing oxygen. This procedure involves the use of two distinct reactors: one for air and the other for fuel. An oxygen carrier circulates between these two reactors to enable the process.

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 conditions. The use of reusable metal oxides obtained from unutilized ore, industrial, or agricultural wastes in the CLC option is considered a more sustainable alternative compared to the combustion of oxy-fuels (Sreenivasulu et al., 2015).

3.4 Biological Carbon Capture Strategy

The process of carbon capture technology involves harnessing the photosynthetic activity of autotrophs for biological purposes. One such method is the use of microalgae for CO_2 fixation through their capacity to transform carbon into biomass via photosynthesis (Li, Li, and Ho, 2022). Microalgae are more efficient in fixing CO_2 compared to terrestrial plants, owing to their simple cellular structure and rapid growth (Singh & Dhar, 2019). Microalgae can sequester CO_2 from various sources, including the atmosphere and industrial exhaust 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). This process of carbon capture can occur effectively within their natural environments, including rivers, lakes, and seas, where the growth and development of microalgae are naturally supported. The approach of microalgae cultivation as a CCU technique primarily focuses on capturing and converting atmospheric carbon into alternative energy sources and valuable products.

Microalgae's capacity to trap carbon emissions, particularly from industrial chimneys, makes it a valuable option for large-scale carbon capture (Daneshvar et al., 2022; Olaizola & Bridges, 2004). The use of microalgae's biologically mediated CCU method holds significant potential as a biotechnological approach to reducing carbon emissions (Daneshvar et al., 2022). Various strategies can enhance microalgae production, such as carbon capture techniques facilitated by mutagenesis, genetic engineering, and the application of nanomaterials. The utilization of nanomaterials significantly impacts the relative electron transfer rate within the photosystem and the number of reactive oxygen species in microalgae (Li et al., 2022). This leads to an overall enhancement in photosynthetic activity, particularly in carotenoid production. The CCS technology using microalgae directly impacts biomass yield and the quantity of carbon sequestered. Additionally, variations in energy, fertilizer, water, and building material demands will ultimately affect the quantity of carbon utilized or emitted (Prayitno et al., 2021).

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). Microalgae include both prokaryotic blue-green algae, specifically Cyanobacteria, and eukaryotic microalgae, which consist of green algae, red algae, and diatoms. These microorganisms outperform alternative raw materials due to their adaptability to harsh environments and their simple yet flexible nutritional requirements. This diverse assemblage of microorganisms transforms inorganic carbon (Ci) into organic carbonaceous substances through photosynthesis. Eukaryotic green algae, diatoms, euglenoids, and prokaryotic cyanobacteria (commonly referred to as microalgae) engage in CO_2 assimilation to produce various biochemical compounds such as lipids, proteins, carbohydrates, pigments, and phenols (Daneshvar et al., 2022).

The cellular absorption of CO_2 from the atmosphere involves the extracellular zinc metalloenzyme carbonic anhydrase (CA) and an active transport mechanism responsible for the uptake of supplementary nutrients, specifically carbonate. CA is classified as a metalloenzyme due to its dependence on zinc (Zn) ions. It promotes CO_2 fixation through nucleophilic attack facilitated by hydroxide ions coordinated to the zinc atoms. This enzymatic process is significant for carbon fixation as it converts CO_2 into bicarbonate, which serves as a substrate for the enzyme of Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) (Mondal et al., 2017). Cyanobacteria and algae have developed unique photosynthetic carbon concentrating mechanisms (CCMs) to enhance the efficiency of capturing CO_2 by RuBisCO enzyme. The CA involvement is essential in the CCM process. CA facilitates the reversible hydration of CO_2 to bicarbonate ions and protons, thus assisting in the fixation of atmospheric CO_2 (Mondal et al., 2016).

The choice of microalgae culture as a CCS method is based on its ability to assimilate CO_2 gas as a primary substrate for photosynthesis, transforming it into organic matter. In Indonesia, the development of CCS technology is progressing, encompassing two primary types: photobioreactors (FBR) and open ponds (Prayitno et al., 2021). Biological methods are regarded as the most economically feasible, ecologically sound, and sustainable means of capturing and storing carbon (Li et al., 2023). Enhancements to carbon capture methodologies involving microalgae within ecological settings, such as marine environments, can be optimized through marine fertilization techniques. This process involves increasing aquatic nutrients while limiting iron nutrients (macronutrients), which have been shown to hinder biomass productivity. It is essential to address the uncertainty regarding potential side effects that could alter the ecological and biochemical characteristics of water (Amount & Bopp, 2006). In controlled environments such as photobioreactors and open ponds, the addition of carbonate nutrients (specifically Na_2CO_3 and $NaHCO_3$) has been shown to enhance microalgae proliferation.

There are several notable benefits associated with utilizing microalgae for carbon capture, including a heightened rate of photosynthesis, the implementation of clean and cost-effective technology, and the generation of diverse high-value by-products. These by-products include biodiesel, pigments with medicinal properties, animal feed for aquaculture, biomass, fertilizers, and various cosmetic products. The biomass generated from microalgae growth has various potential applications, including use as health food and conversion into biofuels. CO_2 sequestration can occur in many forms, such as lipids, carbohydrates, or proteins, depending on the specific species of microalgae. The extraction of lipids from microalgae that have assimilated CO_2 allows 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:

$$CO_2 + H_2O \longrightarrow HCO_3\text{-} + H^+$$

This comprehensive utilization of biomass facilitates a full carbon cycle and enables the production of agrichar, which permanently sequesters CO_2 through biological processes. Thus, CO_2 fixation in photosynthesis shows promising potential due to its inherent energy efficiency, sustainability, and environmental friendliness. In this light, focal points of academic inquiry are the rapid proliferation, exceptional adaptability to extreme environments, and cost-effectiveness of microalgae cultivation.

3.5 The Prospective Advancement of Carbon Capture Technology in Forthcoming Years

The landscape of carbon capture technologies is rapidly evolving, with significant advancements in project development, innovative technologies, and government support. As countries strive to meet their climate goals, these developments underscore the critical role that carbon capture plays in mitigating climate change and achieving net-zero emissions by 2050. The ongoing commitment from industries and governments alike will be essential in scaling these technologies for broader application across various sectors. The advancements in carbon capture technologies demonstrate a robust commitment to addressing climate change through innovative solutions. Projects in Finland, Singapore, and Wyoming highlight the potential for large-scale implementation and integration of carbon capture into various industries. As research continues and new technologies emerge, CCUS is expected to play a crucial role in achieving global net-zero targets by 2050.

As of September 2022, the total capacity of commercial CCS projects in the planning phase—encompassing those already operational, under development, and two with suspended operations—reached 243.97 million tons per annum (Mtpa) of CO_2, marking a significant 44% increase compared to the previous year (Global CCS Institute, 2022). The current global count of CCS technology facilities stands at 194, with 30 facilities operational, 11 under construction, and the rest in the developmental stage (Global CCS Institute, 2022). Among these projects, 94 are in the Americas, with 80 in the United States. Europe hosts 73 projects, with 27 in the United Kingdom. Additionally, there are 21 projects in the Asia-Pacific region and 6 in the Middle East. Several of the newest CCUS developments and projects are the CCU-Kemi Bioproduct Mill CO_2 Capture Project in Finland (with capacity 4.2 million tons of CO_2 per year), CCS-S-Hub Consortium CCS Project in Singapore (2.5 million tons of CO_2 per year), CCS-Orchard One Large-Scale DACCS Facility in Wyoming, USA (2 million tons of CO_2 per year), CCS-Mammoth Direct Air Capture Facility in Iceland (36,000 tons of CO_2 per year), CCU-FrostCC™ Technology, CCU-ArcelorMittal Gent Carbon Capture Pilot Project in Belgium, and CCU-Capture Glass Industry Carbon Capture Project in UK (30,000 tons of CO_2 per year) (Prescouter, 2024).

Today, methods like chemical absorption, physical absorption, and membrane technologies remain in use. However, deploying large-scale CO_2 capture in power plants presents numerous technical hurdles, especially concerning system integration, such as managing energy and flow and integrating it into power generation processes (Markewitz et al., 2012). One of the primary challenges in advancing large-scale carbon capture technology is the substantial financial burden associated with operational and maintenance expenses. The financial viability of carbon capture projects may be compromised due to increased expenses and other issues (Al-Mamoori et al., 2017). In relation to financial considerations, physical and chemical carbon capture technologies incur higher costs compared to the biological approach. Research conducted by Daneshvar et al. (2022) and the National Energy Technology Laboratory (NTEL) substantiates the cost-effectiveness of carbon utilization in the United States. This conclusion is based on the global average price of CO_2, which stands at around USD 62.65 per ton. The proposed plan necessitates a substantial financial investment of around USD 8.20 trillion. However, this cost is partially mitigated by the advantages derived from existing carbon capture techniques, such as enhanced oil recovery. Consequently, the overall expenditure for this strategy until 2050 is estimated to be USD 5.76 trillion.

Achieving this substantial expenditure is technically viable through synergistic endeavors and cooperation among governmental entities, commercial enterprises, and local inhabitants. Significant reductions in CO_2 emissions within the commercial sector can be achieved through cost-saving measures, such as the adoption of industrial bio-CCU. The use of microalgae fixation technology involves a collaborative effort with industrial 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.

While cost estimates vary considerably, the main expenses typically pertain to equipment and energy consumption during the capture and compression stages. Energy consumption is a significant challenge, particularly for electricity for pumps and the necessity for nutrient provision. Moreover, the CO_2 capture stage can decrease the power and efficiency of industrial units and increase their water consumption. To mitigate energy consumption, attention to the design engineering of this technology is necessary, and utilizing renewable energy resources is imperative for reducing carbon emissions. Thus, a comprehensive examination and analysis of the utilization of renewable energy in Indonesia is crucial to enhance the effectiveness and efficiency of carbon capture technology within the industrial sector.

The utilization of microalgae for 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. However, industrial use of microalgae faces challenges such as suboptimal photosynthetic efficiency, high input expenses, and considerable capital requirements (Li et al., 2023). The economic viability of a CO_2 fixation strategy for microalgae cultivation can be improved through integrated approaches that mitigate CO_2 emissions, generate high-value by-products, treat wastewater, and utilize waste (Wang & Lan, 2010). Further advancements in design, raw materials, and industrial processes are necessary for effective carbon capture technology via microalgae cultivation. Improving the efficiency of the upstream process needs (i) careful selection of appropriate microalgae strains, (ii) optimization of nutrient supply by exploring cost-effective and environmentally sustainable alternatives (e.g., utilizing organic wastewater), (iii) refinement of culture operating conditions (e.g., light intensity, pH, and stirring), and (iv) adoption of environmentally friendly and renewable energy sources.

Additionally, downstream processes, such as implementing effective harvesting techniques and utilizing biomass, need further exploration and refinement (Prayitno et al., 2021). Enhancing biomass output from 20% to 60% is crucial to mitigate GHG emissions per kilogram of biomass generated. This can be achieved through the careful selection of appropriate microalgae species and the development of a suitable technological framework tailored to the chosen microalgae type. Optimizing the growth conditions of microalgae for carbon capture can boost biomass productivity, enhance CO_2 absorption, reduce the cultivation footprint, and cut down on operational expenses related to biomass harvesting. Notably, cultivation expenses are primarily driven by the energy-intensive preparation of preculture using tubular photobioreactors (Valdovinos-García et al., 2020). Therefore, the advancement of carbon capture technology must prioritize environmental requirements, specifically the mitigation of GHG emissions, to safeguard the well-being and safety of organisms while considering the economic dimension.

4. Conclusions

The rise in global temperatures is closely linked to the concentration of CO_2 in the Earth's atmosphere, primarily resulting from the combustion of fossil fuels across diverse industrial sectors. Strategies aimed at reducing CO_2 emissions predominantly focus on carbon capture technologies designed to capture and sequester CO_2 to prevent its atmospheric release. Our groundbreaking study expands upon prior research by offering an in-depth review of three pivotal carbon capture strategies: physical, chemical, and biological processes. Our review aims to contribute comprehensive insights into carbon capture technologies and their potential applications to support net zero emission transition.

The effectiveness of carbon capture technologies is shaped by multiple factors, including technological innovation, economic feasibility, regulatory frameworks, integration with existing infrastructures, environmental impact assessments, and challenges related to scalability and deployment. The leading technique (i.e., CCS) involves capturing CO_2 and injecting it into exhausted underground geological formations. An alternative method (i.e., CCUS) repurposes CO_2 for various industrial applications, particularly within the oil and biofuel industries. Various carbon capture techniques exist, including pre-combustion, oxy-combustion, and post-combustion processes, each employing distinct methodologies. Additionally, cultivating microalgae presents a biological approach to carbon capture, which can be conducted in open systems such as retention ponds or in closed systems like photobioreactors. By regulating external parameters such as pH, light intensity, nutrient availability, and temperature, the efficiency of microalgae in carbon fixation can be significantly improved.

Future challenges will revolve around creating efficient and economically viable carbon capture technologies that emphasize high productivity and low operational costs. Indonesia, with its abundant microalgae diversity, holds promise for advancing these technologies. Future research should also investigate the potential of utilizing solid and liquid waste for CO_2 capture and focus on developing innovative methods for CO_2 utilization to produce valuable products.

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