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Carbon Capture and Utilization: A Key Strategy for Greenhouse Gas Mitigation in the Energy Transition

Vishnu Prasanna Devarajan [1*], Venkata Ramanan Madhavan [1], Rajesh Devan [1]

[1] *Faculty of Mechanical Engineering, Institute for Energy Studies, CEG-Anna University, Chennai – 600 025, Tamil Nadu, India*

[*] *Corresponding Author*

Abstract - To mitigate CO_2 emissions, carbon capture and utilisation (CCU) is seen as a crucial complement to carbon capture and storage (CCS) goals for reducing and sequestering CO_2. It represents multiple routes that use CO_2 as a feedstock in manufacturing processes. To ensure a pure and secure supply of CO_2, various carbon capture and separation methods can be utilized. The fundamental division in carbon capture techniques, absorption, adsorption, cryogenic, membrane, and microbial-based systems are predominantly used worldwide. Likewise, CCU processes comprise five broad categories: biological conversion, mineral carbonation, enhanced oil recovery, CO_2 conversion to chemicals and fuels, and direct CO_2 utilisation. Here, we provided a brief overview of the procedures required in CCU development, choices for capture and utilisation, a discussion of the possible role of CCS in the energy transition, and uncertainties that may be present. In conclusion, CCU can be an important tool for reducing the atmospheric concentration of CO_2 (greenhouse gases), especially during the energy transition.

Keywords: CO_2 *capture; greenhouse gases; global warming; carbon capture; CCU.*

1.0 INTRODUCTION AND BACKGROUND

1.1 Global Outlook on CO_2 emissions

Carbon dioxide (CO_2) is a gas generated naturally by humans, animals, fungi, or other microorganisms that rely on living or decaying plants and other anthropogenic activities, primarily through fossil fuel combustion. Carbon dioxide is a gas, potentially a raw material (Vaz et al. 2022; Rubin et al. 2012). The expanding worldwide demands for energy, along with a heavy and heavy reliance on fossil fuel, significantly increase greenhouse gas concentrations in the atmosphere, which have already reached dangerous levels. The fundamental source of global warming is assumed to be carbon dioxide, which has a larger concentration than other gases. Consequently, we are moving towards a conclusive way for worldwide accomplishments to deal with the environmental emergency test for us. We are vowed to arrive at net-zero outflows by mid-century, however ozone-harming substance emanations. This gap between rhetoric and implementation needs to close if we are to have a battling opportunity to arrive at net-zero ozone- greenhouse gas (GHG) by 2050 and restrict the increase in worldwide temperatures to 1.5 °C., In this regard, the 26th Conference of Parties (COP26) of the United Nations Framework Convention on Climate Change represents a significant opportunity to reinforce the global significance of environmental change. The International Energy Agency (IEA) has been endeavouring to help the upsides of COP26 toward global carbon reduction (IEA 2021). Worldwide CO_2 emissions are changing us to move towards sustainable prompts and early top in discharges in electrical sectors; however, decreases across all industries fall the mark regarding what is expected for net-zero outflows in 2050.

Yearly CO_2 flows got back brought about by the COVID-19 pandemic in 2020. These increments from 34 Gt in 2020 to 36 Gt in 2030 and stay around this level until 2050. Suppose outflows are not controlled as

similar changes in that frame of mind of GHS emissions. In that case, the typical surface temperature of our planet will rise around 2.7 °C in 2100 with a 50% probability (IPCC 2018). Furthermore, even at current levels, there is a slight risk of terrible consequences because the climatic reaction to high CO_2 concentrations is uncertain. As the atmospheric CO_2 concentration rises due to CO_2 emissions, that risk increases monotonically. Solar energy and other renewable energies, including the usage of electric vehicles (EV), are just one of several options for decarbonizing the energy system (Sjostrom and Krutka 2010; Smit 2016). There is no way to stop the long-term climatic and geochemical issues brought on by rising CO_2, even though climate engineering is essential for managing climate risk. Hence the carbon capture and utilisation (CCU) has led us to focus on carbon management by using carbon dioxide as a partial substitute for the method by which it is transported and stored. Under standard conditions, CO_2 is a chemically and thermodynamically stable molecule, but it can combine with other chemical inputs to produce other products. As a result, CCU research is quite well-established in developed nations. CCU can first be introduced concurrently with the CCS technology (carbon capture and storage). It's interesting to note that CCU possibilities are already extensively used as a chemical feedstock for fertiliser and other useful chemicals. Additional CO_2 emission reductions through the environmentally friendly use of algae and mineral CO_2 conversions. The steps to carry out CCU, as shown in Fig. 1.

Fig. 1 Steps for Carbon Capture and Utilisation

Remarkably, the Carbon capture and storage (CCS) approaches currently encompass many Physiochemical carbon capture and sequestration techniques. CO_2 capture, CO_2 transit, and CO_2 storage are the three main processes of CCS operation. The huge point for carbon sources to capture is industries (Hägg and Lindbråthen 2005; Naranjo et al. 2011). Common methods for separating and extracting CO_2 from other exhaust components include the ones listed below: Physical adsorption, membrane-based separations, cryogenic distillation, and chemical absorption (Figueroa et al. 2008). The two methods of storing carbon are oceanic storage, which also entails injecting CO_2 into the deep ocean and compressing and transporting CO_2 to geological repositories. Although CCS has the above remarkable storage techniques, it still has several drawbacks, such as the expense of operation and transportation and the possibility of long-term CO_2 environmental leakage (McCoy and Rubin 2008; De Silva et al.2015). The Physio-chemical CCS technologies can do so only at point sources emitting large concentrations of CO_2 (Nouha et al. 2015). Similarly, based on combustion process emission or flue gas, carbon capture could be generally categorized into three stages *pre-combustion*, *post-combustion and Oxy-fuel combustion*. The combustion products of oxy-fuel combustion are primarily CO_2 and water, returning and recovering high-purity CO_2 since oxygen is used in place of air as an oxidant and CO_2 gas provides a recycled discharge medium. Hence, using pure CO_2, possible by separation, is where current thinking for CO_2 conversion and utilization starts. Breaking, recovering, purifying, and utilizing CO_2 from concentrated CO_2 sources or carbon emitters often requires two or more steps based on membrane separation, adsorption, or absorption. Even recovering CO_2 from full sources demands a significant amount of energy. As a result, the Paris Agreement was adopted at COP26, followed by the previous COP to revitalize the international response to climate change,

encourage nations to work together, and set concrete action plans for NDCs (Nationally determined contributions), covering things like GHG emissions reduction and climate change adaptation. Moreover, the technology's key obstacles include CO_2 collection efficiency, carbon capturing rate, and energy required in its volume Similarly, the opportunities for carbon capture utilisation (CCU) are needed to aid the world in reaching its energy and climate goals. To implement CCU, major point sources of CO_2 must be captured, including industries or power plants that burn either fossil fuels or biomass. Another choice is to remove CO_2 directly from the atmosphere. The obtained CO_2 must be converted for further reuse. Otherwise, it should be compressed and transported via pipeline, ship, rail, or truck to be used for several purposes or injected into deep geological formations that trap the CO_2 for long-term storage. In this review, we've briefly considered the steps needed to establish CCU options for energy collection and use and discussed the potential role of carbon capture and storage (CCS). Overview of technologies for reducing atmospheric concentration of CO_2 (greenhouse gases) can be decreased with CCU. Finally, some Life Cycle Assessments (LCA) for promising CCU solutions that other researchers have completed are presented.

2.0. CARBON-DIOXIDE SEPARATION AND CAPTURE TECHNOLOGIES

The following technologies are mainly used for carbon collection and separation among the many carbon emissions sources and types. Although these technologies face unique difficulties during the carbon capture and regeneration process (In Fig. 2, various methods and technologies for capturing CO_2 are illustrated), they ultimately contribute significantly to the conversion and use of CO_2 as fuels and chemical feedstock (Salvi and Jindal 2019).

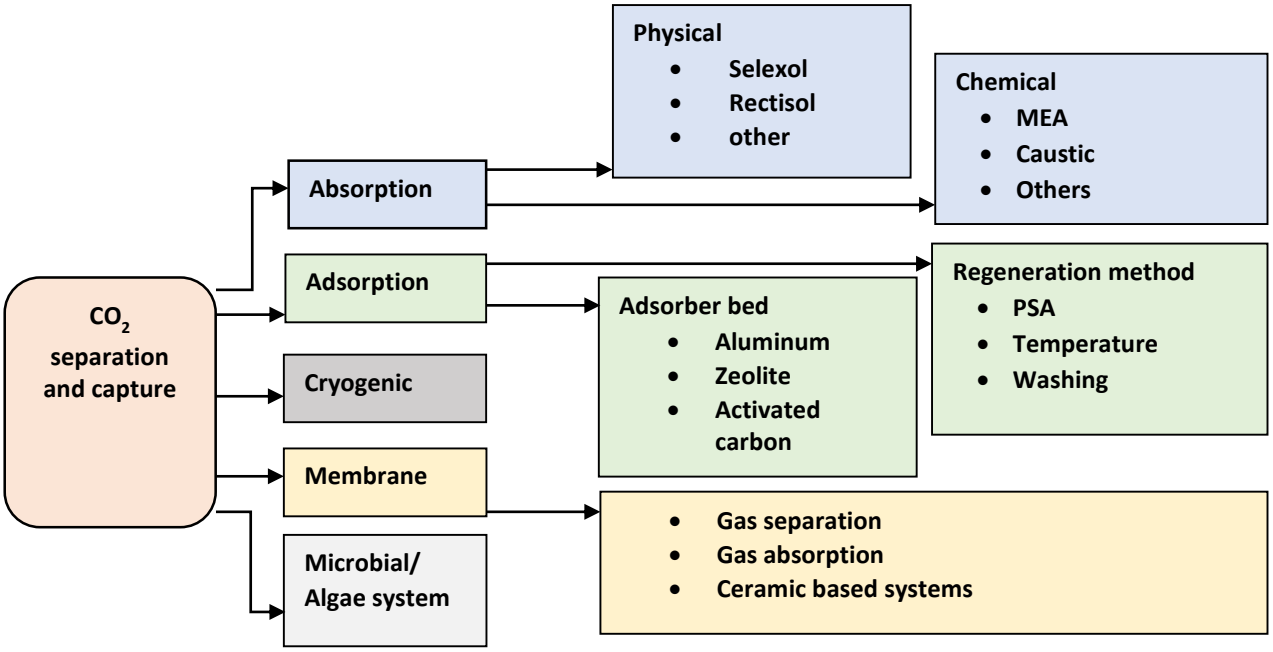

Fig. 2 CO_2 Capture Methods and Technologies

2.1. CO_2 Separation and Capture by Absorption

The following are three distinct terms that pertain to different aspects of absorption, with physical absorption referring to the process of one substance being taken up by another through physical means, chemical absorption referring to the process of one substance reacting with another to form a new compound, and ionic liquid referring to a type of salt that is in a liquid state at room temperature.

1. Physical Absorption
2. Chemical Absorption
3. Ionic Liquid

2.1.1 Physical Absorption

Physical absorption is a proven technology for separating CO_2 from other gases. The physical absorption procedure is straightforward, with just one gas-liquid contactor and several flash tanks for solvent regeneration. In the high-pressure gas-liquid contactor, the CO_2 will be absorbed in the physical solvent before being flashed out in the medium and low-pressure flash tanks. Since no chemical reaction is required for the CO_2 to be interested when using a physical solvent, it can be easily flushed out by lowering the pressure, running inert gas through the solvent, and performing light thermal regeneration. Mota-Martinez et al. 2017 have explained the advantages of solvent selection, which influences the CO_2's solubility; physical absorption works best when operated at high pressure and low temperature. Chowdhury et al. 2013, Darde et al. 2010; Darted et al. 2009 reported that ammonia is more volatile than MEA; it maximises the ammonia compounds' ability to absorb CO_2 and reduce ammonia vapour emissions during the absorption process. Ammonia losses during regeneration, which occur at high temperatures, are another issue. Few researchers (Resnik et al. 2006; Rao and Rubin 2002) have investigated the process optimisation for higher CO_2 concentration load and various engineering solutions to stop ammonia vapour losses from the system while it is in operation.

Many researchers (Albrecht et al. 2008; Donat et al. 2012; Manovic and Anthony 2009; Sánchez-Biezma et al. 2011; Manovic and Anthony 2009; Sánchez-Biezma et al. 2011) have reported about the well-known CaO as a CO_2 absorber in a large-scale circulating fluidised bed (CFB) reactor used for post-combustion of CO_2 collection with CaO. In addition, a large-scale oxy-fired CFB must be integrated into this reactor to allow the breakdown of $CaCO_3$ produced in the carbonator. This kind of technology can provide rich CO_2 to capture from the industries. Idem et al. 2006 delivered the behaviour of CO_2 in light and low-pressure CO_2 sources. One of the more exciting methods to accomplish this goal is absorption via chemical reaction using aqueous alkanolamine solutions. Alkanolamines have been utilised in the industry for a very long time. Some examples include monoethanolamine (MEA), diethanolamine (DEA), di-2-propanolamine (DIPA), and methyl di ethanolamine (MDEA).

2.1.2 Chemical Absorption

The most cutting-edge method of carbon capture at the moment is chemical absorption utilising aqueous amines. Less frequently used physical solvents like Selexol and Rectisol can absorb CO_2 through physical dissolution rather than a chemical reaction (Gao et al. 2018). Later, functionalized (sterically-hindered) amines were created by adding chemical groups to the amines; examples of these compounds are 2-amino-2-methyl-1-propanol (AMP), 2-piperidine ethanol (PE), and 1-8-p-menthanediamine (MDA). These solvents have weaker

CO_2 and amine bonds, which decreases regeneration energy (Idris and Elimer 2014). By combining the advantages of each class of solvent, the amines can also be used for CO_2 absorption to increase uptake and lower costs. For better kinetics and cost trade-off optimization in amine blends of MEA, MDEA, and AMP, piperazine (PZ) is frequently utilised (Zhao et al. 2017). Methods such as amine-type absorbents are appropriate for collecting CO_2 from the exhaust gas. Even at low CO_2 partial pressures, the chemical interaction between CO_2 and amines considerably boosts separation-pushing power. The amount of CO_2 in the feed has little effect on the cost of this approach. As a result, chemical absorption with amines is the most cost-effective method for producing high-purity (>99%) CO_2 vapour from flue gases in a single step. Han et al. 2010 reported on the Electrostatic precipitators (ESPs) based collection of fine and ultrafine particles produced during coal combustion (Edge et al 2011). ESPs use the generation of a corona discharge to charge and collect aerosol particles. Also, the fundamental determinants of particle charging were ionic mass and mobility; thus, a low group and high mobility result in a large quantity of particle charging. Because the content of the surrounding gas influences the ionic characteristics and particle charge states of ESPs, changes in the composition of the gas during oxy-fuel combustion can significantly improve their performance (Han et al. 2010).

2.1.3 Ionic Liquid

Ionic liquids (ILs) are greatly interested in industrial gas capture, particularly CO_2 capture and separation. Several polymer platforms can take advantage of the advantages of ILs, even though bulk ILs might not be an effective industrial-scale solution (owing to high cost, high viscosity, etc.). These include polymerised ionic liquids (PILs), ionic polyimides, supported IL membranes (SILMs), and other hybrid and composite materials. Ionic liquids have recently replaced conventional absorbents due to the advantages of ionic liquids, such as their acting as a liquid at room temperature with ions in the fluid, low volatility, low vapour pressure, and good thermal stability (David et al. 2001; Bates et al. 2002). Additionally, it has a comparatively low energy need for regeneration after CO_2 absorption. However, the two primary challenges to their use in CO_2 capture are their high viscosities and very low working capacities (Cui et al. 2016). The functionalised ILs exhibit higher viscosities than the unfunctionalized ILs, notwithstanding the possibility of obtaining increased capacity. Therefore, the biggest technical issue in successfully using ILs in CCS is reducing viscosity while maintaining its high power significantly (de Riva et al 2017; Shiflett et al. 2010).

2.2. CO_2 Capture by Adsorption

2.2.1 CO_2 Capture by Physical Adsorption

Solid adsorption can be an advanced desire for the CO_2 series because aqueous amine absorption strategies have boundaries inclusive of a slender touch region among gasoline and liquid, low CO_2 loading, and excessive absorbent breakdown. Despite this reality, rate-proscribing for adsorption as CO_2 diffusion is better than amine-based aqueous absorption for CO_2 captures inclusive low pressure (Caglayan and Aksoylu 2013; Xu et al. 2019; Buzanowski et al. 2001; Farooq et al. 1988). The principal downside of moss is its low CO_2 selectivity, as may be observed. The approaches are made at excessive pressures and temperatures, no matter the reality that carbonaceous and MOF substances with better CO_2 adsorption abilities seem like potential CO_2 adsorbents. Silica substances, on the other hand, have a decreased CO_2 adsorption potential and selectivity; however, due to the many steps of OH groups, a chemical change is easier, letting them enhance their CO_2 adsorption potential and

selectivity and so deal with a flue gas with low CO_2 partial pressure and from the air by using PSA (Wu et al. 2010; Ruthven and Farooq 1990).

Many methods for separating and recovering carbon dioxide (CO_2) at various capture scenarios have been developed recently to cut emissions and mitigate the detrimental effects of global warming. In adsorption procedures, highly porous materials such as activated carbons are used, and they are commercially accessible. Pressure Swing Adsorption (PSA) is a cyclic adsorption method for continually separating gas streams. Accordingly, to the researchers (Zhang 2020; Abanades et al. 2004; Abdeen et al. 2016; Alaya et al. 2000) PSA is a method for separating CO_2 from flue gases with a concentration of 5-15 % v/v that involves pressure adjustments to enhance pollutant removal. It is considered viable for CO_2 removal from flue gases having 5-15 % v/v CO_2. A PSA process may have multiple steps, columns, and cycle times to achieve a certain output. One of the most basic designs consists of four stages: pressurisation, feed, blowdown, and purge. A PSA process' purity, recovery, and productivity are typically used to assess its effectiveness. A mixture of 85 % nitrogen and 15 % carbon dioxide (Siqueira et al. 2017). Carbon dioxide and nitrogen breakthrough curves were produced using normal post-combustion capture conditions (Mukherjee et al. 2019). A modelling tool with an experimental PSA unit can help researchers understand the phenomena and have more effective CO_2 adsorption-based capture systems. Activated carbons offer a variety of pore geometries and surface chemistry for gas adsorption, which are used to develop practical pressure swing and heat swing adsorption methods for the separation and purification of gas mixtures (Pevida et al. 2008; Arvind et al. 2002; Chan et al. 1981). For gas adsorption, activated carbons have a wide range of pore shapes and surface chemistry (Shafeeyan et al. 2010)

According to Lu et al. 2008, 3-aminopropyl-triethoxysilane (3-APTS) was used to modify carbon nanotubes (CNTs) and granular activated carbon (GAC) and zeolites for CO_2 adsorption from gas streams. The adsorption properties of zeolites and their correlation with their structure have been studied (Goursot et al. 1997). Also, Hao et al. 2010 have synthesized the nitrogen-doped porous carbon monolith for CO_2 capture. Following the alteration, these adsorbents' surface properties altered, allowing them to absorb more CO_2 gases. The modified CNTs, zeolites, and GAC all had greater CO_2 adsorption capacities under the same circumstances. Regeneration of used adsorbents at a relatively low temperature is now possible because the process of CO_2 adsorption on these adsorbents appears to be mostly due to physical force. Compared to other types of modified carbon and silica adsorbents described in the literature, the APTS-modified CNTs exhibit good CO_2 adsorption performance.

2.2.2 Chemical Adsorbent: Amine-Based

1. Production of supports
2. Use of amine with increased nitrogen content
3. Effective amine exposure

Depending on the interactions between amines and supports, such as weak or strong covalent connections, the amine-impregnated or amine-grafted are the two types of amine-based adsorbents. In most cases, amine-grafted adsorbents outperform amine-impregnated adsorbents in terms of adsorption rate and stability in cyclic runs. However, the impregnation allows for higher amine loadings but causes a high diffusion resistance (Rashidi et al. 2013; Sayari et al. 2011; Hicks et al. 2008; Bui et al. 2018).

2.2.3 Regeneration Process

The regeneration process is an important technique in carbon capture for separation and storage purposes. Recent researchers focus on the development of effective adsorbents with innovation in PSA and VSA processes, including enhancement in activated carbons, carbon molecular sieve (CMS), and zeolite 13X as adsorbents (Bara et al. 2010; Bates et al. 2002; Botero et al. 2009). They looked at the heat of adsorption, work capacity, need for purge, and equilibrium selectivity of 13X and AC. They found the former a better adsorbent for removing bulk CO_2 from gases. Due to the flexible structure, which demonstrates significant pressure-dependent changes in pore volume. It also, provided an optimization technique with the structure of adsorbents and its porosity studies, suitable for the PSA process based on the processing capacity (Krishna and Long 2011; Zhang and Webley 2008). Amrhein et al. 1996 and Cavenati et al. 2004 reported about the PSA column and found that 'it was similar to commercial zeolite adsorbents previously described in the literature. Yong et al. 2002 examined the PSA integration process by modifying the process steps and procedures. Each proposed method, as well as the CO_2 content. The energy consumption, CO_2 recovery rate, and the economic feasibility of using the PSA process to extract CO_2 from power plant exhaust gases are reported (Hu et al. 2008; Yang and Doong 1985). Some authors (Zhang and Webley 2008) used their VSA systems to compare the six and nine-step cycle processes. They demonstrated the type of adsorbent, and operational parameters, including inlet gas pressure, configuration, and kind of adsorbent, which substantially impacts fuel consumption and cost of carbon dioxide capture. Also, in the temperature swing adsorption (TSA) technique, the regeneration is carried out with hot air or steam. Generally, the TSA regeneration process takes longer than in PSA (Siriwardane and Stevens 2009; Soo et al. 2008).

2.3 Cryogenic

Numerous studies on cryogenic CO_2 separation techniques have recently been carried out. For instance, Song et al. 2014 suggested a cryogenic liquefaction system whose backbone is formed by a compressor and flash unit, resulting in a sufficient recovery of cold energy and a reduction in the energy penalty. A unique CO_2 capture process based on a Stirling cooler was created (Song et al. 2019), in which CO_2 is separated in a liquid condition following continuous chilling by three Stirling coolers. In a previous study, we presented a unique system that concurrently achieves CO_2 isolation and compression by utilizing the principle of energy cascade usage and the phase transition mechanism. In a previously refrigerated packed bed of natural gas, including CO_2, H_2O, and inert gases, Hart and Gnanendran (Hart and Gnanendran 2009) showed that CO_2, H_2O, and the permanent gases could be effectively separated using variations in dew and sublimation points. Fronts of temperature and concentration will form and move through the bed at various speeds. To extract the cold energy stored in the packing and prevent an undesirable pressure decrease or clogging, H_2O and CO_2 will condense and de-sublimate, respectively. Various scholars evaluated the results of more research into this method to remove CO_2 from natural gas. These configurations can also be used for upgrading biogas, though some of the suggested systems could require some adjustments (Tuinier et al. 2010; Babar et al. 2018). By adjusting crucial parameters like temperature levels, feed composition, and feed flow rate, Baena-Moreno et al. 2019 investigated an experimental investigation for counter current-switched cryogenic packed beds. They have concluded that reverse configurations can be useful for natural gas with greater CO_2 concentrations, and no chemical absorbent or elevated pressures are required. Additionally, Baena-Moreno *et al*. 2019a have shown that CO_2 and N_2 may be effectively separated. A 1D model that is pseudo-homogeneous describes the process. The resultant simulations closely resemble the results of the

experiments. Research on cryogenic packed beds for CO_2 capture from natural gas and flue gas with high CO_2 content is now underway.

2.4 Membrane

As a non-stop process, gas separation through membranes is attractive in low-carbon technology as it is more efficient than traditional batch processes such as adsorption and absorption. It is viable to feed blended gasoline and go out natural gasoline simultaneously. Membrane selectively permeates preferred additives while maintaining undesirable ones, ensuing in gasoline combination separation. In carbon capture and storage (CCS) operations, carbon dioxide should be captured and stored before it is transported. Membrane separation generation is one of the handiest carbon capture technologies (He et al. 2009; Scholes et al. 2010). For various reasons, membrane technology has huge promise for CO_2 and H_2 separation in such gasification processes. Compared to traditional separation procedures, this method's removal of gas using a selective screen ensures great energy efficiency, a small equipment footprint, and minimal capital costs (Muller et al. 2020; Ostovari et al. 2020; Shelley 2009). Gas separation membranes are frequently used for H_2 recovery in refineries and have been commercially shown for sweetening natural gas (removal of CO_2 and H_2S).

2.4.1 Membranes for pre-combustion.

Membranes for pre-combustion are an enormous way for commercial membrane devices. However, some pilot-scale pre-combustion membrane structures have proved the device's capacity to be scaled up. Some industries have been growing a pilot-scale pre-combustion membrane. This mission improves membrane-primarily based integrated gasification combined cycle (IGCC), resulting in carbon capture of over 95% (Kumar et al. 2013).

2.4.2 Membranes for post-combustion.

Membrane separation for post-combustion is an era that has been around for even as. The membrane acts as a filter. It allows certain molecules to skip via events blocking different molecules from accessing the membrane. Micro-filtration, ultra-filtration, opposite osmosis, ahead osmosis, desalination, and scientific programs have used membranes. Alternatively, gas separation via means of the membrane continues to be in its infancy. Membrane for flue gas separation has sparked a variety of interest inside the CCS place in current years (Ramasubramanian and Ho 2011).

2.4.3 Membranes for oxy-fuel Combustion

The development of an air separation membrane is still in its early stages. Because the ion transport technique requires a lot of energy, air separation membranes can't compete with classic cryogenic air separation for large-scale products. Permeation flow through a unit membrane location below a unit strain distinction through a unit membrane thickness is referred to as permeability, and selectivity is the ratio of various gases' permeabilities throughout the membrane. Membranes have numerous separation mechanisms. The selectivity of multiple gases can be attributed to modifications in molecule size, affinity to membrane material, molecular weight, and different characteristics, relying on the membrane of interest (Habib et al. 2011; Qiao et al. 2012)

2.5 Microalgae System

2.5.1 CO_2 Capture by Microalgae

Microalgae are one of the attractive bio-industrial sources for producing various products. CO_2 sequestration has unique advantages for making sustainable fuel, cosmetic appliances, medicines, bio-fertilizers, and bioactive compounds. Microalgae have mechanisms for effective photosynthesis by collecting inorganic carbon even at a low ambient concentration of carbon dioxide, known as the *Carbon dioxide Concentrating Mechanism* (CCM) (Whitton 2012). Also, microalgae don't need vast land to crop; they can grow in saline water, land, wastewater, and ponds (Wang et al. 2016a). The carbon captured by algae can be used for biomass production, which is the base material for many biofuels, especially biodiesel. There are numerous uses, such as the creation of items with value-added, and the huge potential of microalgae production for low-value bulk products, such as proteins for food/feed applications for nutraceuticals, was described (Wang et al. 2016b; Tang et al. 2011; Singh and Dhar 2019; Vuppaladadiyam 2018). Numerous academics have discussed the value and benefits of carbon collection and use using microalgae in light of recent technological advancements (William and Laurens 2010; Chisti 2007). Chew et al. 2017 evaluation of the most recent technological advancements, economic assessments, and life cycle assessments of microalgae-based production systems.

3.0 CARBON DIOXIDE UTILISATION TECHNOLOGIES

In industries were achieving zero emissions may not be technically or economically feasible, CCU technologies can enable "negative emissions," or the removal of CO_2 from the environment, to offset emissions (Ghiat and Al-Ansari 2021), proposed two noteworthy methods: (1) bioenergy with carbon capture and storage (BECCS), and (2) direct air capture (DAC). The term "BECCS" refers to a process that uses burning biomass to produce electricity while capturing and storing CO_2. If the generated CO_2 is absorbed and stored, facilities can transform biomass into biofuels, making this BECCS technology a biofuels power plant with CCUS (Huang and Tan 2014).

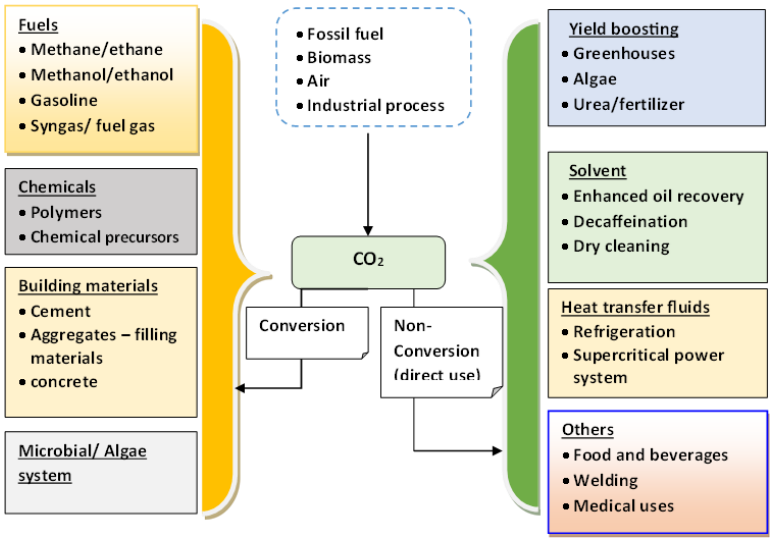

Fig. 3 A simple classification of CO_2 Utilization Pathways

TABLE 1. POTENTIAL INDUSTRIAL WASTES SUITABLE FOR MINERAL CARBONATION (GAO ET AL. 2019: OLAJIRE 2013)

Sample no.	Waste generation from the industry	Mass of CaO
1	Recycling ash from the paper industry	35 %
2	Fly ash from biomass incinerators	20 %
3	Stainless steel slag	65 %
4	Bottom ash from incinerators	20 %
5	Ashes from coal-fired power plant	65 %

TABLE 2. AN INVESTIGATION OF THE LIFE CYCLE ASSESSMENTS (LCAS) OF SEVERAL CCU OPTIONS.

CCU Option	CO_2 Capture Method	Process	Scope	Reference
Acyclic carbonates	Post-combustion capture via MEA	Production of dimethyl carbonate	• LCA versus DMC process comparison • Methanol electrochemistry in potassium methoxide: effects of two commercial technologies	Honda et al. 2014
Biofuel from micro-organisms	Direct injection / post-combustion capture via MEA	Biodiesel production	• When producing biodiesel from microalgae, canola and ultra-low sulfate are compared using life cycle assessments (LCA).	Campbell et al. 2011
CO_2 pure for multiple uses	Pre-combustion capture via rectisol and oxy-fuel combustion	Apply for various process	• To obtain pure CO_2, LCA comparisons of CCS were conducted in German PC, CCGCT, and IGCC power plants.	Viebahn et al. 2007
CO_2 reforming for CH_4	Post-combustion capture via MEA	Dry reforming of methane	• using LCA to compress several synthesis gas methods.	Elbashir et al. 2018
Enhanced oil recovery	Pre-combustion capture via selexol	IGCC or EOR	• comparing the CO_2 capture life cycle assessments of five IGCC	Jaramillo et al. 2009
Mineral carbonation	Post-combustion capture via MEA/ direct use of combustion process	Serpentine mineral carbonation	• LCA scenario analysis for a mineral carbonation facility in Singapore. Mineralization, transportation, and extraction. MEA-based and direct CO_2 capture. By using a natural gas combined cycle (NGCC) power plant, CO_2 reforms methane.	Khoo et al. 2011
Mineral carbonation	Post-combustion capture via MEA	$MgCO_3$ mineral carbonation	• LCA from a coal-fired power plant in Canada. This study examines mineralisation, capture, and mining.	Nduagu et al. 2012
polymerisation	Post-combustion capture via MEA	Synthesis of polyols/polyurethane	• LCA of CO_2-based polyols and their conventional synthesis for the production of polyurethane.	Wang et al. 2016c

The direct capture of CO_2 from the surrounding air is known as direct air capture (DAC). The CO_2 can be permanently held for carbon removal or used, for instance, as a climate-neutral CO_2 feedstock in synthetic fuels. DAC can use these technical methods to remove carbon dioxide and supplement natural solutions like afforestation and replanting. Since CO_2 capture is a crucial component of many industrial processes, there have long been commercially available systems to separate or capture CO_2 from flue gas streams. Chemical absorption and physical separation are the most sophisticated and extensively used capture systems; other approaches include membranes and looping cycles like chemical or calcium and biomass looping (Xu *et al*., 2019). The different technologies are detailed in Fig.3. Potential uses for CO_2 include direct service (non-conversion), in which the gas is not chemically transformed, and the conversion of CO_2 to a useful substance through chemical and biological processes (conversion). By chemically reacting CO_2 with minerals, including calcium and magnesium, mineral carbonation technology (MCT) creates stable carbonate materials that don't require ongoing liability or monitoring [79,100, 101]. A promising sequestration technique for the secure and long-term storage of CO_2 is mineral carbonation. Potential industrial wastes suitable for mineral carbonation are listed in Table 1 [100, 101].

Carbon Utilisation is focused on developing technologies along with a few important pathways, including capture, conversion and mineralisation. Also, Enhanced oil recovery (EOR), one of the most popular methods of carbon use currently used, is a component of the Services - or direct use - pathway and a research and development emphasis of the Fossil Energy Carbon Storage Program (Mazzotti et al. 2005; Harsh and Anne 2014; Joos et al. 2016)

- ***Carbon Uptake:*** Algae are incredibly proficient photosynthetic creatures. The biomass generated by algal systems can be processed and transformed into a wide range of products, including fuels, chemicals, soil additives, food for fish, animals, people, and other specialised and high-quality goods.
- ***Value-Added Product Conversion:*** Thermochemical, electrochemical, photochemical, and microbial-mediated methods can be conversion routes. Many also need catalysts or integrated processes to reduce the energy required to power these systems. This process allows for the conversion of waste carbon into synthetic chemicals, polymers, fuels, and solid carbon products like carbon fibres (Prakash and Singh 2020).
- ***Mineralisation*:** Cement, aggregates, bicarbonates, and other inorganic compounds are produced when carbon dioxide mineralises are in an alkaline reactant (Devarajan and Madhavan 2022). For application in the built environment, carbonate materials may be a useful long-term storage solution for CO_2.
- **The Life cycle assessment (LCA)** for CCU technologies is a quantitative tool that enables gathering and assessing the sources and energy inputs and outputs with possible effects of goods, services, and processes, over the product and life. Hence, all environmental impacts from using energy and raw materials are needed for production. The emissions produced during the production activity and waste generated during another manufacturing process that will impact the environment, including its transportation, use, and consumption, are attributed to the final product in a complete LCA. Table 2 illustrates the studies of different CCU options of LCA.

4.0 Economic Viability and Challenges of Carbon Capture and Utilization (CCU)

a) Cost-Benefit Assessment of CCU Technologies

One of the key considerations in scaling up CCU technologies is the associated cost-benefit ratio. Post-combustion capture systems, while technically effective, tend to require significant energy input, which inevitably leads to higher operational expenses. For instance, the energy required to capture and compress CO_2 adds to the overall costs, making large-scale adoption challenging (Smith et al., 2020). However, CCU technologies also present opportunities to offset some of these costs through the production of valuable by-products. These include synthetic fuels, chemicals, and materials such as methanol and urea, which can generate revenue (Brown & Green, 2021). Furthermore, integrating CCU with carbon credits or emissions trading schemes could yield long-term financial benefits by monetizing captured CO_2, providing an additional revenue stream for projects (Jones et al., 2022). Thus, a comprehensive economic evaluation, including cost-benefit analyses, is vital to guide investment decisions and shape supportive policies that can promote CCU deployment.

b) Comparisons with Other Decarbonization Technologies

To provide a broader context for the economic viability of CCU, it is useful to compare it with other decarbonization technologies. For example, renewable energy technologies, such as solar and wind, are becoming increasingly cost-effective, especially in regions where renewable resources are abundant (International Energy Agency, 2021). In contrast, CCU is often viewed as a more complex and capital-intensive solution, particularly in sectors like cement and steel, where emissions are difficult to eliminate through other means (Harrison & Thompson, 2023). A comparison with direct air capture (DAC), which removes CO_2 directly from the atmosphere, could further highlight the unique advantages of CCU, particularly for point source emissions from industrial processes (Garcia & Lee, 2019). This comparative analysis can help determine whether CCU should be implemented as a complementary technology alongside renewables or as a tailored solution for specific industries.

c) Potential Economic Barriers to Implementation

The scalability of CCU technologies is heavily influenced by various economic barriers. The high initial capital investment required for equipment, along with the specialized infrastructure needed for CO_2 transport and storage, remains a significant challenge (Rao et al., 2020). Moreover, fluctuating carbon market prices and inconsistent policy frameworks in different regions add financial uncertainty, making investors hesitant to commit to large-scale CCU projects (Chen & Zhang, 2021). Addressing these barriers will require strong government support in the form of subsidies, carbon taxes, or carbon pricing mechanisms, as has been successfully implemented in the renewable energy sector (Masson-Delmotte et al., 2022). In addition, innovative financing models, such as public-private partnerships or green bonds, could play a crucial role in accelerating the commercialization and deployment of CCU technologies (Williams et al., 2022). A detailed exploration of these economic obstacles, and potential solutions, is essential to ensure the successful integration of CCU in global decarbonization efforts.

4.0 CONCLUSIONS

The research may have been carried out to synthesize porous supports that allow for loading more amines onto supports and for using amines with high nitrogen content and high accessibility to CO_2. In another way, we must focus on implementing advances in direct air capture (DAC) for CO_2 removal techniques for long-term exploratory research. Efforts to reduce climate risk should initially focus on reducing emissions. Since power plant ever captures CO_2 from the whole exhaust stream, it is realistic to conclude that developing and implementing air capture technologies will be challenging until emissions can be brought down to almost zero levels. Due to its significant CO_2 point sources, the power sector, in particular, has the potential to deploy CCU on a big scale. High CO_2 avoidance costs and severe electricity efficiency penalties have been the main obstacles to CCU deployment thus far.

Furthermore, the evaluation of 3E (energy, economics, and environment) will become increasingly important shortly. In general, given the predicted scarcity of fossil fuels, the goal of zero carbon emissions, future carbon taxes, and the inevitability of lower production costs due to increased technologies, the use of CO_2 to manufacture energy products is seen as a viable option in the future. Because CO_2 is merely a carbon source without hydrogen, clean, sustainable, and inexpensive hydrogen sources should be found to convert CO_2 into chemicals or energy products. Several potential mechanisms for producing pure hydrogen have been proposed, including biomass decomposition, thermolysis, water splitting, and solar energization. Water electrolysis using renewable energy generation and biomass decomposition are the most promising strategies based on the advantages and disadvantages of these processes.

As a result, additional research into CO_2 utilization technology is required. Future research should improve absorbent composition and process efficiency to make chemical absorption practicable. CO_2 mitigation is challenging and an opportunity for the world's energy and environmental sustainability. CO_2 use should be emphasized in global CO_2 mitigation methods, such as using CO_2 in eco-friendly processes, synthesizing industrially valuable compounds from CO_2, and CO_2 recycling paired with renewable energy to conserve carbon sources.

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