Review Article

A Comprehensive Review of Approaches in Carbon Capture, and Utilization to Reduce Greenhouse Gases

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Abstract

Addressing atmospheric CO_2 levels is crucial for mitigating global warming and promoting sustainable fossil fuel use. This review explores various CO_2 capture strategies, including pre-combustion, post-combustion, oxy-fuel combustion, direct air capture, chemical looping, and polymeric membranes. Each strategy is critically evaluated in terms of its advantages, limitations, and overall effectiveness. Additionally, this study discusses advanced separation techniques for captured CO_2, emphasizing recent innovations in membrane technology integrated with cryogenic processes. This integration has the potential to economically extract CO_2 from diverse industrial processes, offering significant benefits in terms of operational cost reduction and increased efficiency. A detailed market analysis is also presented to explore feasible CO_2 utilization options, highlighting potential incentives and motivations for capturing CO_2. Furthermore, the technological readiness level of various capture and separation techniques is assessed, offering insights into their development and progress over time. This comprehensive analysis aims to support the advancement of effective and economically viable CO_2 management solutions, contributing to a more sustainable and climate-resilient future.

Keywords: Biorefinery, Carbon mitigation, Circular economy, CO_2 conversion, Greenhouse gas, Technological readiness level

1 Introduction

Demands for pharmaceutical, chemical, and other industrial products have rapidly increased due to the increase in global populations and industrial activities. Consequently, a large amount of carbon dioxide is emitted and its concentration increases in the biosphere. According to the US Energy Information Administration report, world energy consumption is forecasted to rise by 56% between 2015 and 2040 [1].

Fossil fuels are used as a main source of energy for producing electricity in power plants all over the world. This not only increases the concentration of CO_2 in the atmosphere but also poses major threats to ecosystems, human health, and energy security [2]. In 2015, the burning of fossil fuels resulted in the release of 1925 million metric tons of CO_2 into the atmosphere, which is about 87% of all CO_2 emissions. The development of infrastructure, transportation systems, and industrial plants also contribute to the emission of CO_2, accounting for about 24% and 8% of total energy-related CO_2 emissions. Furthermore, deforestation and other land uses account for about 10-12% of total CO_2 emissions. An increase in the emission of greenhouse gases results in global warming and is expected to pose major threats for future generations. It is predicted by the Intergovernmental panel on Climate Change that concentrations of CO_2 in the atmosphere are expected to reach 570 ppm by 2100 and the average global temperature can increase up to 1.9 °C [3]. Continuous emissions of CO_2 and its abundance in the atmosphere (about 78–80%) have emerged as the most significant factor contributing to global change. Almost 700 billion tons of CO_2 are present in the atmosphere, with 100 billion tons of CO_2 being utilized by photosynthesis. Oil-producing countries, including OPEC members, contribute the most towards CO_2 emission per capita. Qatar and Kuwait produced 49 and 25 tons of emissions per capita, respectively [4]. The higher-income countries, such as the United States of America and Canada contribute most towards global emissions as they have the largest per capita emissions. Currently, the United States of America and Canada contribute 16.2 and 15.6 tons per person of carbon footprint, which is three times greater than the global average in 2017 [5].

Rapid industrialization and globalization are expected to result in a significantly higher carbon footprint in developing countries, which indicates a strong link between development and per capita CO_2 emissions. There is a clear difference in greenhouse gas emissions when countries with similar living standards are compared. The United States of America and Canada have higher GHG emissions than many European countries. A higher proportion of electricity is generated using renewable and nuclear energies in many European countries [6]. These concerns have led scientists and researchers all over the world to focus on lowering CO_2 emissions. Replacing fossil fuels with renewable energy sources is not sufficient to tackle the global warming issue. Therefore, researchers are focusing on utilizing atmospheric CO_2 for the production of fuels and fine chemicals to increase the incentive and motivate this movement [7].

The mechanisms to reduce atmospheric CO_2 that are being supported by the policymaker not only mitigate GHG emissions but also gain social and economic focus. Different countries make agreements at the Conference of the Parties (COP) under the United Nations Framework Convention on Climate Change (UNFCCC) to work on mitigating carbon and look for advanced and optimized methods for this purpose. The conventions also allow member countries to announce their action plans and timeframe to reduce the releases of CO_2. In response to these world mutual agreements, it is essential to develop effective and economically feasible technologies for CO_2 capture and utilization [8]. Recent advancements in capture technologies, such as adsorption, absorption, and membrane separation, along with innovative utilization pathways, including catalytic conversion and biological fixation, have significantly expanded the feasibility and efficiency of Carbon Capture and Utilization (CCU) processes [9] (Figure 1). This review article aims to provide a comprehensive overview of the current state of CO_2 capture and utilization technologies. It examines the latest advancements, the efficiency and scalability of various capture methods, and explores the potential applications and benefits of CO_2 utilization. Additionally, this article highlights key challenges and opportunities for future research and development to mitigate climate change through innovative CO_2 management strategies.

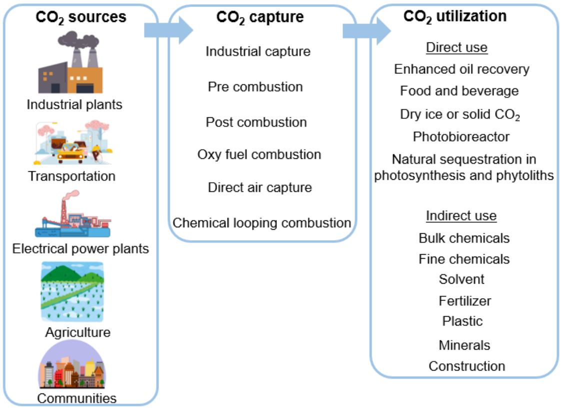

Figure 1: Carbon emission sources and Carbon Capture and Utilization (CCU) processes.

2 CO_2 Capture Strategies

Many technological pathways are available for CO_2 capture including pre-combustion, oxy-fuel combustion, post-combustion, chemical looping combustion, direct air capture and industrial separation [9]. Among all technologies, post-combustion and industrial separation capture technologies are the most used technologies, followed by pre-combustion, oxyfuel combustion, and direct air capture, whereas chemical looping capture is still under the development stage. The low efficiency of current processes and the high electricity consumption pose significant challenges to the commercial viability and profitability of CO_2 capture technologies [10]. The pros and cons of each CO_2 capture technology have also been summarized in Table 1. All the technologies are briefly explained in this section along with their process description.

Table 1: Advantages and disadvantages of different CO_2 capturing strategies.

Capture Technologies	Advantages	Disadvantages	Application	CO_2 Conc. (%v)	Ref.
Post-combustion	• Easier to retrofit existing plants • Matured technology	• High capital and operating cost • High energy requirement • Low partial pressure causes capture efficiency reduction	Gas and coal-fired plants	12–14	[11]
Industrial Separation	• Higher CO_2 concentration • Low operating cost	• Highly energy intensive for aluminum production	Flue gas treatment	3–4	[1]
Pre-Combustion	• Easier to retrofit existing plants • Higher partial pressure improves sorption efficiency • Fully developed technology	• Efficiency and temperature issues • High capital and operating cost • Higher energy is required for the regeneration of sorbent	Coal-gasification plants	11–13	[2], [3]
Oxy-fuel combustion	• Higher CO_2 concentration improves absorption efficiency	• High efficiency drops • Corrosion issues • Energy-intensive O_2 production	Circulating fluidized bed boilers.	N.A.*	[4]–[6]
Direct Air Capture (DAC)	• Reduces CO_2 concentration in the atmosphere • Higher efficiency for CO_2 removal	• Energy-intensive and costly	Urea and ammonia plants	18	[7], [8]
Chemical Looping Combustion (CLC)	• Cheaper CO_2 carrier materials • Higher concentration of CO_2 reduces the energy for air separation	• Under development stage • Desulphurization of fuel before introducing into the reactor	Coal-gasification plants	12–14	[9], [10]

*N.A. Not available

2.1 *Oxy-Fuel combustion capture*

In this technique, CO_2-rich flue gas is produced by combusting fuel at very high temperatures (1300 °C–1400 °C for a gas turbine cycle and 1900 °C for coal-fired boiler) with oxygen separated from air (Figure 2). Apart from that particulate matter, water vapor and traces of contaminants are also produced [10]. An electrostatic precipitator is used to remove the particulates whereas denitrification and desulphurization methods are used to remove NO_x and SO_2 [12]. The gas streams can be cooled down and compressed to remove the water vapor. Since CO_2 is present in the flue gas at high concentration, therefore no physical sorbent or chemical solvent is required to separate it from the flue gas. Once CO_2 is separated, it can then be compressed, transported, and stored. Comparatively, with the low-efficiency penalty of 4%, oxy-fuel combustion is the most energy-efficient technology compared to approximately 10% for post-combustion capture. Nevertheless, industrial application of oxy-fuel combustion is yet to be established [13].

Lignocellulosic biomass and municipal solid waste can be used as fuels in oxy-fuel combustion capture for the production of biogenic and bioenergy CO_2 [14], [15]. Hence, negative or net-zero CO_2 emissions can be achieved. The infrastructure and operating cost of bioenergy-based carbon capture mainly depend on the type of industry, in which it is being used. Based on incentives and policies from governments, bioenergy-based carbon capture can be proven to be more economically efficient than fossil fuel-based carbon capture [16]. A cryogenic air separation process is involved in the oxy-fuel combustion capture, an air separation unit is required to produce pure oxygen for combustion. This process is highly energy-intensive and costly, which is the main challenge in the commercialization of oxy-fuel combustion capture. Almost 15% and 26% of the total electrical energy of power plants and equipment costs, respectively, are consumed by air separation units (ASU) [11]. Several studies have been conducted to develop innovative air separation methods, such as ion-transport and oxygen-transport membranes, and the results have been very promising for producing inexpensive oxygen to be used in the oxy-fuel combustion process. Compared to an air separation unit, utilization of an oxygen-transport membrane unit in the oxy-fuel combustion process for pulverized coal combustion with air can save energy by 0.5% to 9%, whereas integrated coal gasification combined cycle (IGCC) power plant can save energy up to 0.3% to 2.9% [17], [18].

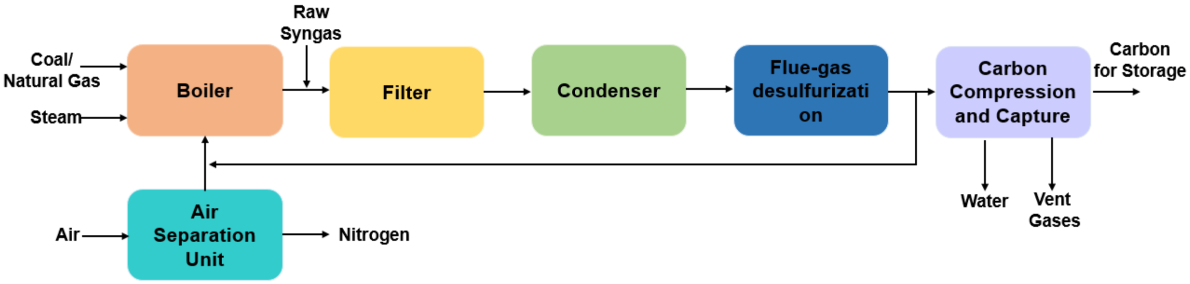

Figure 2: Process description of oxy-fuel combustion for CO_2 capture.

2.2 *Pre-combustion capture*

In pre-combustion capture, CO_2 is captured before fuel combustion takes place [11]. This capturing technology is based on different industrial processes that produce hydrogen and chemical commodities. IGCC power plants can also use this technology [2]. The coal gasification technology has been used in the chemical industry since the early 1900s and it is considered a mature technology for capturing CO_2. First, pre-treatment of coal or natural gas with oxygen or air takes place for the production of synthesis gas through gasification using steam or partial oxidation of natural gas (Figure 3). Then, the catalytic reactor is used for the water-gas shift reaction to convert produced CO into CO_2 and H_2 by reacting with steam [19].

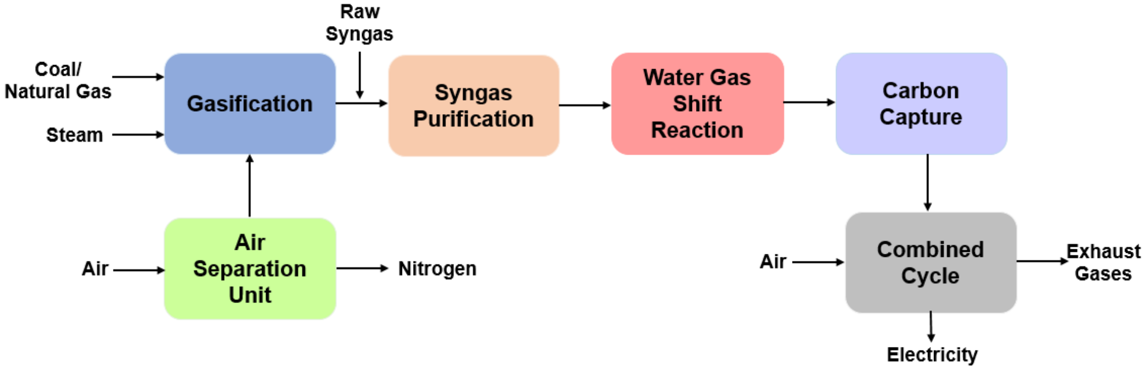

Figure 3: Process description of pre-combustion for CO_2 capture.

Physical or chemical absorption processes can be used to separate CO_2 from H_2. Consequently, H_2-rich flue gas is produced, which can be used for heat and power generation, such as fuel cells, gas turbines, and boilers. The sorption efficiency in the flue gas is increased by the high concentration of CO_2 and partial pressure, which requires less energy for separation and compression of CO_2 compared to post-combustion capture [20]. In one of the IGCC power plants using bituminous coal, the pre-combustion carbon capture energy requirement was lower by 10%/MWh compared to SCPC power plants whereas the CO_2 capture cost was higher by 83 USD/ton-CO_2 [21]. Numerous researchers tend to focus on the application of pre-combustion CO_2 capture on coal-based power generation due to the high cost and complexity of natural gas-based power generation plants. Apart from that the carbon capture by pre-combustion is not economically competitive if it is applied to natural-gas-based power plants. Many separation technologies such as membrane, cryogenic, adsorption, and absorption can be used to achieve carbon capture through pre-combustion capture [18].

2.3 *Post-combustion capture*

In post-combustion capture, combustion of fossil fuels and air takes place and as a result, CO_2 is captured from the produced flue gas (Figure 4). This is a mature technology and can be applied to various existing and future power plants [22]. Usually, the concentration of CO_2 is very low in flue gas streams. However, due to the higher flow rate than many chemical industries, the capturing of CO_2 is efficient. Apart from CO_2, air pollutants, organic and inorganic contaminants, and trace metals are also present in inert gases, such as H_2O vapor, O_2, and N_2, which must be removed or reduced to a lower concentration before the CO_2 capture process [23]. These energy costs and other costs associated with carbon capture must be taken into consideration to achieve a CO_2 concentration above 95.5 %v/v to make it suitable for transportation and storage. The sources of fuel and CO_2 generating process are associated with other factors that affect the efficiency and operating cost of power plants for carbon capture and storage [24].

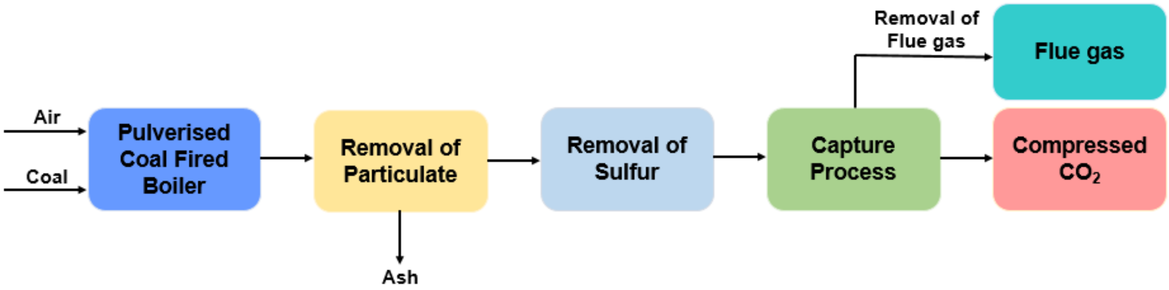

Figure 4: Process description of post-combustion for CO_2 capture.

In one case study of the natural gas plant combined cycle power plants for post-combustion power plants, the plant energy consumption per MWh of net electricity is expected to rise by an average of 15%, whereas a 50% increase can be observed in the cost of electricity per MWh. On the contrary, in supercritical pulverized coal power plants, net electricity against the overall plant energy consumption per MWh is expected to increase by 32% and a 73% cost increase can be seen in the cost of electricity per MWh [4]. In another case study, it has been reported that the low capital and indirect costs make the post-combustion pulverized coal power plants cost effective than pre-combustion IGCC power plants. Many technologies such as adsorption, membrane, biological, and cryogenic can be applied for the separation of CO_2 from post-combustion CO_2 capture [25].

2.4 *Chemical looping combustion (CLC) capture*

Chemical looping combustion is one of the emerging technologies for CO_2 capture from power plants. Instead of air, it involves the oxidation of fuel with metal oxide. Two reactors are interconnected in this process: a fuel reactor in which CO_2 and H_2O vapor are produced after the oxidation of fuel with an O_2 carrier, whereas in an air reactor metal oxidation takes place with air (Figure 5). Flue gas from the fuel reactor that is ready to be stored is used to obtain pure CO_2 after condensing the H_2O vapor [26]. Despite possessing low cost and high efficiency, this technology is still in the development stage due to the complexity of the process. Chemical looping combustion technology was first used for gaseous fuels, such as syngas and natural gas, then the technology extended to be used for solid fuels such as biomass and coal, and lastly, it is being used for liquid fuels [12].

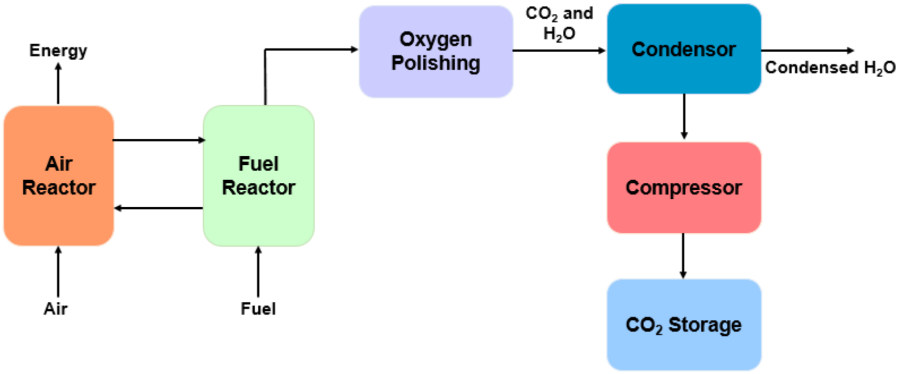

Figure 5: Process description of chemical looping combustion for CO_2 capture.

Feeding air to gas and steam turbines in the natural gas carbon capture with a chemical looping combustion process can be very efficient for the production of power. This integrated process has demonstrated lower CO_2 capture cost and higher efficiency (44.3%) than natural gas carbon capture with post-combustion capture (43.8%). Liquid fuel has not been widely used with fluidized bed reactors, which is the main reason for very limited research on chemical looping combustion for liquid fuels [9]. In one of the studies, ethanol demonstrated the capacity to be used as fuel for a thermal continuous chemical looping combustion unit if liquid fuel is injected directly into the fluidized bed reactor. As a result, 100% CO_2 capture efficiency was achieved at normal operating conditions [12], [13].

2.5 *Direct air capture*

In direct air capture, CO_2 is directly captured from the atmosphere, nevertheless, this technology is still in the development stage and has not been applied in industry. Currently, solid sorbent-based and liquid solvent-based approaches are two pathways to commercialize direct air capture [14] (Figure 6). In the solid sorbent approach, solid sorbents, such as activated carbons, metal-organic frameworks, silica materials, zeolites, etc. are used to adsorb CO_2. As the required temperature of the process to regenerate solid sorbent remains between 80 °C to 100 °C, the energy consumption is very low. Therefore, the CO_2 capture cost of direct air capture is reduced. The estimated cost (~86 USD/ton) for CO_2 capture was lower for solid adsorbents than liquid solvent-based direct air capture [15]. In a liquid solvent-based approach, a strongly alkaline liquid solvent is first used to absorb a very dilute CO_2 in the adsorption column to form $CaCO_3$. Later on, this mixture is separated, dried, and calcined at 800 °C to release concentrated CO_2 and form CaO. A slaker unit is used to hydrate CaO for the regeneration of $Ca(OH)_2$. The process is costly to operate as it has a high energy cost for $Ca(OH)_2$ regeneration per ton of captured CO_2, which makes the process non-feasible for the industry despite capturing an adequate amount of CO_2 [8]. Hence, other aqueous solutions, which have strong bonds with CO_2, such as KOH and NaOH, have also been utilized as alternatives. Researchers have also proposed other pathways, such as photocatalytic CO_2 conversion, electrochemical approaches, and mineral carbonation for direct air capture, however, they have not been widely studied [14].

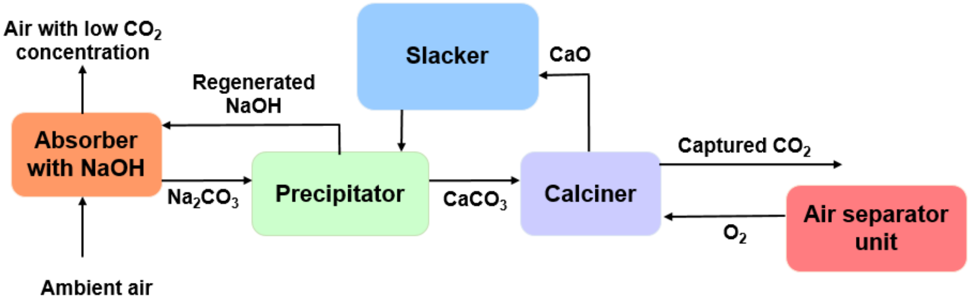

Figure 6: Process description of direct air capture for CO_2 capture.

2.6 *Industrial capture*

The industrial sector is one of the largest sources of CO_2 emissions due to rapid industrialization, which results in the burning of fossil fuels and the emission of CO_2. Different technologies, such as oxy-fuel, post-combustion, and pre-combustion, can be employed for capturing CO_2 from industrial process streams, especially from steel, cement, and ammonia plants [16] (Table 2). Different concentrations of CO_2 are present in natural gas depending on its source. Hence, the CO_2 must be removed from the natural gas before being sold to industry. Currently, carbon capture and utilization strategies revolve around natural gas processing as it offers low-cost capture opportunities and costs around 30 MT CO_2/year [17].

Using post-combustion technology, CO_2 produced from limestone calcination can be captured from cement production plants. The limestone ($CaCO_3$) is combusted by using fossil fuel to produce CaO, an important cement composition. Besides that, substituting air in the cement kiln with pure O_2 can also make way for applying oxy-fuel combustion in cement manufacturing plants, which can increase the concentration of CO_2 in the flue gas by more than 70%. Heidelburg cement in Norway is developing this strategy in the processing plant that can capture 0.4 Mt CO_2/year [27]. Another lime and cement manufacturer in Belgium is developing a CO_2 capturing strategy for lime and cement industries to capture CO_2 from limestone-based indirect calcination process [28]. Research and development on biomass coupled chemical looping combustion, waste material is a target to explore the possibility of usages and studies on fuel pretreatment technical issues. Progress in the development of small commercial units rather than large commercial units. Development in oxygen carriers towards commercial use to ensure safety and environmental limitations [29].

Table 2: Different carbon capture technologies and their applications.

Carbon Capture Technology	Application	Capture Efficiency (%)	Ref.
Oxyfuel combustion	Natural gas processing, Coal-fired power plants	90–100	[30]–[34]
Pre-combustion and post-combustion	Urea, cement curing, methane, soil carbon sequestration and bioenergy	85–90	[33], [35]
Direct separation, oxyfuel membrane, and calcium looping	Cement industry	100	[36], [37]
Membrane separation and adsorption	Natural Gas Processing Plant, ethanol plant	74	[38], [39]
Post-combustion	Power plants with amine solvents	85	[33], [40]
Direct air capture	IGCC plants	82–89	[40], [41]
Cryogenic method	IGCC plants	90–99.99	[40]
Post Combustion	Bioenergy with carbon capture and storage (BECCS) industry	Up to 95	[37], [42], [43]
Polymeric membrane	Natural gas industry	90	[42], [43]
Cryogenic capture	Fuel cell industry	90–99.9	[44], [45]
Direct air capture	Supercritical pulverized coal plant	85–93	[46]
Chemical looping combustion	IGCC for power generation	96–99	[47]
Polymeric membranes	Natural gas industry	70–90	[47], [48]

3 CO_2 Separation

Advances in materials science, chemical engineering, and process optimization have led to a diverse array of separation techniques, such as absorption, adsorption, membrane separation, and cryogenic distillation. Various approaches can be selected based on process requirements, selectivity, technical intensification, and flexibility. For instance, cryogenic separation, membrane separation, and physiochemical absorption are traditionally used to remove CO_2 from polluted gas streams. This section provides a comprehensive overview of the latest advancements in CO_2 separation technologies. By examining both established and emerging methods in the quest for effective CO_2 mitigation strategies.

3.1 *Adsorption*

Adsorption is a widely used technology in capturing CO_2, in which atoms and molecules in a liquid, solid, or gaseous state, are adhesive to a given surface for a long-term period. Adsorbates are atoms, ions, or particles that get stuck to the surface of an adsorbent. The adsorption processes can be covalent bonding, electrostatic attraction, and van der Waals forces. In the adsorption and absorption process, chemical structures are incorporated, which results in the formation of molecular structures based on CO_2.

Eventually, it is heated at the appropriate temperature for recovery [49]. A maximum amount of CO_2 can be collected by this regeneration strategy but the adsorption of CO_2 is an energy-intensive technique as it requires a significant amount of energy for the recovery of adsorbents [50]. Moreover, additional CO_2 can be produced by providing more energy to the system for the regeneration of adsorbents. CO_2 emissions and operating costs can be reduced by applying renewable energy sources and negative emission technologies, such as direct air capture, to regenerate adsorbents. Carbon-based materials mainly consist of a connection between carbon and a substance with distinctive characteristics, such as electrical stability and heat resistance. Materials that are derived from renewable biomass are light in weight and have a higher surface area. Furthermore, the potential of carbon-based materials and their ability to be applied for industrial applications is reflected by their recyclability and cost-efficiency [51].

Capital and operating costs can be reduced for the application of the adsorption process at an industrial scale by extracting the optimized sorbent capacity through an appropriate gas-solid contractor and regeneration system. Operating cost and process efficiency are analyzed by studying different configurations of CO_2-capturing reactors, such as rotating, fluidized, and fixed types [52]. Due to high-pressure drop, limitations in heat/mass transfer, and heat wave formation during CO_2 capture, conventional reactors are not sufficient enough to extract the full potential of sorbent efficiency [53]. These constraints can be addressed by moving bed or rotating reactors to enhance sorbent efficiency. In the Kawasaki carbon capture (KCC) technique, solid sorbents are used in a moving bed system to capture CO_2 on a batch scale of 5-6 tons/day at low steam temperature. In this system, the porous sorbent is soaked in an amine compound to make it selectively desorb for steam at low temperatures (60 °C – 100 °C) [54]. The system consists of both desorption and adsorption reactors and a dryer, in which solid adsorbent absorbs the CO_2 from combustion gas and recycles it back to the adsorption reactor, followed by desorption of CO_2 in a dryer to remove water. Nevertheless, challenges related to heat and mass transfer, and pressure drop still exist in moving bed reactors [55].

3.2 *Absorption*

Henry’s law of solubility can be used for chemical/physical absorption of gas at high pressure and low temperature. Absorptive transportation is the driving force to move gas molecules from the vapor to the fluid phase. Chemical and physical properties assist in determining the solubility of gas in the presence of CO_2. Based on the solvent, gas components can be dissolved through physical and chemical absorption or through a process that is dependent on both chemical and physical absorption [52]. Physical absorption takes place when there is an interaction between liquid and vapor forms of CO_2 molecules in the presence of insufficient intermolecular forces for absorbing the gas. Contrary to chemical absorbents, a lower temperature is required by physical absorbents for gas absorbance as compared to chemical absorbents. Whereas demand for thermal energy is higher for chemical absorbents during regeneration as additional heat is required by the reboiler in the stripper column [56]. It is claimed that the condition with extremely low temperatures and high pressure is required for the annihilation of CO_2 in a physical fluid solution using electrostatic or van der Waals interaction. A wide range of chemicals, such as ethanolamine and ammonia are utilized as reactive absorbents. Key features of different absorbents were combined to create blends whereas inappropriate features were reduced. Ni^{2+} and piperazine in a bubbling reactor were used to study the release rate of NH_3 and CO_2 absorption [57].

Absorption of CO_2 was enhanced by 72% upon the addition of 50 mM/L of Ni^{2+} and 25 mL/L of piperazine, as compared to the addition of NH_3 without adding metal ions. Utilization of NH_3 solution instead of water prevented half of the ammonia from being wasted [1]. Oxidative and heat decay resistance was not boosted by using the mixture of piperazine and 2-amino-2-methyl-1-propanol. Furthermore, the circulatory absorption rate was slowed down by 45% and regeneration energy was reduced by 20%. In another experiment, a blend of piperazine and 2-amino-2methyl-1-propanol with a specific absorption rate, ranging from 14.60 to 26.81 $kmol/m^2.s$, was used to recover CO_2 [58]. Piperazine presence in the mixture with higher concentration could assist the absorption of 99.63% of CO_2. Excellent properties, such as moderate vapor pressure, low environmental impact, high stability, and specific reactivity with CO_2 must be possessed by the absorbent. Diethanolamine, triethanolamine and monoethanolamine are the latest and the most commonly used absorbents due to their high absorption rates and low cost. Nevertheless, amine-based sorption has some drawbacks, such as limited corrosive qualities and CO_2 storage capacity, and high energy requirement to regenerate basic solvents [59].

3.3 *Cryogenic-based capture*

The cryogenic-based capture approach is used to directly extract and separate CO_2 through the principles of cooling and condensation [20]. Liquid CO_2 can be maintained without the addition of other chemicals by compression of the gas at a higher pressure and pumping technology. It is important to separate a gas mixture cryogenically, as the refrigeration separation energy requires a high amount of energy [60]. Moreover, frost CO_2 is present at low temperatures and atmospheric pressure. Cryogenic-based CO_2 capture technology can be economically profitable for the recovery of CO_2 from plants that emit dilute CO_2-rich streams and highly CO_2-rich gas streams, such as electric power plants. Explicitly, during catalytic aromatic hydrocarbon oxidation; benzene was removed from the gaseous mixture using vacuum de-sublimation [44]. An optimized vacuum desublimation technique was studied to remove airborne volatile organic contaminants by making changes to the composition, gas flow rate, pressure, and temperature [61].

Overall energy costs were reduced by using an external cooling loop (ECL) and waste cold energy in a hybrid cryogenic capture technology for capturing CO_2 from flue gas by 30%. In this process, flue gas was first pretreated (drying and cooling) followed by solidification of CO_2 by compressing and cooling, compressing at 100-200 atm and eventually it was reheated before CO_2 was captured as liquid phase along with residual flue gases [62]. Nevertheless, it is crucial to develop an energy-efficient and feasible method for the extraction of gasses from different gas streams and reduce the chances of blockage by water [63].

3.4 *Membrane-based capture*

Membrane technology is used for selective capture of CO_2 from a gas mixture, the physiochemical interactions between the surface properties of membranes and CO_2 gas allow one of the gases to diffuse faster than the others [64]. Membrane-based CO_2 capture is considered cost-competitive if more than 10% of CO_2 is present in the gas mixture. Nevertheless, a few issues, such as high energy, consumption, gas leakage, and low CO_2 selectivity must be addressed and resolved [65]. Bis- triethoxysilyl acetylene, and 3-aminopropyl triethoxysilane were used to develop an amino-integrated organosilica membrane by copolymerization, and high CO_2 capture efficiency and affinity were shown by this membrane. CO_2 permeance from 2550 to 3230 gas permeance units was shown by the tested membrane during the separation of N_2 and CO_2, whereas due to the CO_2-phallic characteristics and pore size selectivity of N_2 and CO_2 reached values between 30 and 40 [66].

Selectivity of CO_2 in a gas mixture was obtained with CH_4 with a CO_2 permeance of 8×10^{-7} mol/m^2.s Pa. During the synthesis of the membrane, a thin layer of metal-organic frameworks (MOFs) can be mixed with a polymer matrix to deposit it on the surface of the membrane [67]. CO_2 selectivity and permeability were enhanced by a newly engineered integrated membrane. Membranes derived from pure polyether block-amide improved CO_2 permeability by 380% when mixed with MOF[$Al_2(OH)_2$] at a filter ratio of 40%, whereas CO_2 selectivity over CH_4 was improved by 68% and CO_2 selectivity over N_2 by 26%. Due to the specific properties of CO_2 and the high porosity of NOTT-300, it can be used in CO_2 uptake composite matrix membranes as a filter [68].

4 CO_2 Utilization

The increase in the standard of living in recent years has contributed to the significant rise in CO_2 emissions. As a result, immediate remedies to curb the negative effects of an increase in CO_2 levels must be addressed. In 2023, global emissions of CO_2 were recorded at 37.4 Gt, mainly from the burning of fossil fuels by the industry and transportation sectors [69]. Regardless of notable advancements in clean energy, 2023 witnessed a 1.1% rise in CO_2 emissions with severe global warming, adverse weather patterns, and the post-COVID-19 economic rebound [70]. The CO_2 emissions are expected to further increase by about 10% from the energy use as predicted by BP's Energy Outlook, by 2040 [71]. Recent research studies have focused on developing cutting-edge technologies to capture, store, and utilize CO_2 to reduce the carbon footprint and sustainable management of the available resources [72], [73]. CO_2 utilization can prove to be of paramount importance in this regard as it involves the transformation of captured CO_2 into valuable products such as fuels, chemicals, and materials. The recent advances in research technology and the international agreements to control global warming to mitigate climate change have played key roles in the implementation of CO_2 utilization worldwide [74]. However, the inability to fix carbon for long, as well as economic feasibility, limit large-scale applications and global implementation of the CO_2 utilization technique.

Captured CO_2 can be used in various industries to produce a wide range of products and to improve hydrocarbon recovery, which can eventually reduce the cost associated with carbon capture and storage. According to the International Energy Agency, approximately 230 Mt CO_2/ year is used globally 57% of total CO_2 is used in the fertilizer industry to produce urea, 34% in the oil and gas industry, 3% for each beverage and food industry, and 3% for other commercial applications, such as crop cultivation and cooling processes. Conversions of CO_2 into chemicals, building materials, and fuels are the potential usage of CO_2 but these processes demand high energy. Therefore, due to high energy costs and commercial challenges, they are still in the research and development stage [75].

The utilization of captured CO_2 cannot fully resolve the issue of climate change and CO_2 emissions as there is a clear deficit between the amount of captured CO_2 and the CO_2 that is being utilized, and the storage duration ranges from days to millennia. A comprehensive analysis of market dynamics and life-cycle assessment is required to quantify the environmental benefits of CO_2 utilization and its emission reduction. Utilization of CO_2 can only be seen as a complement rather than an alternative to CO_2 storage to reduce large-scale emissions [76]. In one of the studies, it was estimated that carbon capture and utilization have a very negligible contribution (0.2 Gt CO_2/year in 2050) towards resolving the CO_2 mitigation challenge. On the other hand, carbon capture and storage have a much higher contribution (7.8 Gt CO_2) year in 2050. CO_2 can be utilized for a wide range of applications, such as direct usage and conversion into other valuable products [77]. The technology readiness level (TRL) and estimated market of CO_2 utilization are tabulated in Table 3.

Table 3: Technology readiness level and estimated market of CO_2-derived products.

Product	CO_2 Used (Mt CO_2/Year)	Production Scale (Mt/year)	Capture Cost (US$/ton)	Selling Price (US$/ton)	TRL	Ref.
Carbonates	0.5	>2.0	657	1000	7 to 8	[78, 79]
Polymers	1.5	15.0	1440	2040	7	[79, 80]
Methanol	10.0	60.0	1740	360	7	
Formaldehyde	6.5	28.0	3500	5000	6	[81]
Food Packaging	8.2	8.2	6900	8200	9	[81]
Industrial gas	6.3	6.3	6300	6800	9	[81]
Beverage carbonation	2.9	2.9	2695	2900	9	[81]
Enhanced oil and gas recovery	25.0	7% to 23% of oil reserve	N.A.*	N.A.	7 to 9	[79, 80]
Algae cultivation for biodiesel	2.0	1.0	1247	2000	4 to 7	[79, 82]

*not available

4.1 *Direct usage*

The direct utilization of CO_2 encompasses various applications, where it is used without undergoing chemical conversion. One of the most promising business applications for direct CO_2 use is enhanced oil recovery (EOR). One of the steps in this process is CO_2 injection, which boosts oil recovery from an oil-bearing reservoir. The CO_2 utilized in EOR is very often obtained from natural origin, i.e., either originating from natural CO_2 reservoirs or captured from industrial sources [83]. The injected CO_2 serves to enhance oil recovery by reducing its viscosity to flow through production wells, permanently immobilizing CO_2 in the reservoir. CO_2 is also injected into the coal seams to enhance methane extraction for enhanced coal bed methane recovery [84]. CO_2 can also be stored by carbonation in beverages, such as beer, soda, and sparkling water to impart a unique taste and frizzy texture. Another application of CO_2 is in the Modified Atmosphere Packaging (MAP) of food. This entails the substitution of the air inside a package with gas mixtures containing CO_2. MAP technique is used to increase the expected lifespan of perishable items, such as meat, poultry, fruits, and vegetables by inhibiting the growth of bacteria and fungi responsible for the spoilage of food [85]. Moreover, dry ice, or solid CO_2, is also used for refrigeration and transportation of perishable goods because of its low temperature and ability to sublimate.

Plants directly absorb CO_2 to prepare glucose, from which they liberate oxygen by converting light energy into chemical energy. Highly purified CO_2 with some heat can be used to stimulate plant growth for the improvement of crop cultivation. Elevated CO_2 levels in greenhouses can significantly boost the growth and yield of valuable crops like tomatoes, cucumbers, and lettuce. For instance, if the CO_2 concentration from 200 ppm to 1000 ppm in the greenhouse is enriched, it can lead to a rise in the yield of red leaf lettuce by 30% [69]. However, flue gases that contain different impurities, such as NO_X, SO_X, or heavy metals are highly toxic for a chemical process and should be avoided in greenhouses. Biogas upgrading plants are suitable source of CO_2 for greenhouses as it can produce highly concentrated CO_2 streams, which consist of extra heat to be used directly in the greenhouse. Traditionally, crop cultivation requires about 0.50 kg CO_2/h per 100 m^2 to 0.70 kg CO_2/h per 100 m^2. Utilization of CO_2 in the greenhouse is a mature strategy to be used to enhance crop yield [80]. CO_2 is directly used in algae cultivation as 1 kg of algal biomass can sequester approximately 1.83 kg of CO_2 and thus can be used to provide bioenergy for commercial use [86]. This process usually occurs in photobioreactors or open ponds where CO_2 is bubbled through water to increase the rate of photosynthesis. The produced biomass can be transformed into a wide range of bio-based products such as biofuels, and animal feed, which makes algae cultivation a sustainable method to utilize the captured CO_2 for renewable energy and product generation.

CO_2 can be utilized biologically by plants, and autotrophic microorganisms, particularly microalgae, to create useful products through the natural process of photosynthesis. CO_2 fixation of this form is cost-effective and environmentally benign. Microalgae can fix approximately 1.83 kg of CO_2 per kg of biomass, making them a viable alternative to fossil fuels [87]. Microalgae, such as *Chlorella* and *Spirulina,* use the CO_2 dissolved in water for photosynthesis. This process involves the Calvin-Benson cycle, which uses light energy to transform CO_2 into organic compounds, and the enzyme ribulose bisphosphate carboxylase-oxygenase (Rubisco). Microalgae can grow in a wide range of environments and effectively fix CO_2 from sources like flue gas, which has high concentrations of both CO_2 and other gases like NO_x and SO_x. The choice of microalgae species is critical for certain applications, such as utilizing high CO_2 concentrations from industrial emissions. The species capable of handling CO_2 concentrations above 40%, can be used to capture CO_2 from flue gas produced during the burning of fossil fuels. Microalgae and cyanobacteria can perform photosynthesis to capture CO_2 into biomass that can further be converted into biofuels and bio-based chemicals. Some bacteria, such as acetogens, are capable of converting CO_2 into organic acids, alcohols, and other chemicals through metabolic pathways [88]. Enzymatic conversion shows high selectivity and yield under mild conditions due to the stimulation of natural biological processes under such conditions. Enzymes, such as carbonic anhydrase and formate dehydrogenase catalyze the reduction of CO_2 to formate and other chemicals, thereby utilizing CO_2 effectively [89]. The efficiency of CO_2 fixation is significantly affected by pH, light intensity, culture temperature, and CO_2 concentration [90]. Temperatures of 291–298 K, pH values of 6-8, and CO_2 concentrations of 10–20% are generally considered the ideal growth conditions [91], [92]. Studies have demonstrated that the ability of microalgae to fix CO_2 and adapt to different environmental conditions can be further improved through genetic modification [93]. This entails the creation of metabolic pathways that can boost photosynthesis to enhance the efficiency of carbon capture and fixation. For example, the application of CRISPR/Cas9 technology has improved the capacity of some algae strains to sequester CO_2 and increase their efficacy in lowering atmospheric CO_2 concentrations [94], [95]. On the other hand, fermentation offers another opportunity to utilize CO_2 as a substrate or co-substrate to produce various chemicals, such as succinic acid, fumaric acid, malic acid, etc., using native or engineered microorganisms [96], [97]. The traditional fermentation route, for example, bioethanol production, releases large amounts of CO_2. This high-purity biogenic CO_2 can be utilized in gas fermentation, rather than using contaminated flue gas.

Agricultural activities play a significant role in the release of CO_2 into the atmosphere, contributing to global greenhouse gas emissions [98]. Among these activities, rice cultivation, as a major staple crop, stands out due to its unique impact on CO_2 levels, primarily through the management of flooded rice paddies. Rice paddies are flooded to support anaerobic conditions that facilitate the growth of rice plants and enhance nutrient availability [98]. However, this anaerobic environment promotes the decomposition of organic matter in the soil, leading to the production and release of methane (CH_4) and CO_2 [99]. Methane, in particular, is a potent greenhouse gas, with a much higher global warming potential than CO_2 over shorter time frames. Quantitatively, rice cultivation contributes significantly to global methane emissions, estimated to be approximately 5–17% of total methane emissions worldwide. In terms of CO_2 emissions, flooded rice paddies are estimated to release about 20–30 million tons of CO_2 annually [100], [101]. The release of CO_2 from rice paddies occurs primarily through two processes: microbial decomposition of organic matter in the soil under anaerobic conditions and the oxidation of organic carbon when fields are drained. These processes are influenced by water management practices, soil characteristics, and agricultural techniques employed by farmers [99].

Phytoliths are microscopic structures composed of silica that form within the cells of many plants. These silica bodies accumulate in various plant tissues, including leaves, stems, and roots, and are eventually deposited in the soil upon plant decomposition or through leaf and stem shedding [102]. The process of phytolith formation begins with the uptake of dissolved silica from the soil by plant roots. Once absorbed, silica is transported within the plant and deposited in the cells as solid silica bodies, which take on intricate and characteristic shapes depending on the plant species [103]. Phytoliths play several roles in plants, including structural support and defense against herbivores. However, their significance extends beyond plant physiology to environmental processes, particularly in carbon capturing and cycling [104]. When plants die and decompose, phytoliths containing silica remain intact in the soil for extended periods. Phytoliths can encapsulate organic carbon from plant material, effectively sequestering carbon in a stable form. This process helps prevent the release of CO_2 back into the atmosphere, thus acting as a long-term carbon sink [104]. This process is crucial in mitigating the greenhouse effect and global warming. Research into phytoliths and their role in carbon sequestration is ongoing, with studies exploring the potential of agricultural practices that promote phytolith formation to enhance carbon capture and soil carbon storage [105], [106]. Studies have shown that phytoliths can sequester significant amounts of carbon over time. For example, research in tropical forests estimated that phytoliths could sequester approximately 0.5 to 1.6 tons of carbon per hectare annually, depending on plant species and environmental conditions [107].

Silica bodies in phytoliths improve soil structure and porosity, enhancing water retention and nutrient availability for plant growth [108]. For instance, in regions where silica-poor soils are prevalent, adding phytolith-rich materials or promoting plants that accumulate phytoliths can improve soil quality and agricultural productivity. Case studies have demonstrated that incorporating phytolith-rich residues into agricultural soils can increase crop yields and reduce the need for synthetic fertilizers, thus promoting sustainable farming practices. In China, researchers have utilized rice husk ash, rich in phytoliths, as a sustainable additive in concrete production. This approach not only reduces the environmental impact of construction materials but also enhances their performance. Similarly, in Australia, phytolith-rich grass residues have been used to improve soil fertility in degraded agricultural lands, demonstrating the potential of phytoliths in restoring ecosystem health and productivity [109]. In the Amazon rainforest, studies have demonstrated the substantial carbon sequestration potential of phytoliths. Research estimates suggest that phytoliths contribute to storing approximately 0.3 to 0.8 tons of carbon per hectare annually in Amazonian soils. This natural process helps mitigate the effects of deforestation and supports the region's ecological stability [110].

4.2 *CO_2 Conversion into different products*

CO_2 can be sequestered by using it as feedstock for the sustainable production of fuels or chemicals such as urea, formic acid, methanol, cyclic carbonates, and salicylic acid. Economic feasibility studies are pertinent for the widespread adoption of such processes, considering the uncertainties in the demand in the market, prevalent government policies, and legislations such as carbon taxes. CO_2 can be converted into chemicals and fuels by various methods, such as electrochemical, thermocatalytic, photochemical, biochemical, and hybrid processes [9]. Recent CO_2 conversion technologies are discussed with a significant focus on their ability to reduce greenhouse gas emissions by spanning over different products of economic viability. Methane, syngas, and methanol are commercially established products that can be further used as fuel for the production of other fuels such as gasoline, diesel, and aviation fuels. Fuels derived from CO_2 are mostly used in the transport sector, for instance, if methanol meets the quality standards it can be used as a blend with gasoline whereas methane can be used for power generation. Hydrogenation and methanation are two of the technologically matured conversion pathways of CO_2 into methanol and methane, respectively (Scheme 1–2) [70]. Methanation of CO_2 results in the production of CH_4 and H_2O as the reaction between CO_2 and H_2 takes place. The reaction has high equilibrium conversion between 30 °C and 400 °C and usage of suitable catalysts can result in 99% selectivity of CH_4 [71]. This method is widely used to generate methane, which is an essential feedstock in the chemical industry and can be converted to formaldehyde, acetic acid, and other value-added chemicals [111].

Sabatier reaction

$$CO_2 + 4H_2 \rightleftarrows CH_4 + 2H_2O \quad \Delta H^0_{298K} = -164 \text{ kJ/mol}$$

Reverse water gas shift reaction

$$CO_2 + H_2 \rightleftarrows CO + H_2O \quad \Delta H^0_{298K} = 41 \text{ kJ/mol}$$

Side reactions

$$nCO_2 + (3n+1)H_2 \rightleftarrows C_nH_{2n+2} + 2nH_2O$$

$$nCO_2 + (3n)H_2 \rightleftarrows C_nH_{2n} + 2nH_2O$$

Scheme 1. Catalytic CO_2 methanation with side reactions.

$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O \quad \Delta H^0_{298K} = -49.4 \text{ kJ/mol}$$

$$CO_2 + H_2 \rightleftarrows CO + H_2O \quad \Delta H^0_{298K} = +41 \text{ kJ/mol}$$

$$CO + 2H_2 \rightleftarrows CH_3OH \quad \Delta H^0_{298K} = -90.4 \text{ kJ/mol}$$

Scheme 2. Reactions involved in CO_2 hydrogenation to methanol.

Catalytic CO_2 methanation, known as the Sabatier reaction, is an important strategy to produce methane, which can be used as fuel or feedstock for producing a range of chemicals [20]. Methanation of CO_2 involves the reaction with hydrogen and results in the simultaneous formation of CH_4 and H_2O. This reaction is carried out in a fixed-bed reactor at 150–500 °C and 1–100 bar pressure using the supported metal catalysts, such as Ni, Co, etc. The simplicity of the reaction, high CO_2 conversion, and high methane selectivity at moderate temperatures are advantages of this route. The CO_2 methanation reaction is thermodynamically feasible and exothermic with a negative change in the number of moles (Scheme 1). The reaction thus shows high equilibrium CO_2 conversion and more than 99% selectivity of CH_4 at low temperatures and high pressures (Figure 7) [71]. However, the equilibrium CO_2 conversion and methane yield decreases at high temperatures and low pressures. The process involves several competing reactions, such as reverse water gas shift reaction and alkanes/alkenes forming reaction. The reverse water gas shift reaction is endothermic and favorable at high temperatures, reducing the equilibrium methane yield at elevated temperatures. Nevertheless, while the high temperatures favor the kinetics, the methane selectivity reaches a peak at a certain temperature and then decreases with a further temperature rise [112] Although the methanol production process is less energy-intensive than the methane production process, most of the research work has been conducted on the production of CO_2-derived methane. Almost 70 plants are operational in European countries that produce CO_2-derived methane. However, hydrogen manufacturing is the primary energy-consuming step in this process. Recently, a techno-economic analysis of the CO_2 methanation process was conducted using CO_2 from 1000 MW capacity coal-fired thermal power plant for two different calcium looping-based integrated carbon capture and utilization (ICCU)-methanation [113]. Waste heat recovery was found to be the key to reduce manufacturing costs. Following the waste heat recovery, the manufacturing cost of methane was 575.78 USD/ton. However, the cost could be further reduced to 492.95 USD/ton considering the carbon tax, making it cost-competitive to natural gas (477.09 €/ton).

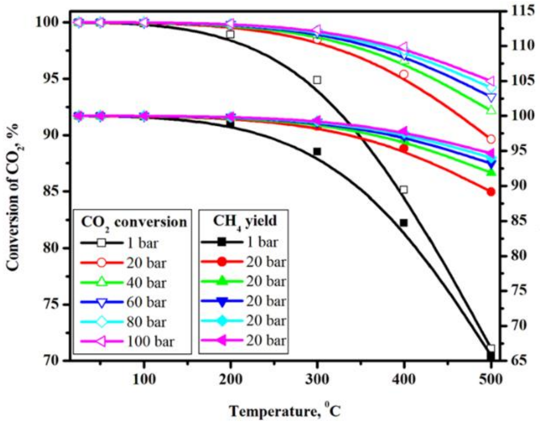

Figure 7: Effect of temperature and pressure on equilibrium CO_2 conversion and CH_4 selectivity. Conditions: CO_2:H_2=1:4 and CO_2, CO, H_2, CH_4, water, ethane, and ethylene as reaction products. Data generated using Aspen Plus.

CO_2 hydrogenation to methanol: Methanol is an important petrochemical with diverse applications. Different materials and chemicals, such as plastics, synthetic rubber, and solvents, can be produced from methanol. Olefins, especially propylene, can also be produced from methanol for use in health and hygiene, food production, and processing and for the production of polymers to make aromatics and plastics (such as xylene, toluene, and benzene). Currently, methanol-derived olefins are being produced in China, whereas methanol-derived aromatics are still in the research and development stage. The catalytic hydrogenation of CO_2 into methanol emerges as a promising method to mitigate carbon emissions and global warming. Methanol production is highly energy intensive as the H_2 is synthesized by electrolysis of H_2O [80]. Metal or metal oxide can be used as a catalyst at moderate operating conditions (20–100 bar pressure and 150–250 °C temperature) for hydrogenation of concentrated CO_2 to produce methanol. The reaction has thermodynamic limitations and is favorable only at low temperatures and high pressure (Scheme 2, Figure 8). On the other hand, the reverse water gas shift reaction is a competitive reaction and favorable at high temperatures. Therefore, this process suffers from low methanol selectivity. The catalysts thus play an important role in activating CO_2 at low temperatures with moderate CO_2 conversion and high methanol selectivity. The Cu-based catalysts are used in traditional methanol manufacturing processes from syngas and are widely investigated for CO_2 hydrogenation to produce methanol. However, they show poor catalytic activity at low temperatures [114]. Several other mixed metal oxide-based catalysts, for example, ZnO/ZrO_2, is actively conceded for this reaction. However, the economics (base selling price = 356.43 USD/ton methanol) of this process is not favorable due to the high cost of feedstock, especially hydrogen [115]. Although the methanol production process is less energy intensive than the methane production process. Most of the research works have been conducted on the production of CO_2-derived methane. Almost 70 plants are operational in European countries that produce CO_2-derived methane. Metal or metal oxide can be used as a catalyst at moderate operating conditions (pressure and temperature) for hydrogenation of concentrated CO_2 to produce methanol. Methanol production is highly energy intensive as the H_2 is synthesized by electrolysis of H_2O [80].

Reverse water gas shift reaction: Syngas is an important building block chemical in the petrochemical industry and starting material for various chemical products, including methanol, NH_3, urea, fuels, etc. Reverse water gas shift reaction can be used to produce syngas from CO_2 (Scheme 1–2). The reaction is endothermic and favorable at high temperatures. The methanation and CO hydrogenation to CH_4 are the key side reactions under the operating conditions, reducing CO selectivity. However, the equilibrium methane selectivity becomes negligible above 700 °C under atmospheric pressure [116]. The role of catalysts is thus extremely important in operating the reaction at moderate temperatures with high CO selectivity and CO_2 conversion. Several investigations employed a diverse range of catalysts for this reaction, such as noble metals (Ru, Pt, etc.), transition metals (Ni, Cu, Fe, etc.), and bimetals coupled with traditional support or oxygen vacant metal oxides (CeO_2).

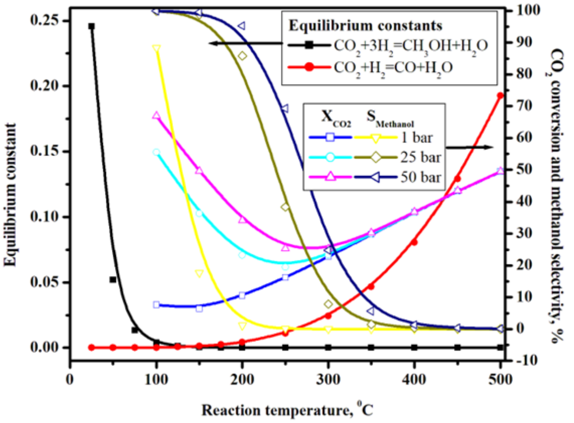

Figure 8: Effect of temperature on equilibrium constants, CO_2 conversion, and methanol selectivity. Conditions: CO_2:H_2=1:2 and CO_2, CO, H_2, CH_3OH, and water as reaction products. Data generated using Aspen Plus.

Different materials and chemicals, such as plastics, synthetic rubber, and solvents can be produced using CO_2. Olefins can also be produced using methanol for use in health and hygiene, food production and processing and for the production of polymers to make aromatics and plastics (such as xylene, toluene, benzene). Currently, methanol-derived olefins are being produced in China whereas methanol-derived aromatics are still in the research and development stage. Novomer Inc. in the US manufactures chemicals and polymers using innovative and low-energy methods. In this method, the zinc-based catalyst is used to produce polycarbonates by reacting CO_2 with epoxide at low operating conditions. 50 wt % of CO_2 is estimated to be present in synthesized polymers [72]. Moreover, CO_2 can be used in the cement industry for concrete curing and cement production. Utilization of CO_2 for concrete curing is an alternative to the conventional high energy-intensive autoclave and steam curing process. Concrete production involves concrete curing which makes its potential commercialization easier as it is still in the small-scale demonstration. In one study, it was estimated that 899 kt/year concrete products can be produced by consuming 96 kt CO_2/year through concrete curing technology. Concrete curing technology operates in a highly competitive commodity market hence the capital investment is very low, which is one of the barriers to concrete curing technology [72].

Electrochemical reduction of CO_2 involves its reduction at the cathode of an electrochemical cell to produce products, such as carbon monoxide, formic acid, methane, ethylene, and ethanol. Copper-based catalysts show good potential for converting CO_2 into multicarbon products, which is important for the chemical and fuel industries, such as Equation (1) [117].

$$CO_2 + 2H + 2e^{-} \rightarrow CO + H_2O \qquad (1)$$

The photocatalytic conversion is a promising way of converting solar energy into fuel and chemicals using CO_2 reduction. Heterogeneous photocatalysts, mainly titanium dioxide (TiO_2), under sun-irradiation, are excited to produce electron-hole pairs that lead to the reduction of CO_2. The latter may yield methanol, methane, and other hydrocarbons. Similarly, photoelectrochemical cells use sunlight to generate electricity that drives the electrochemical reduction of CO_2 [118].

Recently, industries have initiated the use of CO_2 derivatives rather than plastics to form polymers. A typical example is the fabrication of polyoxymethylene (POM) instead of polyethylene and polypropylene. Nevertheless, the commercial-scale applications of such polymers are limited due to their low catalytic activity and weak thermal and mechanical properties. The copolymerization of CO_2 with epoxides results in the formation of polycarbonates that have applications in electronics, automobiles, and construction materials [119]. The reaction of CO_2 with diols produces polyols that can be used to make polyurethanes (PUs). CO_2-based polymers have shown significant promise in the preparation of PU foams, offering thermal stability comparable to conventional PU materials. Thus, CO_2 derivatives are effective in yielding sustainable polymers thereby providing a prominent method for CO_2 utilization.

Urea is one of the common fertilizers that is manufactured from CO_2 and ammonia. Traditionally, urea was manufactured by reacting CO_2 with ammonia, which is produced by steam reforming of natural gas, followed by the reaction of hydrogen with nitrogen. For a sustainable economy, the integration of traditional fossil with renewable energy sources has been investigated [120]. For instance, greenhouse gas emissions could be reduced by 65% using hydrogen-rich syngas produced from biomass gasification as an industrial process to produce hydrogen rather than using natural gas reforming [74]. Another innovative method is the utilization of power plant flue gas to capture CO_2 for the production of urea, with increased yields and lower environmental hazards [121]. The urea produced by this method is known as "Blue urea" and depicts an important route to convert captured CO_2 into a value-added chemical compound [122], [123]. However, such urea-integrated systems are only conceptual to date and have to be considered for scale-up into commercial applications**.** Approximately, 0.735 tons of CO_2 is consumed to produce 1 ton of urea. The urea costs somewhere between 205 USD/ton to 285 USD/ton. When urea is in contact with H_2O after applying it to the land, it produces NH_3, which is produced by the plants whereas the resultant CO_2 gets released into the atmosphere [72]. Optimization of urea yield is considered a mature technology that is implemented widely on an industrial scale. The global market of urea is forecasted to reach 260 Mt/year against the CO_2 utilization of 132 Mt/year by the year 2025. Uncertainty and volatility in demand and price of NH_3 and urea are the main hurdles in deploying urea yield-boosting technology, hence long-term planning becomes difficult for policymakers owing to the high capital cost for carbon capture infrastructure [78].

CO_2 mineralization, or accelerated carbonation, is an exothermic process and, therefore, a thermodynamically spontaneous way of converting industrial CO_2 emissions into stable natural carbonate minerals spontaneously. This technique may employ different feedstocks, including natural silicate ores and alkaline solid wastes, such as iron and steel slags, incinerator ashes, and cement and concrete waste [124]–[126]. The processes of mineralization may be direct, indirect, or multiphase to obtain high-purity chemicals. These processes comprise carbonation curing for improving the strength and durability of cement-based materials or electrochemical mineralization to produce hydrogen or electricity. CO_2 is reacted with metal oxides to form stable carbonates, such as magnesium carbonate ($MgCO_3$) or calcium carbonate ($CaCO_3$) (Equation (2)). This process is mimicked by natural weathering and provides a permanent reservoir for CO_2. The resulting carbonates can also be tapped for another added-value stream in construction materials [127].

$$MgO + CO_2 \rightarrow MgCO_3 \qquad (2)$$

Carbonation also has significant advantages, such as utilizing waste materials, reducing environmental impacts, and providing valuable construction materials with applications in the circular economy. These technologies, applied in conjunction with the use of steel slag and various other industrial wastes, have been demonstrated at a pilot scale. Life cycle assessments have shown potential for carrying a negative global warming impact in large scale applications, which supports their general environmental viability. However, high energy consumption, the necessity of process optimization, and difficulty in scaling up to industrial levels have limited the expansion of carbonation technology. Notably, the scale-up of such technologies to the industrial level remains still out of reach. Future research and policy support are crucial to overcoming these bottlenecks and implementing CO_2 conversion technologies on a large scale [128].

5 Challenges in Industrial Applications

Researching innovative green technologies in agriculture, chemical, and power generation sectors is significant to eliminate future greenhouse gas emissions. A tool called Technology Readiness Level (TRL) was developed by the National Aeronautics and Space Administration (NASA) in 1990, which analyzes the maturity of technology. TRL also demonstrates the feasibility of large-scale existing technology. In CO_2 capture, the level of technology is estimated by TRL by examining its cost, environmental impacts, and time. Technologies have different stages research (TRL 1 and TRL 2), development (TRL 3 to TRL 5), and demonstration (TRL 6 to TRL 9) in carbon capture applications. Oxyfuel combustion, direct air capture, membrane polymeric, and post-combustion have reached the demonstration scale (TRL 7) whereas the commercial scale (TRL9) has been achieved by pre-combustion. Solvent-post-combustion and chemical looping combustion have achieved pilot scale (TRL 6) [73]. It has also been reported that membrane-dense inorganic, gas turbine-oxyfuel combustion and ionic liquid-post-combustion are still in laboratory-scale plants (TRL5). Commercial scale (TRL9) has been achieved by carbon storage technology in CO_2-enhanced oil recovery, saline production, and amine-used power plants post-combustion [74]. Proof of concept in the laboratory (TRL3) and minimum level of formulation (TRL2) have been achieved by mineral storage and ocean storage whereas depleted oil and gas fields and CO_2-enhanced gas recovery are still at the demonstration level (TRL7). Hence, implementing decarbonization techniques in the industrial sector is expected to show significant progress. Specific emission, carbon capture ratio, carbon capture index, and relative emissivity are some indicators available to determine the emission and capture level of CO_2. Nevertheless, the constraints in examining the TRL level are the lack of awareness about the technology and the effort required to move from one level of TRL to the next [30].

The novel solvent is highly appreciated in the post-combustion route, which includes efficient recycling capacity, low corrosiveness and degradation, low production of by-products, and lower production cost and environmental impact. Nevertheless, condensation of water is one of the challenges in membrane separation. Hence, it is significant to consider the selectivity and permeability of gases, such as NO_x, SO_x, and CO_x to ensure effective emanating and penetrating through membranes. On the other hand, pre-combustion is a more promising technique but it requires enhancement in the overall efficiency of the process. Solvent consumption to a lesser extent can be avoided by maintaining a low temperature for the process of solvent regeneration [73]. Better efficiency is shown by pre-combustion as compared to post-combustion but pre-combustion has higher operational cost. The high operational cost factor can be avoided by finding a solvent that moderates all the disadvantages. New technologies such as ion transport with chemical looping must be considered for separation of air mixture in the oxy-fuel technique. Currently, post-combustion is widely used for carbon capture and storage. The captured carbon is either used as raw material to produce other chemicals or is used in refrigerant welding, and fire extinguishers [129].

Many CO_2 capture projects are being constructed with a focus on CO_2 storage to achieve the zero-emissions global goal by 2050. According to the 2021 census, the second highest carbon capture projects are found in Europe followed by the Asian region. Two projects funded by the Australian government are being constructed in Indonesia and Malaysia. The amount of captured carbon has increased from 10.3 metric tons in 2020 to 15 metric tons in 2021 [130]. Despite having the lowest number of carbon capture projects, the Middle East has managed to capture 10% of global carbon capture, which accounts for approximately 5 metric tons of CO_2 per year. Moreover, carbon capture facilities are gaining popularity in industries such as the fertilizer industry, steel industry, and H_2 power production from natural gas. The world's largest carbon capture and storage project is located in the United States, it is helping in the transportation and storage of CO_2 for 31 bioethanol plants, with a capacity of 11 metric tons. Steam reforming of natural gas takes place to produce blue hydrogen. The Aramis project captures a significant amount of CO_2 in the Netherlands [74].

Many projects such as Hatfield in 2014 with a capacity of 5 metric tons per year of CO_2 injection, Trailblazer in the USA with a CO_2 injection capacity of 4.3 metric tons per year, and Greenger in China with a capacity of 0.7 metric tons per year, have been constructed to infuse CO_2. A project was constructed in Canada in 2015 with 3.6 metric tons per year of CO_2 to store the captured carbon permanently. Nevertheless, the stored CO_2 can be utilized as a raw material in different manufacturing processes, apart from that it can also be used to improve oil production as injection of CO_2 in oilfields enables the oil to flow smoothly, which enhances the oil recovery [131]. Carbon capture, storage, and utilization (CCSU) technologies play a significant role in reducing greenhouse gas emissions and achieving net-zero CO_2 emissions. Many CCSU projects were proposed between 2010 and 2021, these projects can be categorized as advanced development, under construction, and operating development. CO_2 capture potential can be increased significantly from 40 Mt CO_2/year to 130–150 MtCO_2/year upon launching all the projects [132]. China, Korea, Australia, Europe, and the United States have integrated facilities for carbon capture, utilization, and storage. In 2021, 92, 66, 5, and 20 projects were proposed for early development, advanced development, under construction, and operating construction, respectively. In the mid-1980s, a natural gas processing unit in the USA started CO_2 capture for local oil producers. During the Sleipner CO_2 storage, deep saline production was targeted in Norway in 1996 whereas in 2010 around 8.4 Mt/year of CO_2 was captured from Century plant through enhanced oil recovery [133]. Saudia Arabia (2015), China (2018) Qatar (2019), and Canada (2020) managed to achieve maximum carbon capture capacity of 0.8, 1.4, 2.2, and 1.5 Mt/year, respectively. It is significant to consider that large-scale carbon capture, utilization, and storage facilities mainly rely on processes such as natural gas processing, fertilizer production, hydrogen production, ethanol production, steel production, and coal-power generation as primary sources, and use CO_2 to improve oil recovery [131].

The cost of different carbon capture technologies has been estimated by the Department of Energy, National Energy Technology Laboratory, USA. Post-combustion in sub and supercritical pulverized technology in coal plants is estimated to cost around 45 USD/ton of CO_2 to capture whereas the post-combustion combined cycle plants in natural gas processing is estimated to cost 79.6 USD/ton of CO_2 to capture [134]. The carbon capture cost is estimated to be 70 USD/ton of CO_2 and 105 USD/ton of CO_2 for the Petra Nova and Boundary Dam plants, respectively. Integration of gasification and combined cycle plant with pre-combustion technology has a design cost of 119.4 USD/ton CO_2 and capture cost of 136.0 USD/ton CO_2, hence it is not in operation due to high costs. While air separation plants combined with oxy-fuel combustion cost about 36–67 USD/ton CO_2 to capture [85]. A carbon capture facility with a capacity of 10 metric tons of CO_2 costs around 10 USD/ton of CO_2 for compression, 0.3–3.0 USD/ton of CO_2 for pipeline transportation, and 0.1–5.9 USD/ton of CO_2 for injection. The captured CO_2 can function as fertilizer in the production of urea, with a breakeven manufacturing cost of 100 USD/ton of CO_2, whereas the breakeven cost to produce fuel using captured CO_2 is 670 USD/ton of CO_2. CO_2 captured from concrete and building materials can be utilized in the production of concrete materials with a production cost of approximately 50 USD/ton of CO_2 [135]. As per cost estimation by the National Academies of Sciences, Engineering, and Medicine (NASEM), captured CO_2 using post-combustion costs 105 USD/ton of CO_2 for the production of electricity in a biomass power plant. Consequently, CO_2 capturing cost using post-combustion from pulverized coal plants is lower as compared to pre-combustion technology integrated gasification combined cycle plants. Furthermore, the utilization cost of captured CO_2 has increased by 2% for natural gas processing, 4–5 % for bioethanol, 31–41 %, and 68% for cement [79].

6 Conclusions

The capture of CO_2 does not only bring environmental benefits but also possesses social and economic benefits. Reducing the emission of GHG is even more focused through different pollution control mechanisms due to the impact it is causing on climate change. R&D sectors aim to develop the mechanisms that are being designed by the policymaker not only to mitigate GHG emissions but also to gain social and economic focus. UN member countries make agreements at world conventions to work on mitigating carbon and look for advanced and optimized methods for this purpose. The conventions also allow different countries to have transactions of carbon dioxide based on energy requirements and supply and demand of CO_2. This way CO_2 makes revenues for countries who have reached their CO_2 reduction quota. Different technologies have been discussed to capture and separate CO_2, which brings us to the conclusion that due to the utilization of less energy CO_2 can efficiently be captured from industries by implementing the absorption separation process. Then it can be sold to manufacturers of various value-added chemicals, such as methanol as it has market demand. There is still a huge research gap in CO_2 capture as far as energy intensity is concerned as this is one of the factors that is stopping industries from implementing this technology. Hence, it is significant to look for an optimized way with less energy requirement per ton of captured carbon.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] T. Ahmad and D. Zhang, "A critical review of comparative global historical energy consumption and future demand: The story told so far," *Energy Reports*, vol. 6, pp. 1973–1991, 2020.

[2] A. Kausar and I. Ahmad, "Footmarks of graphene nanocomposites towards carbon capturing—Next membrane materials," *Next Materials*, vol. 5, 2024, Art. no. 100276.

[3] A. Kona, P. Bertoldi, F. Monforti-Ferrario, S. Rivas, and J. F. Dallemand, "Covenant of mayors signatories leading the way towards 1.5 degree global warming pathway," *Sustainable Cities and Society*, vol. 41, pp. 568–575, 2018.

[4] Z. Wang, Z. Huang, Y. Huang, C. Wittram, Y. Zhuang, S. Wang, and B.Nie, "Synergy of carbon capture, waste heat recovery and hydrogen production for industrial decarbonisation," *Energy Conversion and Management*, vol. 312, 2024, Art. no. 118568.

[5] D. Bose, R. Bhattacharya, T. Kaur, R. Pandya, A. Sarkar, A. Ray, S.Mondal, A.Mondal, P.Ghosh, and R. I. Chemudupati, "Innovative approaches for carbon capture and storage as crucial measures for emission reduction within industrial sectors," *Carbon Capture Science & Technology*, vol. 12, 2024, Art. no. 100238.

[6] Energy Information Administration (US), *Annual Energy Outlook 2007: With Projections To 2030*. Washington, DC: Government Printing Office, 2007.

[7] M. Sriariyanun and B. Dharmalingam, "From waste to wealth: Challenges in producing value-added biochemicals from lignocellulose biorefinery," *Journal of Applied Science and Emerging Technology*, vol. 22, no. 3, 2023, Art. no. e900001.

[8] Y. Wang, Y. Liu, and B. Gu, "COP26: Progress, challenges, and outlook," *Springer*, vol. 39, no. 8, pp. 1209–1216, 2022.

[9] H, Dang, B. Guan, J. Chen, Z. Ma, Y. Chen, J. Zhang, Z. Guo, L. Chen, J. Hu, C. Yi, S. Yao, and Z. Huang, "Research on carbon dioxide capture materials used for carbon dioxide capture, utilization, and storage technology: A review," *Environmental Science and Pollution*

Research, vol. 31, pp. 33259–33302, 2024.

[10] M. Kheirinik, S. Ahmed, and N. Rahmanian, “Comparative techno-economic analysis of carbon capture processes: Pre-combustion, post-combustion, and oxy-fuel combustion operations,” *Sustainability*, vol. 13, no. 24, 2021, Art. no. 13567.

[11] Z. Sun, Q. Wu, C. Zhao, H. Li, and A. Zhang, “A review of NO_x control by MILD-oxy combustion,” *Journal of the Energy Institute*, vol. 113, 2023, Art. no. 101502.

[12] D. Y. C. Leung, G. Caramanna, and M. M. Maroto-Valer, “An overview of current status of carbon dioxide capture and storage technologies,” *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 426–443, 2014.

[13] P. Wienchol, A. Szlęk, and M. Ditaranto, “Waste-to-energy technology integrated with carbon capture–Challenges and opportunities,” *Energy*, vol. 198, 2020, Art. no. 117352.

[14] S. Areeya, E. J. Panakkal, M. Sriariyanun, T. Kangsadan, A. Tawai, S. Amornraksa, U. W. Hartley, and P. Yasurin, “A review on chemical pretreatment of lignocellulosic biomass for the production of bioproducts: Mechanisms, challenges and applications,” *Applied Science and Engineering Progress*, vol. 16, no. 3, 2023, Art. no. 6767.

[15] S. Areeya, E. J. Panakkal, P. Kunmanee, A. Tawai, S. Amornraksa, M. Sriariyanun, Kaoloun, N. Hartini, Y. S. Cheng, M. Kchaou, S. Dasari, and M. P. Gundupalli, “A review of sugarcane biorefinery: From waste to value-added products,” *Applied Science and Engineering Progress*, vol. 17, no. 3, 2024, Art. no. 7402.

[16] L. Rosa, D. L. Sanchez, and M. Mazzotti, “Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe,” *Energy & Environmental Science*, vol. 14, no. 5, pp. 3086–3097, 2021.

[17] R. López, C. Fernández, O. Martínez, and M. Sánchez, “Techno-economic analysis of a 15 MW corn-rape oxy-combustion power plant,” *Fuel Processing Technology*, vol. 142, pp. 296–304, 2016.

[18] R. Falkenstein-Smith, P. Zeng, and J. Ahn, “Investigation of oxygen transport membrane reactors for oxy-fuel combustion and carbon capture purposes,” *Proceedings of the Combustion Institute*, vol. 36, no. 3, pp. 3969–3976, 2017.

[19] F. De Meyer and S. Jouenne, “Industrial carbon capture by absorption: Recent advances and path forward,” *Current Opinion in Chemical Engineering*, vol. 38, 2022, Art. no. 100868.

[20] K. H. Smith, H. E. Ashkanani, B. I. Morsi, and N. S. Siefert, “Physical solvents and techno-economic analysis for pre-combustion CO_2 capture: A review,” *International Journal of Greenhouse Gas Control*, vol. 118, 2022, Art. no. 103694.

[21] H. E. Ashkanani, R. Wang, W. Shi, N. S. Siefert, R. L. Thompson, K. Smith, J.A. Steckel, I.K. Gamwo, D. Hopkinson, K. Resnik, and B.I. Morsi, “Levelized cost of CO_2 captured using five physical solvents in pre-combustion applications,” *International Journal of Greenhouse Gas Control*, vol. 101, 2020, Art. no. 103135.

[22] R. Stanger, T. Wall, R. Spörl, M. Paneru, S. Grathwohl, M. Weidmann, G. Scheffknecht, D. McDonald, K. Myöhänen, J. Ritvanen, S. Rahiala, T. Hyppänen, J. Mletzko, A. Kather, and S. Santos, “Oxyfuel combustion for CO_2 capture in power plants,” *International journal of greenhouse gas control*, vol. 40, pp. 55–125, 2015.

[23] R. Sanz, G. Calleja, A. Arencibia, and E. S. Sanz-Pérez, “Amino functionalized mesostructured SBA-15 silica for CO_2 capture: Exploring the relation between the adsorption capacity and the distribution of amino groups by TEM,” *Microporous and Mesoporous Materials*, vol. 158, pp. 309–317, 2012.

[24] A. A. Okesola, A. A. Oyedeji, A. F. Abdulhamid, J. Olowo, B. E. Ayodele, and T. W. Alabi, “Direct air capture: A review of carbon dioxide capture from the air,” *IOP Conference Series: Materials Science and Engineering*, vol. 413, 2018, Art. no. 012077.

[25] A. Nandy, C. Loha, S. Gu, P. Sarkar, M. K. Karmakar, and P. K. Chatterjee, “Present status and overview of chemical looping combustion technology,” *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 597–619, 2016.

[26] A. Lyngfelt, “Chemical looping combustion: Status and development challenges,” *Energy & Fuels*, vol. 34, no. 8, pp. 9077–9093, 2020.

[27] L. I. Eide and D. W. Bailey, “Precombustion decarbonisation processes,” *Oil & Gas Science and Technology*, vol. 60, no. 3, pp. 475–484, 2005.

[28] D. Jansen, M. Gazzani, G. Manzolini, E. van Dijk, and M. Carbo, “Pre-combustion CO_2 capture,” *International Journal of Greenhouse Gas Control*, vol. 40, no. 1, pp. 67–187, 2015.

[29] M. Gazzani, E. Macchi, and G. Manzolini, “CO_2 capture in natural gas combined cycle with SEWGS. Part A: Thermodynamic performances,” *International Journal of Greenhouse Gas Control*, vol. 12, pp. 493–501, 2013.

[30] M. Kanniche, R. Gros-Bonnivard, P. Jaud, J. Valle-Marcos, J. M. Amann, and C. Bouallou, “Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture,” *Applied Thermal Engineering*, vol. 30, no. 1, pp. 53–62, 2010.

[31] M. Younas, M. Sohail, L. K. Leong, M. J. Bashir, and S. Sumathi, “Feasibility of CO_2 adsorption by solid adsorbents: A review on low-temperature systems,” *International Journal of Environmental Science and Technology*, vol. 13, pp, 1839–1860, 2016.

[32] T. C. Merkel, H. Lin, X. Wei, and R. Baker, “Power plant post-combustion carbon dioxide capture: An opportunity for membranes,” *Journal of Membrane Science*, vol. 359, no. 1–2, pp. 126–139, 2010.

[33] E. De Visser, C. Hendriks, M. Barrio, M. J. Mølnvik, G. de Koeijer, S. Liljemark, and Y. Le Gallo, “Dynamis CO_2 quality recommendations,” *International Journal of Greenhouse Gas Control*, vol. 2, no. 4, pp. 478–484, 2008.

[34] E. S. Rubin, J. E. Davison, and H. J. Herzog, “The cost of CO_2 capture and storage,” *International Journal of Greenhouse Gas Control*, vol. 40, pp. 378–400, 2015.

[35] P. Moldenhauer, C. Linderholm, M. Rydén, and A. Lyngfelt, “Avoiding CO_2 capture effort and cost for negative CO_2 emissions using industrial waste in chemical-looping combustion/gasification of biomass,” *Mitigation and Adaptation Strategies for Global Change*, vol. 25, no. 1, pp. 1–24, 2020.

[36] S. Abuelgasim, W. Wang, and A. Abdalazeez, “A brief review for chemical looping combustion as a promising CO_2 capture technology: Fundamentals and progress,” *Science of the Total Environment*, vol. 764, 2021, Art. no. 142892.

[37] L.F. de Diego, A. Serrano, F. García-Labiano, E. García-Díez, A. Abad, P. Gayán, J. Andanez, “Bioethanol combustion with CO_2 capture in a 1 kWth Chemical Looping Combustion prototype: Suitability of the oxygen carrier,” *Chemical Engineering Journal*, vol. 283, pp. 1405–1413, 2016.

[38] E. S. Sanz-Pérez, C. R. Murdock, S. A. Didas, and C. W. Jones, “Direct capture of CO_2 from ambient air,” *Chemical Reviews*, vol. 116, no. 19, pp. 11840–11876, 2016.

[39] M. Fasihi, O. Efimova, and C. Breyer, “Techno-economic assessment of CO_2 direct air capture plants,” *Journal of Cleaner Production*, vol. 224, pp. 957–980, 2019.

[40] P. C. Psarras, S. Comello, P. Bains, P. Charoensawadpong, S. Reichelstein, and J. Wilcox, “Carbon capture and utilization in the industrial sector,” *Environmental Science & Technology*, vol. 51, no. 19, pp. 11440–11449, 2017.

[41] T. Wilberforce, A. Olabi, E. T. Sayed, K. Elsaid, and M. A. Abdelkareem, “Progress in carbon capture technologies,” *Science of the Total Environment*, vol. 761, 2021, Art. no. 143203.

[42] P. Gabrielli, M. Gazzani, and M. Mazzotti. “The role of carbon capture and utilization, carbon capture and storage, and biomass to enable a net-zero-CO_2 emissions chemical industry,” *Industrial & Engineering Chemistry Research*, vol. 59, no. 15, pp. 7033–7045, 2020.

[43] T. Hills, D. Leeson, N. Florin, and P. Fennell, “Carbon capture in the cement industry: Technologies, progress, and retrofitting,” *Environmental Science & Technology*, vol. 50, no. 1, pp. 368–377, pp. 2016.

[44] L. Rosa and M. Mazzotti. “Potential for hydrogen production from sustainable biomass with carbon capture and storage,” *Renewable and Sustainable Energy Reviews*, vol. 157, 2022, Art. no. 112123.

[45] M. Bui, C. S. Adjiman, A. Bardow, E. J. Anthony, A. Boston, S. Brown, P. S. Fennell, S. Fuss, A. Galindo, L. A. Hackett, J. P. Hallett, H. J. Herzogj, G. Jackson, J. Kemper, S. Krevor, G. C. Maitland, M. Matuszewski, I. S. Metcalfe, C. Petit, G. Puxty, J. Reimer, D. M. Reiner, E. S. Rubin, S. A. Scott, N. Shah, B. Smit, J. P. M. Truslerl, P. Webley, J. Wilcox, and N. M. Dowell, “Carbon capture and storage (CCS): The way forward,” *Energy & Environmental Science*, vol. 11, no. 5, pp. 1062–1176, 2018.

[46] M. A. Nemitallah, M. A. Habib, H.M. Badr, S. A. Said, A. Jamal, R. Ben-Mansour, E. M. Mokheimer, and K. Mezghani, "Oxy-fuel combustion technology: Current status, applications, and trends," *International Journal of Energy Research*, vol. 41, no. 12, pp. 1670–1708, 2017.

[47] M. A. Sabri, S. Al Jitan, D. Bahamon, L. F. Vega, and G. Palmisano, "Current and future perspectives on catalytic-based integrated carbon capture and utilization," *Science of the Total Environment*, vol. 790, 2021, Art. no. 148081.

[48] M.G. Plaza, S. Martínez, and F. Rubiera, "CO_2 capture, use, and storage in the cement industry: State of the art and expectations," *Energies*, vol. 13, no. 21, 2020, Art. no. 5692.

[49] F. Kazemifar, "A review of technologies for carbon capture, sequestration, and utilization: Cost, capacity, and technology readiness," *Greenhouse Gases: Science and Technology*, vol. 12, no. 1, pp. 200–230, 2022.

[50] S. Vaz Jr, A. P. R. de Souza, and B. E. L. Baeta, "Technologies for carbon dioxide capture: A review applied to energy sectors," *Cleaner Engineering and Technology*, vol. 8, 2022, Art. no. 100456.

[51] W. Y. Hong, "A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO_2 emissions future," *Carbon Capture Science & Technology*, vol. 3, 2022, Art. no. 100044.

[52] H. Singh, C. Li, P. Cheng, X. Wang, and Q. Liu, "A critical review of technologies, costs, and projects for production of carbon-neutral liquid e-fuels from hydrogen and captured CO_2," *Energy Advances*, vol. 1, no. 9, pp. 580–605, 2022.

[53] C. Font-Palma, D. Cann, and C. Udemu, "Review of cryogenic carbon capture innovations and their potential applications," *C*, vol. 7, no. 3, 2021, Art. no. 58.

[54] J. A. Garcia, M. Villen-Guzman, J. M. Rodriguez-Maroto, and J. M. Paz-Garcia, "Technical analysis of CO_2 capture pathways and technologies," *Journal of Environmental Chemical Engineering*, vol. 10, no. 5, 2022, Art. no. 108470.

[55] B. Dziejarski, R. Krzyżyńska, and K. Andersson, "Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment," *Fuel*, vol. 342, 2023, Art. no. 127776.

[56] A. H. Ruhaimi, C. N. C. Hitam, M. A. A. Aziz, N. H. A. Hamid, H. D. Setiabudi, and L. P. Teh, "The role of surface and structural functionalisation on graphene adsorbent nanomaterial for CO_2 adsorption application: Recent progress and future prospects," *Renewable and Sustainable Energy Reviews*, vol. 167, 2022, Art. no. 112840.

[57] S. Li, Yuan, S. Deng, L. Zhao, and K. B. Lee, "A review on biomass-derived CO_2 adsorption capture: Adsorbent, adsorber, adsorption, and advice," *Renewable and Sustainable Energy Reviews*, vol. 152, 2021, Art. no. 111708.

[58] A. Zaker, S. ben Hammouda, J. Sun, X. Wang, X. Li, and Z. Chen, "Carbon-based materials for CO_2 capture: Their production, modification and performance," *Journal of Environmental Chemical Engineering*, vol. 11, no. 3, 2023, Art. no. 109741.

[59] A. Allangawi, E.F. Alzaimoor, H.H. Shanaah, H.A. Mohammed, H. Saqer, A.A. El-Fattah, and A.H Kamel, "Carbon capture materials in post-combustion: Adsorption and absorption-based processes," *C*, vol. 9, no. 1, 2023, Art. no. 17.

[60] C. Dhoke, A. Zaabout, S. Cloete, and S. Amini, "Review on reactor configurations for adsorption-based CO_2 capture," *Industrial & Engineering Chemistry Research*, vol. 60, no. 10, pp. 3779–3798, 2021.

[61] F. Raganati, F. Miccio, and P. Ammendola, "Adsorption of carbon dioxide for post-combustion capture: A review," *Energy & Fuels*, vol. 35, no. 16, pp. 12845–12868, 2021.

[62] T. Okumura, K. Yoshizawa, S. Nishibe, H. Iwasaki, M. Kazari, and T. Hori, "Parametric testing of a pilot-scale design for a moving-bed CO_2 capture system using low-temperature steam," *Energy Procedia*, vol. 114, pp. 2322–2329, 2017.

[63] J. W. Lee, I. T. Pineda, J. H. Lee, and Y. T. Kang, "Combined CO_2 absorption/regeneration performance enhancement by using nanoabsorbents," *Applied Energy*, vol. 178, pp. 164–176, 2016.

[64] W. L. Theo, J. S. Lim, H. Hashim, A. A. Mustaffa, and W. S. Ho, "Review of pre-combustion capture and ionic liquid in carbon capture and storage," *Applied Energy*, vol. 183, pp. 1633–1663, 2016.

[65] S. Ma, C. Gongda, Z. Sijie, W. Jiaqi, G. Ran, M. Lan, and C. Jin, “Experimental study of mixed additive of Ni (II) and piperazine on ammonia escape in CO_2 capture using ammonia solution,” *Applied Energy*, vol. 169, pp. 597–606, 2016.

[66] A. A. Khan, G. N. Halder, and A. K. Saha, “Experimental investigation of sorption characteristics of capturing carbon dioxide into piperazine activated aqueous 2-amino-2-methyl-1-propanol solution in a packed column,” *International Journal of Greenhouse Gas Control*, vol. 44, pp. 217–226, 2016.

[67] F. Chu, C. Jon, L. Yang, X. Du, and Y. Yang, “CO_2 absorption characteristics in ammonia solution inside the structured packed column,” *Industrial & Engineering Chemistry Research*, vol. 55, no.12, pp. 3696–3709, 2016.

[68] Y.N. Wang, J. Pfotenhauer, X. Zhi, L. Qiu, and J. Li, “Transient model of carbon dioxide desublimation from nitrogen-carbon dioxide gas mixture,” *International Journal of Heat and Mass Transfer*, vol. 127, pp. 339–347, 2018.

[69] IEA (International Energy Agency), *CO_2 Emissions in 2023*. Paris: International Energy Agency, 2024.

[70] Z. Liu, Z. Deng, S. J. Davis, and P. Ciais, “Global carbon emissions in 2023,” *Nature Reviews Earth & Environment*, vol. 5, no. 4, pp. 253–254, 2024.

[71] British Petroleum. “BP Energy Outlook 2023.” bp.com. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023 (accessed Oct. 3, 2023).

[72] CarbonBrief. “Analysis: Global CO_2 emissions could peak as soon as 2023.” carbonbrief.org. https://www.carbonbrief.org/analysis-global-co2-emissions-could-peak-as-soon-as-2023-iea-data-reveals/ (accessed Oct. 26, 2023).

[73] E. De Cian, F. Sferra, and M. Tavoni, “The influence of economic growth, population, and fossil fuel scarcity on energy investments,” *Clim Change*, vol. 136, pp. 39–55, 2016.

[74] H. Ritchie, P. Rosado, and M. Roser. “CO_2 and other greenhouse gas emissions.” ourworldindata.org. https://ourworldindata.org/co2-and-greenhouse-gas-emissions (accessed Oct. 10, 2023).

[75] M. Shen, L. Tong, S. Yin, C. Liu, L. Wang, W. Feng, and Y. Ding, “Cryogenic technology progress for CO_2 capture under carbon neutrality goals: A review,” *Separation and Purification Technology*, vol. 299, 2022, Art. no. 121734.

[76] L. Baxter, A. Baxter, and S. Burt, “Cryogenic CO_2 capture as a cost-effective CO_2 capture process,” in *International Pittsburgh Coal Conference*, pp. 1–14, 2009.

[77] I. Sreedhar, R. Vaidhiswaran, B. M. Kamani, and A. Venugopal, “Process and engineering trends in membrane-based carbon capture,” *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 659–684, 2017.

[78] A. Corti, D. Fiaschi, and L. Lombardi, “Carbon dioxide removal in power generation using membrane technology,” *Energy*, vol. 29, no. 12–15, pp. 2025–2043, 2004.

[79] N. Prasetya, N. F. Himma, P. D. Sutrisna, I. G. Wenten, and B. P. Ladewig, “A review on emerging organic-containing microporous material membranes for carbon capture and separation,” *Chemical Engineering Journal*, vol. 391, 2020, Art. no. 123575.

[80] A. G. Olabi, A. H. Alami, M. Ayoub, H. Aljaghoub, S. Alasad, A. Inayat, M. A. Abdelkareem, K.-J. Chae, and E. T. Sayed, “Membrane-based carbon capture: Recent progress, challenges, and their role in achieving the sustainable development goals,” *Chemosphere*, vol. 320, 2023, Art. no. 137996.

[81] N. Ferrari, L. Mancuso, J. Davison, P. Chiesa, E. Martelli, and M. C. Romano, “Oxy-turbine for Power Plant with CO_2 capture,” *Energy Procedia*, vol. 114, pp. 471–480, 2017.

[82] N. Habib, Z. Shamair, N. Tara, A.-S. Nizami, F. H. Akhtar, N. M. Ahmad, M. A. Gilani, M. R. Bilad, and A. L. Khan, “Development of highly permeable and selective mixed matrix membranes based on Pebax® 1657 and NOTT-300 for CO_2 capture,” *Separation and Purification Technology*, vol. 234, 2020, Art. no. 116101.

[83] Z. Zhang, S.-Y. Pan, H. Li, J. Cai, A. G. Olabi, E. J. Anthony, and V. Manovic, “Recent advances in carbon dioxide utilization,” *Renewable and Sustainable Energy Reviews*, vol. 125, 2020, Art. no. 109799.

[84] M. Asif, L. Wang, R. Wang, H. Wang, and R. D. Hazlett, “Mechanisms in CO_2-enhanced coalbed methane recovery process,” *Advances*

in Geo-Energy Research, vol. 6, no. 6, pp. 531–534, 2022.

[85] C. H. Huang and C. S. Tan, “A review: CO_2 utilization,” *Aerosol and Air Quality Research*, vol. 14, no. 2, pp. 480–499, 2014.

[86] A. Wang, J. Lv, J. Wang, and K. Shi, “CO_2 enrichment in greenhouse production: Towards a sustainable approach,” *Frontiers in Plant Science*, vol. 13, 2022, Art. no. 1029901.

[87] P. Show and M. Sriariyanun, “Prospect of lipid biphasic system in microalgae research,” *Applied Science and Engineering Progress*, vol. 14, no. 3, pp. 295–296, 2021.

[88] P. R. Yaashikaa, P. S. Kumar, S. J. Varjani, and A. Saravanan, “A review on photochemical, biochemical and electrochemical transformation of CO_2 into value-added products,” *Journal of CO_2 Utilization*, vol. 33, pp. 131–147, 2019.

[89] N.V.D. Long, J. Lee, K.-K. Koo, P. Luis, and M. Lee, “Recent progress and novel applications in enzymatic conversion of carbon dioxide,” *Energies*, vol. 10, no. 4, 2017, Art. no. 473.

[90] H. Chang, X. Quan, N. Zhong, Z. Zhang, C. Lu, G. Li, Z. Cheng, and L. Yang, “High-efficiency nutrients reclamation from landfill leachate by microalgae Chlorella vulgaris in membrane photobioreactor for bio-lipid production,” *Bioresource Technology*, vol. 266, pp. 374–381, 2018.

[91] D.D.W. Tsai, R. Ramaraj and P. Honglay Chen, “Growth condition study of algae function in ecosystem for CO_2 bio-fixation,” *Journal of Photochemistry and Photobiology*, vol. 107, pp. 27–34, 2012.

[92] S. Miyachi, I. Iwasaki, and Y. Shiraiwa, “Historical perspective on microalgal and cyanobacterial acclimation to low-and extremely high-CO_2 conditions,” *Photosynthesis research*, vol. 77, pp. 139–153, 2003.

[93] B. Wang, J. Wang, W. Zhang, and D. R. Meldrum, “Application of synthetic biology in cyanobacteria and algae,” *Frontiers in microbiology*, vol. 3, 2012, Art. no. 344.

[94] S. E. Shin, J. M. Lim, H. G. Koh, E. K. Kim, N. K. Kang, S. Jeon, S. Kwon, W. S. Shin, B. Lee, K. Hwangbo, J. Kim, S. H. Ye, J. Y. Yun, H. Seo, H. M. Oh, K. J. Kim, J. S. Kim, W. J. Jeong, Y. K. Chang, and B. R. Jeong, “CRISPR/Cas9-induced knockout and knock-in mutations in *Chlamydomonas reinhardtii*,” *Scientific Reports*, vol. 6, no. 1, 2016, Art. no. 27810.

[95] Q. Wang, Y. Lu, Y. Xin, L. Wei, S. Huang, and J. Xu, “Genome editing of model oleaginous microalgae *Nannochloropsis* spp. by CRISPR/Cas9,” *The Plant Journal*, vol. 88, no. 6, pp. 1071–1081, 2016.

[96] M. Sriariyanun, M. P. Gundupalli, V. Phakeenuya, T. Phusantisampan, Y. S. Cheng, and P. Venkatachalam, “Biorefinery approaches for production of cellulosic ethanol fuel using recombinant engineered microorganisms,” *Journal of Applied Science and Engineering*, vol. 27, no. 2, pp. 1985–2005, 2024.

[97] D.U. Malusare, D.P. Ghumra and M.D. Yadav, “Bioconversion of CO_2 and potential of gas fermentation for mainstream applications: Critical advances and engineering challenges,” *The Canadian Journal of Chemical Engineering*, vol. 101, no. 12, pp. 6774–6791, 2023.

[98] K. Gupta, R. Kumar, K. K. Baruah, S. Hazarika, S. Karmakar, and N. Bordoloi, “Greenhouse gas emission from rice fields: a review from Indian context,” *Environmental Science and Pollution Research*, vol. 28, no. 24, pp. 30551–30572, 2021.

[99] A. S. S. Thomas, W. Pongprayoon, K. Cheenkachorn, and M. Sriariyanun, “Plant-microbe interactions-insights and views for applications in sustainable agriculture,” *Applied Science and Engineering Progress*, vol. 15, no. 1, 2022, Art. no. 5286, doi: 10.14416/j.asep.2021.07.008.

[100] A. Ahmad, M. Zoli, C. Latella, and J. Bacenetti, “Rice cultivation and processing: Highlights from a life cycle thinking perspective,” *Science of the Total Environment*, vol. 871, 2023, Art. no. 162079.

[101] S. Hussain, S. Peng, S. Fahad, A. Khaliq, J. Huang, K. Cui, and L. Nie, “Rice management interventions to mitigate greenhouse gas emissions: A review,” *Environmental Science and Pollution Research*, vol. 22, pp. 3342–3360, 2015.

[102] N. Zexer, S. Kumar, and R. Elbaum, “Silica deposition in plants: Scaffolding the mineralization,” *Annals of Botany*, vol. 131, no. 6, pp. 897–908, 2023.

[103] O. Katz, “Silicon and plant–animal interactions: Towards an evolutionary framework,” *Plants*, vol. 9, no. 4, 2020, Art. no. 430.

[104] A.L. Khan, “Silicon: A valuable soil element for improving plant growth and CO_2

sequestration," *Journal of Advanced Research*, 2024.

[105] R. Gao, L. Zhuo, Y. Duan, C. Yan, Z. Yue, Z. Zhao, P. Wu, "Effects of alternate wetting and drying irrigation on yield, water-saving, and emission reduction in rice fields: A global meta-analysis," *Agricultural and Forest Meteorology*, vol. 353, 2024, Art. no. 110075.

[106] R. Wassmann, H. U. Neue, R. S. Lantin, L. V. Buendia, and H. Rennenberg, "Characterization of methane emissions from rice fields in Asia. I. Comparison among field sites in five countries," *Nutrient Cycling in Agroecosystems*, vol. 58, pp. 1–12, 2000.

[107] Z. Song, K. McGrouther, H. Wang, "Occurrence, turnover and carbon sequestration potential of phytoliths in terrestrial ecosystems," Earth-Science Reviews, vol. 158, pp. 19–30, 2016

[108] T. Ball, K. Chandler-Ezell, R. Dickau, N. Duncan, T. C. Hart, J. Iriarte, C. Lentfer, A. Logan, H. Lu, M. Madella, and D. M. Pearsall, "Phytoliths as a tool for investigations of agricultural origins and dispersals around the world," *Journal of Archaeological Science*, vol. 68, pp. 32–45, 2016.

[109] L. N. Hudson, T. Newbold, S. Contu, S. L. Hill, I. Lysenko, A. De Palma, H. R. Phillips, T. I. Alhusseini, F. E. Bedford, D. J. Bennett, and H. Booth, "The database of the PREDICTS (projecting responses of ecological diversity in changing terrestrial systems) project," *Ecology and evolution*, vol. 7, no. 1, pp. 145-188, 2017.

[110] W. Qadar, R. Dar, and I. Rashid "Phytolith particulate matter and its potential human and environmental effects." *Environmental Pollution*, vol. 327, 2023, Art. no. 121541.

[111] E. Alper and O. Y. Orhan, "CO_2 utilization: Developments in conversion processes," *Petroleum*, vol. 3, no.1, pp. 109–126, 2017.

[112] M. Younas, L. L. Kong, M. J. Bashir, H. Nadeem, A. Shehzad, and S. Sethupathi, "Recent advancements, fundamental challenges, and opportunities in catalytic methanation of CO_2," *Energy & Fuels*, vol. 30, no. 11, pp. 8815–8831, 2016.

[113] Z. Lv, H. Du, S. Xu, T. Deng, J. Ruan, and C. Qin, "Techno-economic analysis on CO_2 mitigation by integrated carbon capture and methanation," *Applied Energy*, vol. 355, 2024, Art. no. 122242.

[114] X. Jiang, X. Nie, X. Guo, C. Song, and J. G. Chen, "Recent advances in carbon dioxide hydrogenation to methanol via heterogeneous catalysis," *Chemical reviews*, vol. 120, no. 15, pp. 7984–8034, 2020.

[115] J. Nyári, M. Magdeldin, M. Larmi, M. Järvinen, and A. Santasalo-Aarnio, "Techno-economic barriers of an industrial-scale methanol CCU-plant," *Journal of CO_2 Utilization*, vol. 39, 2020, Art. no. 101166.

[116] M. González-Castaño, B. Dorneanu and H. Arellano-García, "The reverse water gas shift reaction: a process systems engineering perspective," *Reaction Chemistry and Engineering*, vol. 6, no. 6, pp. 954–976, 2021.

[117] A. J. Garza, A. T. Bell, and M. Head-Gordon, "Mechanism of CO_2 reduction at copper surfaces: Pathways to C_2 products," *ACS catalysis*, vol. 8, no. 2, pp. 1490–1499, 2018.

[118] S. C. Roy, O. K. Varghese, M. Paulose, and C. A. Grimes, "Toward solar fuels: Photocatalytic conversion of carbon dioxide to hydrocarbons," *ACS nano*, vol. 4, no. 3, pp. 1259–1278, 2010.

[119] I. Omae, "Aspects of carbon dioxide utilization," *Catalysis today*, vol. 115, no. 1–4, pp. 33–52, 2006.

[120] A. Khan, A. Abbas and R. Dickson. "Towards a low-carbon future: Exploring green urea synthesis for sustainable agriculture," *Green Chemistry*, vol. 26, no. 3, pp. 1551–1565, 2024.

[121] E. Koohestanian, J. Sadeghi, D. Mohebbi-Kalhori, F. Shahraki, and A. Samimi, "A novel process for CO_2 capture from the flue gases to produce urea and ammonia," *Energy*, vol. 144, pp. 279–285, 2018.

[122] F. Barzagli, F. Mani and M. Peruzzini, "From greenhouse gas to feedstock: Formation of ammonium carbamate from CO_2 and NH_3 in organic solvents and its catalytic conversion into urea under mild conditions," *Green chemistry*, vol. 13, no. 5, pp. 1267–1274, 2011.

[123] J. G. Driver, R. E. Owen, T. Makanyire, J. A. Lake, J. McGregor, and P. Styring, "Blue urea: Fertilizer with reduced environmental impact," *Frontiers in Energy Research*, vol. 7, 2019, Art. no. 88.

[124] E. Georgakopoulos, R. M. Santos, Y. W. Chiang, and V. Manovic, "Influence of process parameters on carbonation rate and conversion of steelmaking slags–Introduction of the 'carbonation weathering rate'," *Greenhouse Gases: Science and Technology*, vol. 6, no. 4, pp. 470–491, 2016.

[125] S. J. Gerdemann, W. K. O'Connor, D. C. Dahlin, L. R. Penner, and H. Rush, “Ex situ aqueous mineral carbonation,” *Environmental Science & Technology*, vol. 41, no. 7, pp. 2587–2593, 2007.

[126] S. Y. Pan, P. C. Chiang, W. Pan, and H. Kim, “Advances in state-of-art valorization technologies for captured CO_2 toward sustainable carbon cycle,” *Critical Reviews in Environmental Science and Technology*, vol. 48, no. 5, pp. 471–534, 2018.

[127] M. Aresta, A. Dibenedetto, and E. Quaranta, *Reaction Mechanisms in Carbon Dioxide Conversion*. Heidelberg, Berlin: Springer, 2016.

[128] H. Naims, “Economics of carbon dioxide capture and utilization—a supply and demand perspective,” *Environmental Science and Pollution Research*, vol. 23, pp. 22226–22241, 2016.

[129] S. Chen, R. Yu, A. Soomro, and W. Xiang, “Thermodynamic assessment and optimization of a pressurized fluidized bed oxy-fuel combustion power plant with CO_2 capture,” *Energy*, vol. 175, pp. 445–455, 2019.

[130] A. Saravanan, D. V. N. Vo, S. Jeevanantham, V. Bhuvaneswari, V. A. Narayanan, P. R Yaashikaa, S. Swetha, and B. Reshma, “A comprehensive review on different approaches for CO_2 utilization and conversion pathways,” *Chemical Engineering Science*, vol. 236, 2021, Art. no. 116515.

[131] S. Chakrabortty, R. Kumar, J. Nayak, B.-H. Jeon, S. K. Dargar, S. K. Tripathy, P. Pal, G.-S. Ha, K. H. Kim, and M. Jasinski, “Green synthesis of MeOH derivatives through in situ catalytic transformations of captured CO_2 in a membrane integrated photo-microreactor system: A state-of-art review for carbon capture and utilization,” *Renewable and Sustainable Energy Reviews*, vol. 182, 2023, Art. no. 113417.

[132] M. Aresta, A. Dibenedetto, and A. Angelini, “The changing paradigm in CO_2 utilization,” *Journal of CO_2 Utilization*, vol. 3, pp. 65–73, 2013.

[133] J. Patricio, A. Angelis-Dimakis, A. Castillo-Castillo, Y. Kalmykova, and L. Rosado, “Method to identify opportunities for CCU at regional level—Matching sources and receivers,” *Journal of CO_2 Utilization*, vol. 22, pp. 330–345, 2017.

[134] D. Baskaran, P. Saravanan, L. Nagarajan, and H.-S. Byun, “An overview of technologies for Capturing, Storing, and utilizing carbon Dioxide: Technology Readiness, large-scale Demonstration, and cost,” *Chemical Engineering Journal*, 2024, Art. no. 151998.

[135] C. Hepburn, E. Adlen, J. Beddington, E. A. Carter, S. Fuss, N. M. Dowell, J. C. Minx, P. Smith, and C. K. Williams, “The technological and economic prospects for CO_2 utilization and removal,” *Nature*, vol. 575, no. 7781, pp. 87–97, 2019.