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Review

Advances in Carbon Capture and Use (CCU) Technologies: A Comprehensive Review and CO_2 Mitigation Potential Analysis

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Abstract: One of society's major current challenges is carbon dioxide emissions and their consequences. In this context, new technologies for carbon dioxide (CO_2) capture have attracted much attention. One of these is carbon capture and utilization (CCU). This work focuses on the latest trends in a holistic approach to carbon dioxide capture and utilization. Absorption, adsorption, membranes, and chemical looping are considered for CO_2 capture. Each CO_2 capture technology is described, and its benefits and drawbacks are discussed. For the use of carbon dioxide, various possible applications of CCU are described, starting with the utilization of carbon dioxide in agriculture and proceeding to the conversion of CO_2 into fuels (catalytic processes), chemicals (photocatalytic processes), polymers, and building supplies. For decades, carbon dioxide has been used in industrial processes, such as CO_2-enhanced oil recovery, the food industry, organic compound production (such as urea), water treatment, and, therefore, the production of flame retardants and coolants. There also are several new CO_2-utilization technologies at various stages of development and exploitation, such as electrochemical conversion to fuels, CO_2-enhanced oil recovery, and supercritical CO_2. At the end of this review, future opportunities are discussed regarding machine learning (ML) and life cycle assessment (LCA).

Keywords: CO_2 capture and utilization; pre- and post-combustion CO_2 capture; catalytic conversion of CO_2; direct utilization of CO_2

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1. Introduction

Overreliance on fossil fuels has contributed to a critical energy crisis and to the increase in carbon dioxide in the atmosphere. CO_2 is by far the most dangerous greenhouse gas per unit of concentration emitted by humans [1]. According to the International Energy Agency (IEA) [2], about 36 billion tons of carbon dioxide are emitted each year through transportation, power generation, cement manufacturing, deforestation, agriculture, and many other practices [2]. Most of the carbon dioxide emitted today will remain in the atmosphere for over 1000 years [3–5]. According to the National Ocean and Atmospheric Administration (NOAA) data, the average concentration of carbon dioxide in the atmosphere has increased dramatically, from 172–300 ppm before the last industrial era to 419 ppm in May 2021. In recent decades, extreme weather and signs of climate disaster, such as ocean acidification, air pollution, tsunamis, droughts, and species extinctions, have been seen as a result of climate warming and the effect of accumulation carbon dioxide emissions [6,7].

The Intergovernmental Panel on Climate Change (IPCC) has determined that the main causes of the increase in the carbon dioxide concentration are fossil fuel burning

(mainly from industrial sources such as cement and power plants, iron manufacturing, and the chemical industry) and deforestation (agriculture). Human activity is responsible for most of the greenhouse gas (GHG) emissions. Carbon dioxide accounts for nearly 77% (or 35 billion tons) of greenhouse gas emissions, seriously affecting the environment and people's way of life; this quantity of GHG can be associated with detrimental effects on human health, such as headaches and respiratory diseases [7]. Therefore, there is a crucial need to curb carbon dioxide emissions for the benefit of future generations. In this context, carbon dioxide capture and utilization (CCU) technology has gained considerable attention due to its important role in reducing greenhouse gas emissions [6–8].

Carbon capture and utilization (CCU) and carbon capture and storage (CCS) technologies play an increasingly important role since the purpose of their use is to promote the recycling of carbon dioxide (CO_2) in the form of raw material—for example, in the replacement of fossil fuels, for the chemical industry, or even to produce new carbon-based materials. This use of CCU or CCS technologies can effectively contribute to creating net negative greenhouse gas emissions. Given growing interest in the subject, several works have been carried out in recent years. These include works explicitly addressing the issue of processes and technologies—that is, more pioneering works on the means of capturing and storing CO_2. In addition, several works have focused on the technical and economic feasibility of these technologies, since, in the first analysis, it has been verified that all of them, without considering their ability to capture and store CO_2, are intensive energy consumers and require significant initial investment for their implementation. In other words, these projects tend to require significant investment in the CAPEX and OPEX phases, which require complex feasibility analysis processes for correct decision making, as described in the recent work by Liu et al. [9]. These authors suggest that their decision-making model can be used regarding investment to be made in the technology learning effect process, which uses the component-based two-factor technology learning curve approach to predict the component costs. This process can also be implemented for enhanced oil recovery projects with CO_2 (CO_2-EOR), for which the price of a barrel of oil must reach USD 80. However, the same authors also concluded that, for methanol synthesis projects, the price per ton of methanol must reach USD 580 to justify the use of this technology. In other words, according to the authors, investment in CO_2-MET projects is more economical than that in CO_2-EOR projects. As seen in work by Liu et al. [9], in addition to Wich et al., Pires da Mota Costa et al., and Dimitriou et al. [10–12], after the technical validation of the methods to be used, the subsequent economic and financial validation assumes a decisive role in the feasibility of the projects.

Another relevant aspect is the analysis of the potential environmental impacts of these technologies, namely through a life-cycle assessment (LCA), as a way of guaranteeing that the CCU and CCS processes have environmental advantages over conventional production processes. Based on this perspective, authors such as Garcia-Garcia et al. [13] performed thorough and systematic environmental impact analyses. These authors conclude that, although the creation of net negative greenhouse gas emissions may initially seem to be a highly favorable aspect, the fact that these processes are energy-intensive means that, to achieve environmental improvements, renewable energy must be used, mainly producing hydrogen from water electrolysis. In other words, the use of these CCU and CCS technologies depends not only on the technological process of capturing and storing CO_2, but also on the development of forms of renewable energy that can contribute to the efficiency of the process.

In recent years, significant progress has been made in increasing the availability of CCU materials (fuels, chemicals, and building materials that convert CO_2), and their performance, to effectively reduce CO_2 emissions. Given the lack of reviews of the progress of promising state-of-the-art CCU technologies, there is an urgent need for a full and timely summary of these advanced technologies and a comprehensive understanding of them. The purpose of this work is to outline and comprehensively describe recent progress in CCU. Research and/or review articles are surveyed to discover innovative aspects and

technologies related to pre- and post-combustion CO_2 capture, liquid and solid sorbents, carbon dioxide conversion via homogeneous and heterogeneous catalysis, and the direct use of carbon dioxide. First, we summarize the CCU scheme and discuss details of the processes involved. Next, we present a framework for the performance of liquid and solid CO_2 capture materials under different operating conditions and propose possible scenarios to improve their carbon capture capacity and progress in CO_2 utilization in different fields, systematically comparing and discussing their industrial applications. Finally, we present future perspectives and technological advances in the field.

2. CCU Technologies

2.1. Framework

CO_2 capture options involve carbon capture and storage (CCS), which continually stores carbon dioxide and prevents it from entering the air, and carbon capture and utilization (CCU), which absorbs carbon dioxide in various industrial supply chains. CCS and CCU both aid a circular carbon economy, where carbon emissions are reduced, reused, recovered, and removed. Overall, CCU processes are critical to addressing global emissions and carbon-intensive manufacturing. The CCU scenario is considered an outstanding approach to combating anthropogenic carbon emissions [14–16]. Carbon capture is the most economical way to control industrial point-source carbon emissions [6,7,14]. Subsequent use refers to the use of captured carbon dioxide to synthesize value-added compounds or enhance oil recovery [6,7].

CCU concentrates on resource efficiency and aligns with the concept of a circular economy [17]: the capture and use of carbon dioxide provides the benefits of mitigating climate change and producing economically viable products [18]. The promising energy-saving techniques and their utilization in value-added merchandise are essential to the industry's uptake of CCU. Despite research, technical and economic barriers limit most laboratory-scale technologies [16]. CCU comprises four steps: CO_2 capture, CO_2 utilization, CO_2 storage, and CO_2 transportation [6,19,20]. In this work, capture and utilization are described.

2.2. CO_2 Capture

Carbon dioxide is emitted via burning fossil fuels by industrial sources, such as hydrogen power plants, cement manufacturers, coal gasification, power conversion, iron and steel plants, chemical production, and the petroleum industry [6,20]. Carbon capture methods are divided into two types: CO_2 capture techniques and CO_2 separation techniques [16].

CO_2 capture technologies consist of the dissociation and storage of CO_2 generated in industrial processes, or the removal of oxygen from the air, thereby decreasing the difficulty of capture and reducing the energetic demand [21]. Carbon capture technology is classified into three approaches: post-combustion capture, oxy-fuel combustion, and pre-combustion capture, of which post-combustion is a globally used approach. Pre-combustion separation is usually adopted to produce syngas (H_2 and CO) through chemical reactions: CO and H_2O are converted into CO_2 and H_2 through further conversion reactions, and then CO_2 is separated out. This technique is largely utilized in natural gas boilers and coal-fired power plants [21,22]. By contrast, post-combustion techniques, such as absorption, adsorption, chemical looping, or membranes, isolate CO_2 in the flue gas [16].

The oxygen-enriched combustion technique usually adopts pure oxygen or a mixture of air/carbon dioxide rather than oxygen for combustion. After denitrification and combustion, an elevated-purity CO_2 can result for direct storage, which also has significant benefits compared with general combustion air. Oxygen-enriched fuel combustion produces CO_2 and H_2O, and about 75% less flue gas compared to oxy-fuel combustion [16,23]. Several physical and chemical methods are used in capture technology, containing solvent-based absorption, solid sorbents, membranes for CO_2 capture, and chemical looping, as shown in Figure 1 [16,21,22,24].

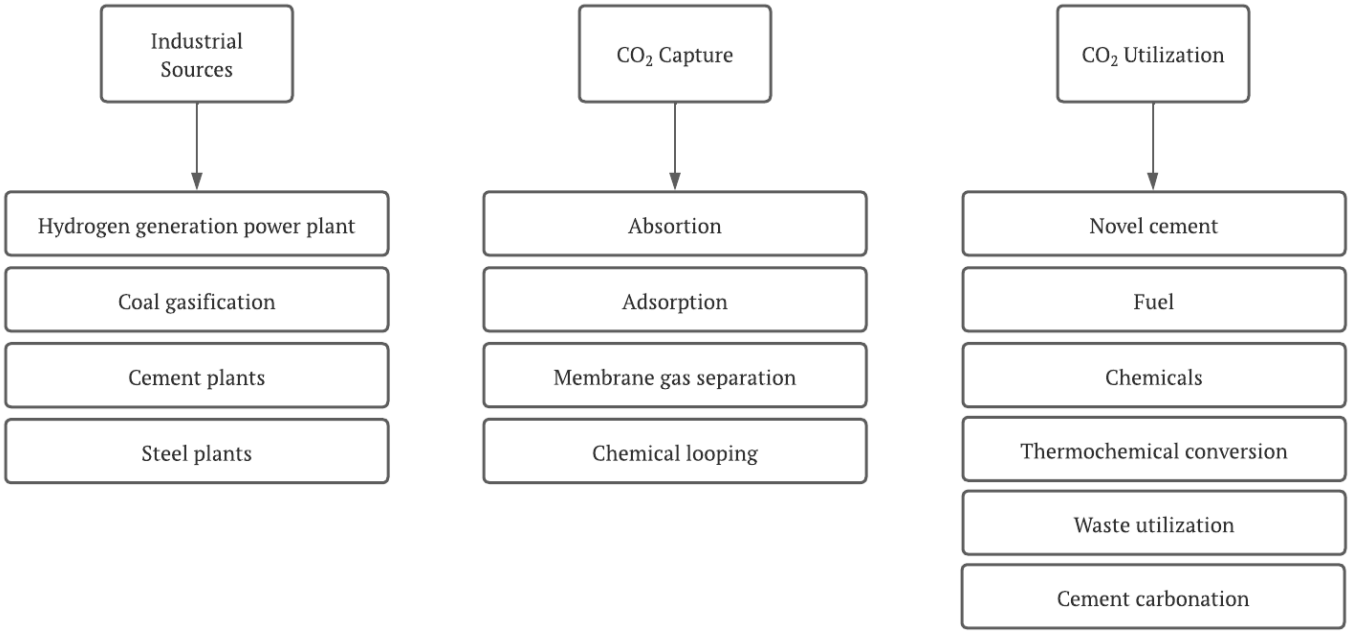

Figure 1. Scheme of CCU technologies (adapted from [6,20]).

Financially, carbon capture projects currently cost around 60–110 USD per ton globally and are expected to drop to around 30–50 USD per ton by 2030. This will encourage the rollout of the technology on a commercial scale [22]. As shown in Figure 2, the main CO_2 separation techniques are absorption, adsorption, membranes, and chemical looping. The next section provides more information about these methods [24,25].

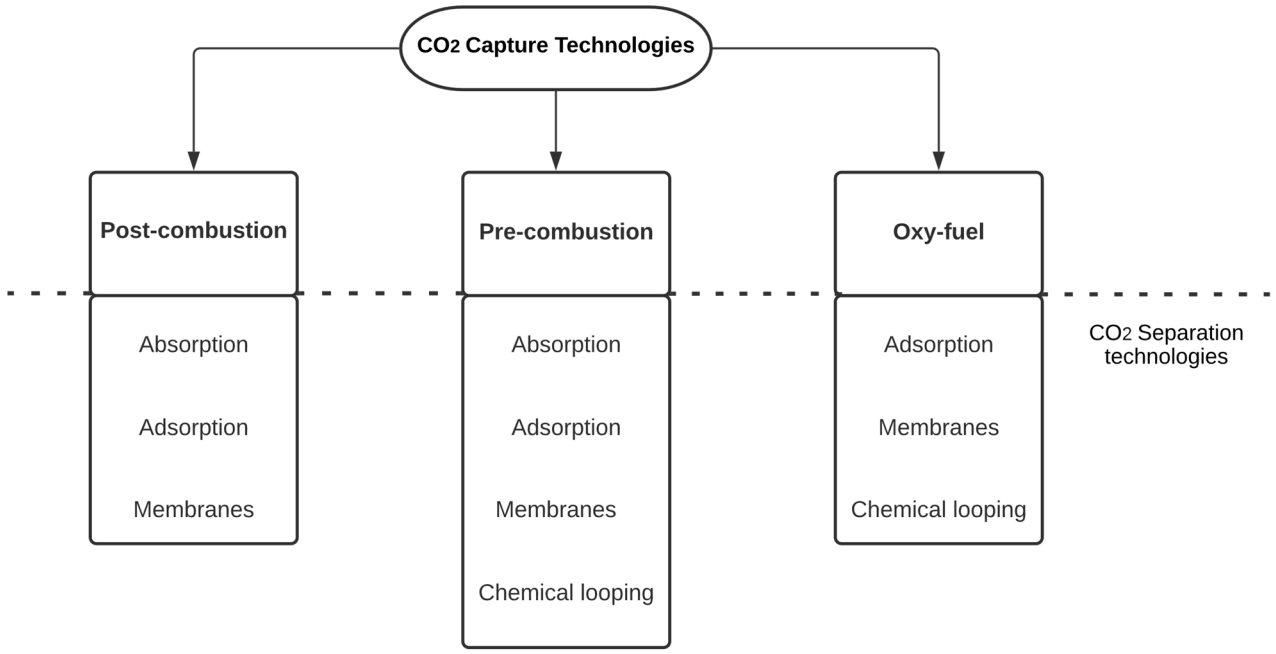

Figure 2. CO_2 capture and separation technology (adapted from [16,20]).

2.2.1. Absorption-Based CO_2 Capture

In absorption methods for CO_2 capture, a liquid absorbent (solvent) physically or chemically isolates CO_2 from flue gas by forming a solution or compound (Figure 3). This technique has been used extensively both post-combustion (using chemical solvents) and pre-combustion (using a physical solvent) [5,16,26]. Chemisorption of amine-based

solvents such as ammonia, monoethanolamine (MEA), diethanolamine (DEA), and N-methyldiethanolamine (MDEA), in addition to basic solvents such as $Ca(OH)_2$ and NaOH, are the main post-treatment methods [5,27]. Two of the benefits of this method are the low cost and elevated stability; however, it has drawbacks such as an elevated energy demand for solvent regeneration, high corrosiveness, elevated toxicity, volatility, and high cost [20,22]. At present, the energy demand for CO_2 capture at the Boundary Dam and Petra Nova projects is around 0.25–0.30 $MW \cdot h \cdot t^{-1}$ CO_2, resulting in a loss in energy efficiency. Alternatively, CO_2 storage solutions based on KOH and K_2CO_3 have been considered [22]. Aqueous solutions of amino acids and ionic liquids have been investigated [28,29]. Compared with amine-based technology, amino acid-based technology has the advantages of low toxicity, high biodegradation potential, and low evaporation rate [30]. However, further works on the economic feasibility and degradation viability of amino acids are required [20,30]. Currently, ionic liquids have been classified as viable alternatives to the traditional physical solvents utilized in the abovementioned procedure because of their basic behaviors, including low volatility, vapor pressure, elevated thermal stability at high temperatures, and low requirements, including regeneration demand energy. Nonetheless, their low operational capacity is a major barrier to their common use in carbon capture [5,16].

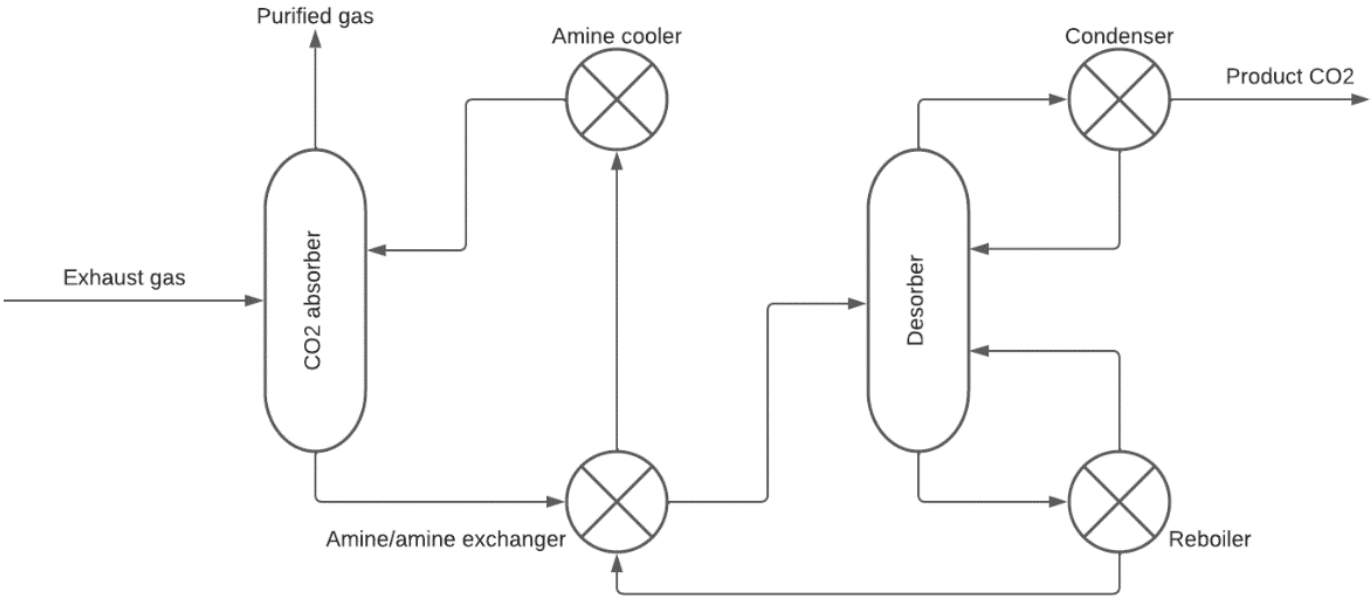

Figure 3. Principle for a standard CO_2 removal process based on absorption followed by desorption in amine solution (adapted from [31]).

2.2.2. Adsorption-Based CO_2 Capture

The adsorption-based CO_2 capture process includes the bulk phase transfer of CO_2 molecules in the flue gas to a solid surface at atmospheric pressure and high temperature (Figure 4). The attached CO_2 molecules, called adsorbates, form a thin film on the surface of a solid material, called an adsorbent. In addition, adsorption-based CO_2 capture has attracted extensive interest due to its simple process, low energy consumption, and low cost. However, the low recovery of CO_2 remains a challenge [5,32,33]. CO_2 capture on porous solids is a promising way to extract CO_2 from flue gas in different production methods, if the adsorption mechanism is based on the affinity of CO_2 for adsorption on the adsorbate surface [20]. Various adsorbents have been studied for CO_2 capture from pre- and post-combustion flue gases. Normally, the adsorbents adopted are categorized as elevated-temperature or low-temperature materials. The main category of elevated-temperature materials encompasses hydrotalcites, alkali metal, or alkaline earth metal oxides such as calcium oxide, alkali metal silicates and zirconates, and double salts, while low-temperature

adsorbents include traditional porous materials such as zeolites and carbon-based materials [8,34–38]. These include activated carbon, carbon nanotubes, carbon nanofibers, graphene, and molecular sieves, in addition to newer classes such as MOFs, porous polymer networks (PPNs), and covalent organic frameworks (COFs) [5,34]. Adsorption is the most promising method, compared with absorption and other industrial methods, because it has the following advantages: (i) better performance [39], (ii) long-term stability [32], (iii) lowest regeneration cost [33], (iv) does not regenerate toxic substances [40], and (v) is inexpensive. There are two main types: (i) physisorption (van der Waals attraction) and (ii) chemisorption (interaction of chemical bonds) [32,33,39]. In the physisorption process, molecules of CO_2 attach to the pore walls of the adsorbent through van der Waals and pole–pole interactions [33,41]. The heat of adsorption values for the physisorption process is close to the sublimation heat, and the values are in the range of 25–40 kJ/mol [33,42,43]. This is considered a reversible process, where the adsorption/desorption of the gas molecules can be achieved under the effect of temperature and pressure [33,44]. The CO_2 adsorption at ambient temperature mainly occurs by physisorption, and the gas capture is directly related to the porous texture of the adsorbent surface [33,45,46]. It has been reported that narrow micropores (0.33–1 nm) are responsible for the CO_2 adsorption performance [33,47]. To overcome the low gas selectivity for CO_2 in physisorbents, chemical adsorption is widely performed on the surface of the porous materials by incorporating basic groups that effectively interact with the acidic CO_2 gas molecules [33,48–50]. Among different basic groups, the amine is commonly used for the surface modification of CO_2 adsorbents [33,41]. The CO_2 gas molecule forms a chemical bond with the adsorption sites in chemisorption. Usually, CO_2 adsorption at elevated temperatures (above 140 °C) is mainly ruled by chemisorption [33,45,51]. Both chemisorption and physisorption can occur in the temperature range of 25–140 °C. The heat of adsorption for chemisorbents can vary between 60 to 100 kJ/mol depending on the chemical functionality and bonding nature.

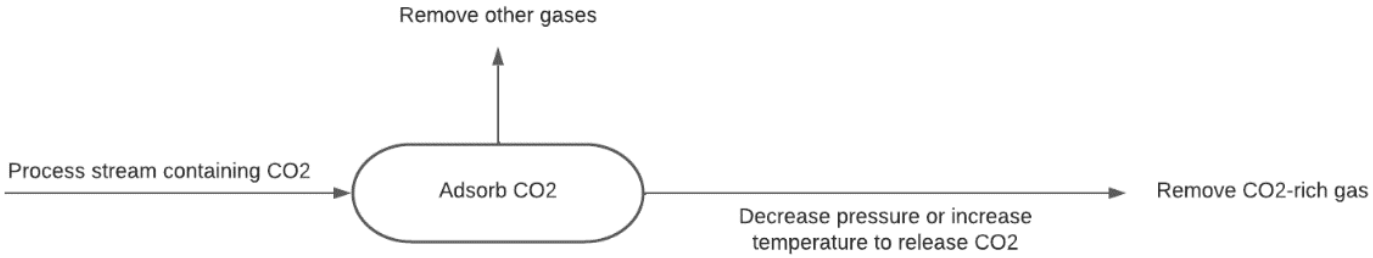

Figure 4. Carbon dioxide separation by adsorption (adapted from [52]).

2.2.3. Membrane-Based CO_2 Separation

In membrane-based gas separation, the gas flow is commonly precipitated by a pressure differential through the membrane, and separation is achieved when the flue gas permeates across the pores of the membrane (Figure 5). The process combines membrane separation and amine absorption, raising the mass transfer area (movement of mass) by 400–1500%. In addition, gas separation offers several advantages, such as energy efficiency, cost effectiveness, ease of operation, scalability, and environmental friendliness, compared with other CO_2 capture methods [16,53]. Polymer-based films show promise due to their ease of processing and mechanical properties. However, they suffer from inherent problems, such as the competition between gas permeability and selectivity, in addition to poor durability (e.g., low heat and chemical resistance), plasticization, and aging, which affect their gas separation performance [20,54]. Inorganic membranes have drawbacks such as elevated cost and difficult manufacturing. Mixed-matrix membranes (MMMs) incorporate a polymer matrix with functional features such as zeolites, carbon molecular sieves (CMS), and carbon nanotubes. In terms of challenges and prospects, membranes are generally expensive due to the large quantity of energy required to pressurize the gas. Clearly, more research is needed for material development and composition design [16,20].

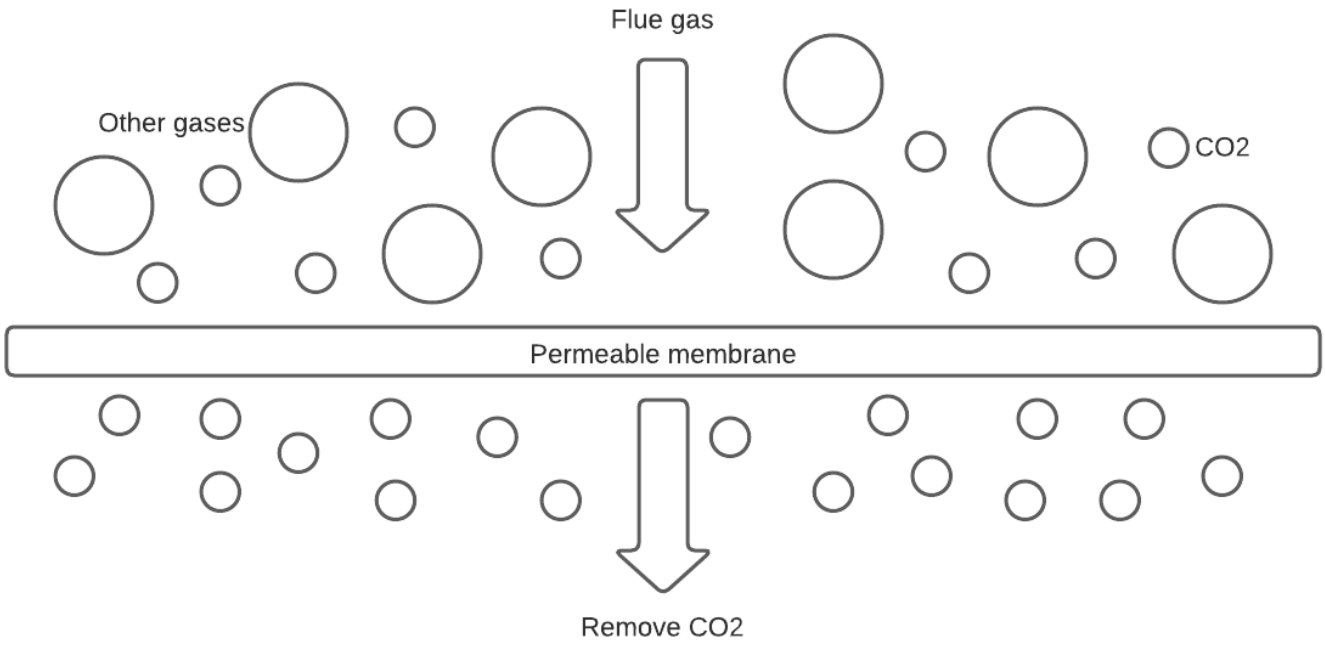

Figure 5. Membrane separation technology in carbon capture (adapted from [55]).

2.2.4. Chemical Looping-Based CO_2 Capture

Chemical looping applies indirect combustion of fossil fuels and renewable fuels, dividing the combustion procedure into a two-stage process (Figure 6). First, the fuel reduces metal oxides (an oxidant that transfers oxygen into the fuel) to the metal reduction column. The resulting metals (e.g., iron, manganese, or copper) are then oxidized in an oxidation tower. Metal oxides are formed as a result of the reaction. These compounds are transported to a second reactor, where they react with the fuel. Metal oxides are reduced during combustion, generating energy and flue gas as CO_2 and H_2O streams. Flue gas can be condensed to obtain pure CO_2 [56,57]. The system (chemical looping-based CO_2 uptake) involves two interconnected reactors, named the air reactor (AR) and the fuel reactor (FR), where oxidation and reduction reactions, respectively, occur. In the FR, the gaseous fuel ($C_nH_{2m}O_p$) reacts with the oxygen carrier (Me_xO_y), which is reduced to a metal (Me) or a reduced form (Me_xO_{y-1}), while the fuel is transformed to CO_2 + H_2O, according to the reaction in Equation (1). Then, the reduced oxygen carrier is transferred to the AR, where it is oxidized by oxygen, according to the reaction in Equation (2). Thus, this process occurs in two stages, avoiding direct contact between the fuel and the air [57].

$$(2n + m - p)M_xO_y + C_nH_{2m}O_p \rightarrow (2n + m - p)M_xO_{y-1} + nCO_2 + mH_2\Delta H_r \quad (1)$$

$$(2n + m - p)M_xO_{y-1} + \left(n + \frac{m}{2} - \frac{p}{2}\right) O_2 \rightarrow (2n + m - p)M_xO_y\Delta H_0 \quad (2)$$

A key feature of this technology is the emission of exhaust gas, the main component of which is carbon dioxide, which can be recuperated by cooling. The technique has shown good results for further development, and various ceramic materials, such as $NiO/NiAl_2O_4$, have been investigated [20,56]. The large-scale application of this method is dependent on the availability of air carriers. For chemical looping operations, some essential metal oxides' properties are important, such as high chemical activity, mechanical stability (in fluidized bed), resistance to caking, high melting point (to resist reaction temperatures and avoid caking), long-term stability under repeated oxidation/reduction, and cost [5,58].

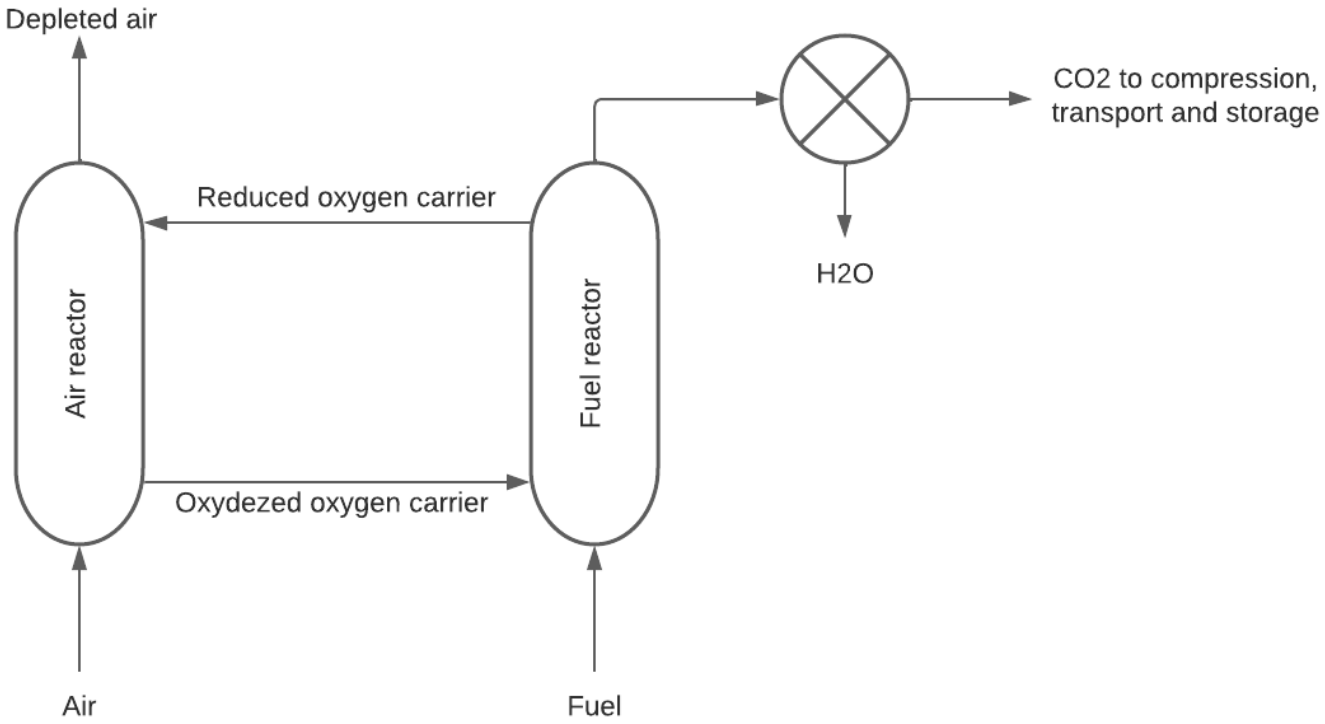

Figure 6. CO_2 capture with chemical looping combustion of gaseous fuels (adapted from [59]).

3. Recent Developments and Potential Uses

CO_2 has been utilized in various sectors and processes, as shown in Figure 7. Carbon dioxide is used in the chemical, oil, and power industries, in the food processing and pharmaceutical sector, and in the pulp and paper steel sector, among other uses [7,60].

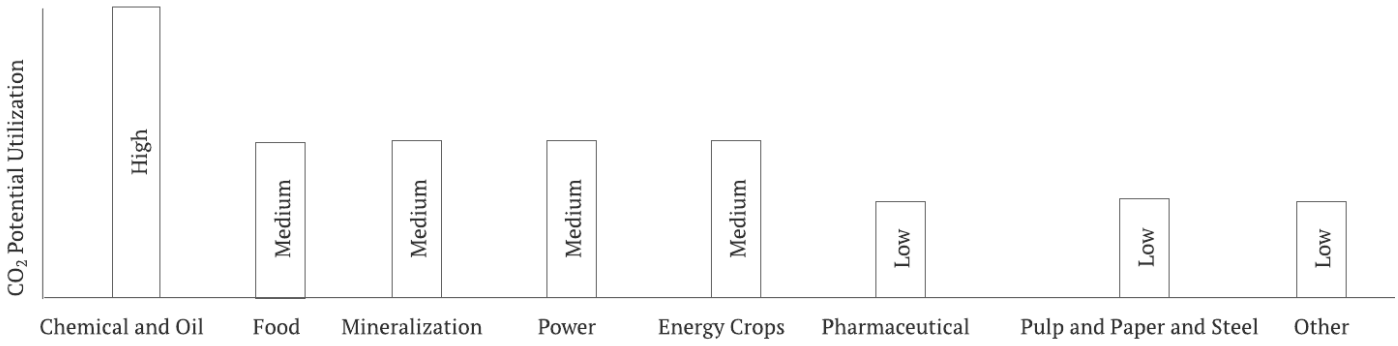

Figure 7. CO_2 utilization by sector (adapted from [60]).

The greatest global capacity for CO_2 utilization is by the chemical and petroleum industries, with the greatest potential for enhanced oil recovery (EOR) (estimated up to 300 Mtpa), urea synthesis, polymer manufacturing processes for fuels, and chemical synthesis of, e.g., sustainable alcohol and acids [61–63]. The cement industry also has a huge absorption potential of up to 300 Mtpa. For the food industry, moderate potential exists, mainly in beverage carbonation, packaging, decaffeination, and horticulture [60,64]. If the supercritical carbon dioxide cycle in the power industry is not limited to today's existing geothermal power plants and heat pump applications, overseas markets for potential future applications are expected to include nuclear power, coal, biomass, and natural gas to waste incinerators, such as small thermal power cogeneration application [60,65]. The CO_2 utilization potential is estimated to be around 300 Mtpa [60]. The Global Carbon Dioxide

Initiative provides a USD 0.8–1.1 trillion annual market for carbon-based products, as it consumes more than 10% of the world's annual carbon dioxide emissions [60,63].

There are two other approaches to the use of carbon dioxide: direct use of carbon dioxide (physical) and conversion of carbon dioxide into useful chemicals [7,66]. However, the scope for direct use of CO_2 is limited and the impact on overall CO_2 reduction is also limited. The chemical conversion is carried out using CO_2 as a soft oxidant [7]. The potential uses are the oxidative dehydrogenation of ethylbenzene, ethane, and propane, with CO_2 used as a smooth oxidant; the transformation of CO_2 to organic polycarbonates and cyclic carbonates by adding CO_2 into phenol; and the transformation of CO_2 to alcohols, such as methanol, and acids, such as formic acid [7,67].

In recent years, CO_2 has been utilized in several industrial processes [6]. There are several technical approaches to transform CO_2 into consumer products and suitable procedures, such as catalytic, photocatalytic, photosynthetic, electrochemical, mineralization, and biological (using microorganisms) processes [68]. The electrochemical process uses an electrolyzer (an apparatus that produces hydrogen through a chemical process (electrolysis) capable of separating the hydrogen and oxygen molecules) to reduce CO_2 to CO. H_2 is generated by the electrolysis of water and is a common reactant for converting CO_2 to CH_4, CH_3OH, etc. The electrolysis process is expensive and requires a high energy demand [68].

Dongliang et al. [69] utilized green hydrogen to produce methanol through carbon dioxide hydrogenation; instead of releasing the greenhouse gases into the atmosphere, methanol obtained was diverted to a local project (1.8 Mt/y). In addition, Aresta [70] demonstrated that ethanol derived from atmospheric CO_2 should have the same benefits as bioethanol, with the added benefit that its synthesis produces fewer pollutants than those produced by fermenting sugars. Peng et al. [71] applied photocatalysts to transform CO_2 to fuel by a solar-driven process.

Chen et al. [72] studied an efficient solid CO_2 adsorbent with a hierarchical micro-mesoporous structure and a large number of amine groups with high affinity for carbon dioxide, achieving CO_2 capture of 3.32 mmol $CO_2 \cdot g^{-1}$ adsorbent at a temperature range of 303–343 K; compared with other materials used in the literature, this is a promising value. Additionally, Peres et al. [36] researched CO_2 adsorption using porous carbon by sugarcane bagasse waste feedstock (the process included carbonization, followed by activation with KOH); they achieved a CO_2 capture of 1.22 mmol $CO_2 \cdot g^{-1}$ adsorbent at room temperature. In addition, Ma et al. [35] performed the synthesis of nitrogen-doped porous carbons from polyacrylonitrile fibers as efficient CO_2 adsorbents via a simple two-step synthesis process (carbonization followed by KOH activation) and achieved a CO_2 removal of 3.95 mmol $CO_2 \cdot g^{-1}$ adsorbent at room temperature.

Another interesting study by Cho et al. [73] designed a process for recycling desalination wastewater, utilizing CO_2 as $CaCO_3$ and $MgCO_3$ in the CCU process. The results showed that about 91% of the CO_2 in the flue gas was captured and used. In addition, the maximum global profit of the proposed process was 73.23 USD per ton of CO_2, which means it is profitable and suitable for large-capacity processes, compared with other alternative CCU processes. Baena-Moreno et al. [74] proposed a new process for carbon dioxide capture and utilization appropriate for small and medium-sized applications. They utilized potassium and calcium wastes as alternative low-energy pathways for carbon capture and waste recycling, promoting a circular carbon economy. Hernandéz et al. [75] reported, for the first time, a feasible process for converting CO_2 to cyclic carbonate (a reagent that can be prepared using carbon dioxide), which can even improve catalytic activity and avoid the use of energy-consuming technologies by solving the problem of catalyst separation from reaction products and compatibility with reaction steps [18]. Additionally, Yao et al. [76] focused on the analysis of the technical and economic viability of addressing CO_2 capture in the context of the steel sector. CO_2 can be utilized in catalytic processes with CO_2 reduction methods. One of these processes is the photocatalytic reduction of carbon dioxide. The photocatalytic method of CO_2 photoreduction starts with light absorption in semiconductors, which allows electron-hole pairs to form in nanocrystals. These charge carriers migrate

to the surface of the material and reduce or oxidize the adsorbed molecules [77]. The following reactions occur:

$$CO_2 + e^- \rightarrow CO_2^- \ (-1.90\ V) \quad (3)$$

$$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH\ (-0.61\ V) \quad (4)$$

$$CO_2 + 2H^+ + 2e^- \rightarrow CO + H_2O\ (-0.53\ V) \quad (5)$$

$$CO_2 + 4H^+ + 4e^- \rightarrow CH_2O + H_2O\ (-0.48\ V) \quad (6)$$

$$CO_2 + 6H^+ + 6e^- \rightarrow CH_3OH + H_2O\ (-0.38\ V) \quad (7)$$

$$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O\ (-0.24\ V) \quad (8)$$

$$2H_2O + 4H^+ \rightarrow O_2 + 4H^+\ (0.81\ V) \quad (9)$$

$$2H^+ + 2e^- \rightarrow H_2\ (-0.42\ V) \quad (10)$$

One of the major benefits of photocatalytic processes is the direct use of photons, rather than the initial transformation to power. However, these procedures are elaborate and involve several methods, such as electron and proton transfer and bond formation [68].

Celaya et al. [77] examined the conversion of CO_2 to hydrocarbons via a photocatalytic process on M-doped titanate nanotubes (formed from amorphous TiO_2 using a relatively mild hydrothermal reaction conditions (0.05–1 M NaOH, 110 °C), forming parahydrophobic surfaces) (M = Ni and Cu). Ma et al. [78] proposed a feasible strategy for CO_2 reduction (photocatalytic) with H_2O in an aerobic condition by the high CO_2/O_2 adsorption selectivity of polymers, and effective charge separation for CO_2 reduction and H_2O oxidation on Pd (II) sites and hollow TiO_2, respectively. Sun et al. [79] investigated the viability of indium oxide-supported silver catalysts in the hydrogenation of CO_2 to methanol conversion by density functional theory (DFT). Alternatively, biocatalytic conversion of CO_2 has received great attention. Gomes et al. [80] reported a biocatalytic cascade transformation of CO_2 to methanol by enzymes co-immobilized in a tailored silicon-containing mesostructured porous foam. Additionally, Rasouli et al. [81] presented a hybrid enzymatic carbon dioxide absorption process in an enhanced flat-membrane contactor with immobilized human carbonic anhydrase II (hCA II) enzyme.

In the electrochemical field, advances have been made in CO_2 capture, mainly involving quinones. Hemmatifar et al. [82] presented a feasible and customizable electrochemical method for direct CO_2 capture by a bipolar cell, which utilizes the affinity of redox-active quinone moieties towards CO_2 molecules.

4. Future Opportunities

In the future, CO_2 technologies have great potential to limit CO_2 global emissions, but there are challenges to be faced. In this context, several studies have focused on CO_2 technologies and have received great attention. Gupta and Li [20] summarized several studies of CCU processes using machine learning (ML). Orlov et al. [83] produced an original computational approach combining kinetic experiments, molecular simulations, and machine learning for the screening of hundreds of potential solvent candidates and identified a class of tertiary amines that capture CO_2 faster than typical solvents. In the same way, Jin et al. [84] established two different regression models based on machine learning methods to estimate carbon dioxide levels in solvents. The methods used were an adaptive augmented support vector (SVR) machine and an adaptive augmented Gaussian process (GPR) to approximate the carbon dioxide loading in solvents for environmental applications. Zhu et al. [85] designed a quantitative structure–property relationship using a machine learning model, considering 6244 CO_2 adsorption datasets of 155 porous carbon materials, to predict CO_2 adsorption capture and examine the importance of physicochemical effects. The results showed that the random forest (RF) model presented promising accuracy and prediction performance based on the physicochemical proprieties and adsorption

conditions of porous carbon materials and the test dataset ($R^2 > 0.9$). All these studies are significant because mathematical simulations of CO_2 capture can save on time (laboratory and preparation) and costs (reagents).

Another important tool that is promising for CO_2 technologies is the life cycle assessment (LCA). LCA considers the whole life cycle of products and processes (cradle to grave thinking), from raw material extraction (cradle) and transportation, through fabrication and product utilization, to recycling and final disposal of waste (grave). In this context, several life cycle assessments have been carried out for different CCU processes, which were mainly supported by assumptions [68]. He et al. [86] studied the environmental benefits of harnessing carbon dioxide by back-converting water gas to syngas to produce liquid fuels and generate electricity. The CO_2 source is an ideal tertiary hydrogen synthesis unit-supported iron-based chemical loop combustion, which can absorb carbon with almost no energy demand. Life cycle emissions were measured at 129.98 kg CO_2 eq.·MWh^{-1}, corresponding to a 60% share of CO_2 emissions from liquid fuel production (using exergy distribution as an example). In this system, CO_2 capture using nearly zero energy could be achieved using a three-stage Fe-based chemical looping combustion (CLC) hydrogen generation system (CLHG) to obtain the CO_2 source, which benefited from the advantages of CLC to realize inherent carbon capture. In the fuel reactor (FR), CH_4 is indirectly combusted to generate CO_2 and steam. Then, the reduced form of OC (FeO) is subsequently oxidized by steam to generate H_2 in a steam reactor (SR). Finally, the partially oxidized OC (Fe_3O_4) from the SR is further oxidized by air to its original form (Fe_2O_3) in an air reactor (AR). In addition, within the framework of "cradle to cradle" thinking, Battuecas et al. [87] studied a new method to produce nano-calcium carbonate as a cement filler using carbon dioxide from cement waste gas. In this work, two pathways for CO_2 capture were evaluated, followed by the synthesis of $CaCO_3$ via mineral carbonation. Three protocols for synthesizing $CaCO_3$ nanoparticles were evaluated, aiming to use waste as raw materials and recycle them to reduce emissions. The three scenarios were considered using a life cycle analysis approach. Rosental et al. [88] provided cradle-to-gate-based life cycle assessments to produce a wide range of organic chemicals: methanol, ethylene, propylene, benzene, toluene, and mixed xylenes. The LCA results showed that the production of the studied chemicals by the CCU process will decrease greenhouse gas emissions by 88–97% when using electricity from offshore wind turbines compared to fossil-based synthesis routes. Simultaneously, other environmental impacts, such as eutrophication processes and ozone depletion, will increase [89–92]. All these studies are significant, given that the LCA can calculate economic values, relative environmental impacts, and feasibility, and identify the most important factors.

5. Conclusions

Decreasing carbon dioxide emissions and slowing the greenhouse effect is essential for human life, global environmental safety, and sustainable development. In this short review, the state of the art and future opportunities of CCU are discussed from a holistic perspective. Certainly, recent years have seen significant progress in terms of the development of several CCU technologies. CO_2 can be utilized in several processes in the chemical and oil industry (urea production, fuels), the food industry (refrigeration, food processing), mineralization (baking soda, CO_2 concrete curing), power (heat pumps), energy crops (algae cultivation), pharmaceuticals (chemical synthesis), pulp and paper steel (injection to metal casting), and more (e.g., water treatment). In recent years, captured CO_2 has been converted into marketable products, and CCU technology has come a long way. Many methods for the preparation of fuels/chemicals by CO_2 copolymerization via catalysis (photocatalysis and biocatalysis), electrochemistry, and the biotransformation of CO_2 are already present in the local market. Going forward, CCU will continue to make temporary progress, mainly in more technologically advanced areas such as CO_2-derived polymers, CO_2 carbonization, and methanol fabrication. In the long term, CCU will be a crucial element of a circular

carbon economy. For the future, technologies such as machine learning and life cycle assessment are promising.

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