






Review

A Comprehensive Review on Recent Advancements in Absorption-Based Post Combustion Carbon Capture Technologies to Obtain a Sustainable Energy Sector with Clean Environment

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Abstract: CO₂ capture, use, and storage have been identified as significant strategies for reducing greenhouse gas emissions induced by the usage of fossil fuels. The current review focuses on the concepts of post-combustion capture technologies based on absorption mechanisms. Among all other developed technologies, researchers have proposed absorption as the most mature carbon capture technology for industrial-scale application. Absorption-based carbon capture can be classified into chemical and physical absorption, and researchers have developed different solvents and absorbent materials to investigate their performance in CO₂ capture. This paper comprehensively reviewed these established solvents and absorbents with their performance parameters in the CO₂ absorption approach. Besides the improvement in widely applied absorbents such as amine-based absorbents, recently, researchers have been working to develop some advanced nanomaterials such as nanofluids and nano-emulsions. This review focuses on the application of such absorption mechanisms that can contribute to capturing CO₂ in a compact, environment-friendly, and safe way. This paper also provides future research direction for further development in absorption-based CO₂ capture.

Keywords: carbon capture; post-combustion; absorption; absorbents; physical absorption; chemical absorption

1. Introduction

Global warming caused by greenhouse gas emissions, especially carbon dioxide, is a major concern throughout the world. Attempts are being undertaken continually to prevent the extent of future environmental change caused by rising emissions of greenhouse gases. If not regulated, rising temperatures will eventually lead to rising sea levels, increasing the probability of flooding and storms. The Intergovernmental Panel on Climate Change (IPCC) estimates that by the year 2100, the CO₂ content in the atmosphere shall reach 570 ppmv, the sea level will increase by 3.8 m, and the global mean temperature will rise by 2 °C with major consequences on the environment [1–4]. According to the ensemble-mean results of state-of-the-art Earth System Models (ESMs), climate warming throughout the

21st century is forecasted to be between 1.0 and 3.7 °C, depending on future greenhouse gas emissions [5,6]. The United Nations Framework Convention on Climate Change (UNFCCC) held its 21st Conference of the Parties (COP21) in Paris, France, where the primary goal of COP21 was to establish a lawful climate agreement among 195 countries of the United Nations to keep the global temperature rise since 1800 even below 2.0 °C (ideally 1.5 °C) by 2100 [7].

Absorption technologies can be integrated with both pre-combustion and post-combustion processes for carbon capture, and this process can be classified into chemical absorption and physical absorption. A basic chemical absorption system is composed of three main parts: solvent, absorber, and stripper. In the absorber, flue gases from various CO₂ emitters, such as coal power plants, come into contact with the lean solution in a counter-current mechanism in the absorber. The solvents then absorb CO₂, resulting in lower carbon dioxide levels in the exhaust gases. The stripper then regenerates the solvent-rich CO₂. This regenerated light solution comes back to the absorber, and compressed CO₂ is gathered and transferred to the stripper's top. Chemical absorption has been the most reliable marketed method for many years; however, it has yet to be scaled up in CO₂ capture in power plants. Numerous studies have been conducted and published for the creation of efficient gas–liquid contactor systems, solvent structures, and stripper configurations to maximize CC with little energy penalty [8,9]. The central concept was to optimize surface area and mass transfer for absorption and desorption procedures [10]. Packed bed (PB), bubble column, spray column, rotating packed bed (RPB), and tray tower absorber layouts were applied. Some modification methods, such as the addition of numerous columns, vapor recompression and heat integration in the stripping phase, split flows, and matrix stripping, have been observed to increase performance [11–14].

In the preceding introductory part, the urgency of carbon capture and the many technologically viable alternatives in obtaining a similar result to mitigate the serious threat of global warming have been highlighted. In the following sections, the development patterns in the key technologies of carbon capture are thoroughly explored, and future difficulties and possibilities in each of them are reviewed. In each section, a table summarizing the overall findings has been included.

Status of Global CO₂ Emissions

CO₂ is emitted from different sources, and the largest amount of CO₂ has been emitted from power plants and energy sectors. Therefore, with increasing energy production, the amount of CO₂ emission also increases. Figure 1 shows the top 10 CO₂-emitting countries, and it is clear that in recent years, China has been emitting the largest amount of CO₂ because it has been producing the largest amount of energy. From the year 1990 to 2005, CO₂ emissions increased by nearly 4000 million metric tons, while a sudden increase was observed in 2015, when the amount of CO₂ emissions passed 10,000 million metric tons (MMT). Finally, in 2021, China's CO₂ emissions reached 12,000 MMT, and China became the largest CO₂ emitter in the world. According to CO₂ emissions statistics, the United States has been the second-largest emitter for the last two decades (2000–2021). From Figure 1, it can be observed that from 1990 to 2021, the CO₂ emissions in the United States were not drastic. The amount of CO₂ emissions was always in the range of 4000 to 6000 MMT.

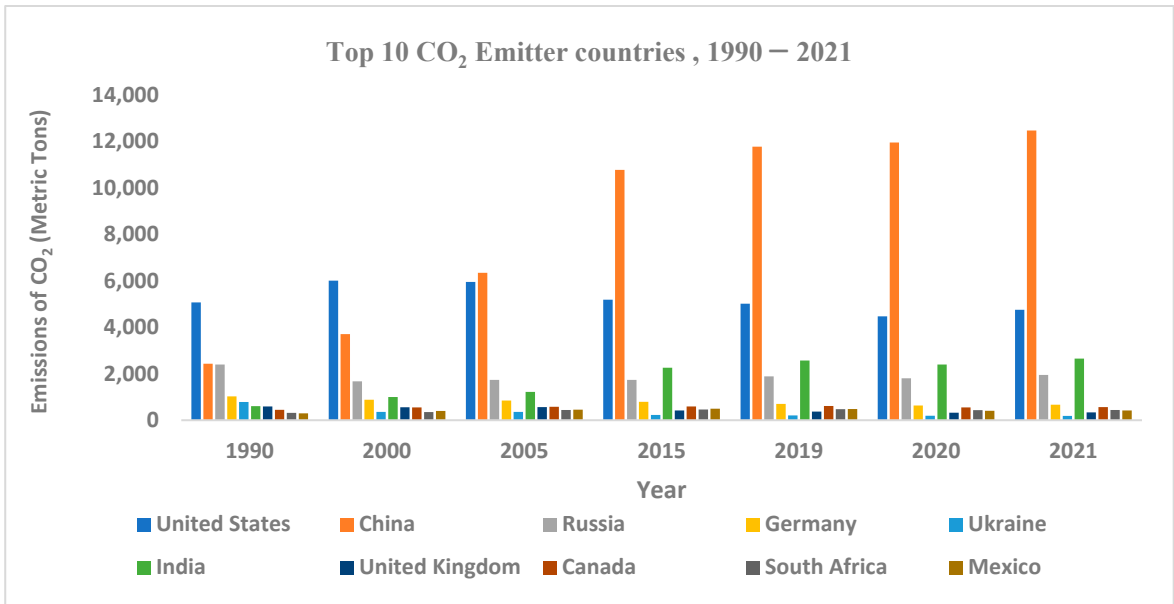


Figure 1. Top 10 countries that emit the largest amount of CO₂, 1990–2021. (Data from the EDGAR website).

Major CO₂ emitters in the U.S. are listed in Figure 2, including power plants, chemical and metal processing industries, petroleum and natural gas systems, food processing, coal mining, and other different major sources. These major emitters can be promising for capturing CO₂ due to the large amount of exhaust CO₂ in the system.

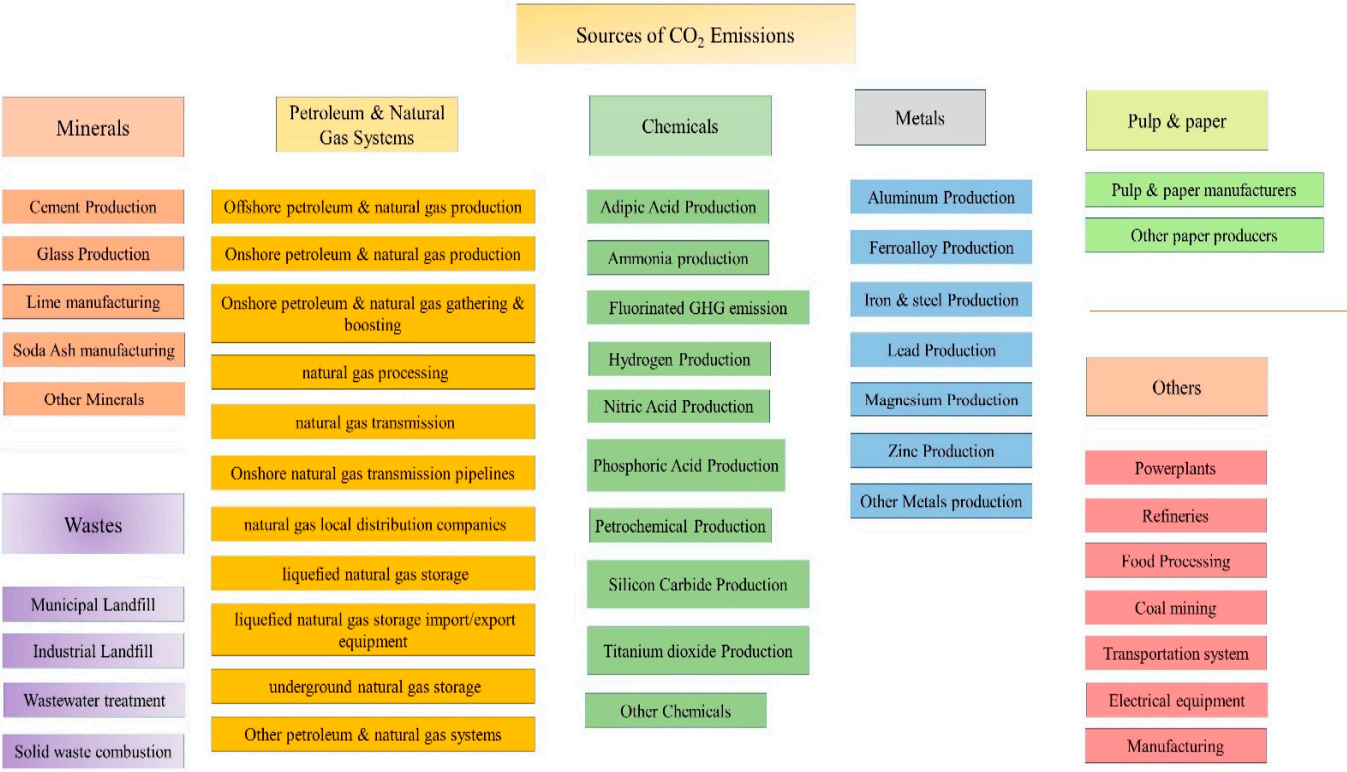


Figure 2. Different sources of Carbon Dioxide emissions in the environment.

Power plants are the largest source of emitted CO₂, which is clear from Figure 3. According to the EPA dataset, in the United States, there are 1369 facilities in total, from

which 1660 MMT of CO₂ was emitted in the year 2019. As populations grow, more power sectors are built, which leads to increased energy consumption. As a result, more power plants are developed, which causes a higher amount of CO₂ emissions. The EPA has developed a statewide plan to control CO₂ emissions from power plants, and these plans are listed in Section 111(d) of the Clean Air Act, where the EPA set different performance standards for multiple sources of pollution, which includes power plants. According to the EPA's clean power plan, states have the responsibility to cut off 30% of CO₂ emissions from power plant sectors from 2005 to 2030. To implement these acts, states have started implementing different policies to minimize power sectors' climate impact [15]. The EPA has focused on four major opportunities to reduce CO₂ emission from electricity production sectors, and these opportunities include the increased efficiency of fossil-fired power plants and fuel switching, renewable energy, increased end-use energy efficiency, and carbon capture and sequestration (CCS) [16,17].

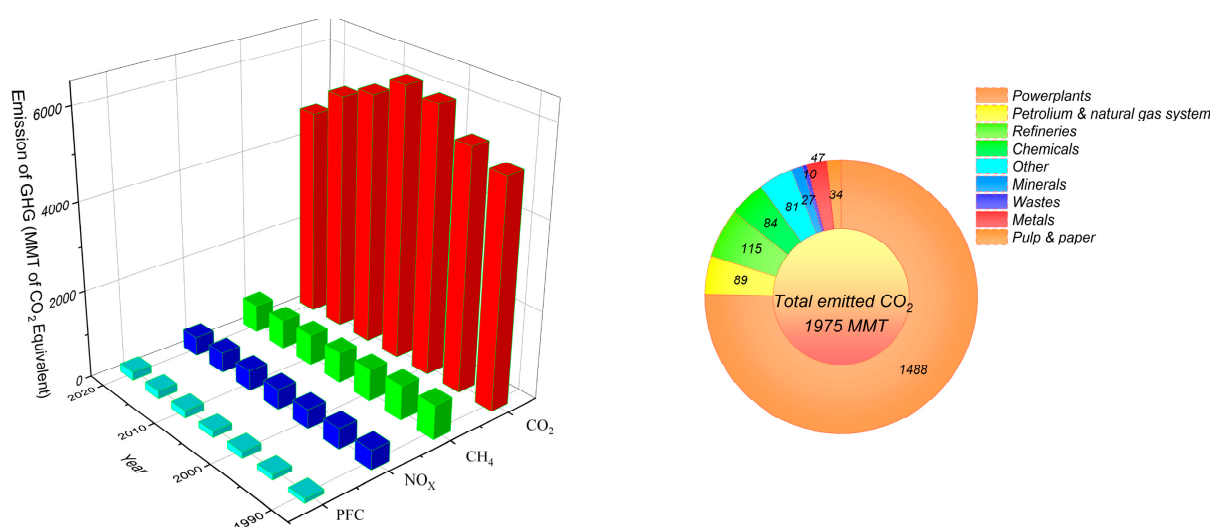


Figure 3. Amount of greenhouse gas emissions during the period of 1990–2020 and CO₂ emissions from different sectors in the USA.

2. Absorption-Based Carbon Capture

2.1. Physical Absorption

Henry's law is considered the base of the physical absorption process for CO₂ capture. The operating condition should have high pressure and low temperature in the case of CO₂ absorption, whereas it is just the opposite for CO₂ desorption. Several solvents are already being used commercially to produce synthesis gas and hydrogen [18,19]. In recent years, ionic liquid (IL) is achieving much attention for physical absorption due to its uncommon characteristics such as non-toxicity, lower vapor pressure, higher thermal stability, and high polarity. Table 1 summarizes the physical absorption processes with applicable absorbent materials, advantages, and applications.

Table 1. Several physical absorption processes with applicable absorbent materials, advantages, and applications.

Absorption Process	Used Absorbent	Advantage	Application
Selexol	Dimethyl ether/propylene glycol	Low vapor pressure, low toxicity, and less corrosive solvent	Remove both CO ₂ and H ₂ S at low temperature
Rectisol	Methanol	Less corrosive and more stable absorbent	CO ₂ removal from sulfur-containing gas
Purisol	N-methyl pyrrolidone	Low energy consumption	CO ₂ removal from sulfur-containing gas
Morphysorb	Morpholine	Operation cost is 30% to 40% lower than that for Selexol	Selective removal of H ₂ S from CO ₂
Fluor	Propylene carbonate	Solubility of CO ₂ in the solvent is high	Suitable for gases containing CO ₂ partial pressure higher than 60 psig

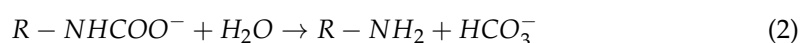
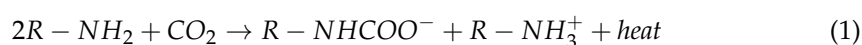
2.2. Chemical Absorption

The most researched and established approach, the chemical absorption process, normally consists of two phases. In the chemical absorption process, the exhaust CO₂ mixes with a chemical solvent through a chemical reaction and forms an intermediate compound whose bond is weak enough to get back the original form of CO₂ and solvent by applying heat to the intermediate compound. In the first step, when CO₂-containing gas is introduced from the bottom into a column of packed bed absorber, the CO₂ reacts with the absorbent. In the second step, the CO₂-rich absorbent enters a stripper where it is regenerated before being pumped back to the absorber for cyclic applications. The process' compression, transportation, and storage portions receive the net CO₂ emissions from the stripper. In regard to chemical absorption, CO₂ capture technology, alkali absorbents, inorganic and organic solvents with amine bases, and ILs are the most employed absorbents. Amine aqueous solvents were initially applied for chemical absorption CO₂ capture. After further research on chemical absorption technologies, mono-ethanolamine (MEA) appeared to be the most applicable amine solvent due to its high absorptivity of CO₂.

3. Developed Chemical Absorption Processes

3.1. Amine-Based Absorption

Amines are ammonia-derived compounds where at least one hydrogen molecule is replaced by an organic compound. Different amine solvents such as MEA, DEA, and MFEA have been applied for the last few decades in natural gas industries, where they also exhibit the potential to capture CO₂, making them attractive candidates in carbon capture technologies [20]. The CO₂ capture process via amine-based absorption follows the reactions (Equations (1) and (2)), where R is an alkanol group. The amine reacts as a weak base to neutralize acidic CO₂ and forms carbamate (R-NHCOO[−]) through Reaction (1) and finally forms bicarbonate in the presence of moisture that follows Reaction (2) [18].



According to this mechanism, most of the CO₂ absorbed will cause the liquid amine capture system to produce bicarbonate. The binding between the absorbent and CO₂ is weakened by either raising the temperature or decreasing the pressure of the solution, which removes the CO₂ from the liquid amine solvent to a water stream and regenerates the solvent for further usage [21]. Higher energy requirements for solvent regeneration, slower reactivity rates, and lower absorption rates are the major barriers to conventional

amine-based solvents. To withstand such limitations, Bitar Karami et al. have reported that the nonporous hyper-cross-linked polymeric (HCP) networks can be employed as CO₂ absorption rate promoters, and they can dramatically increase CO₂ capture via absorption in N-methyldiethanolamine (MDEA) sorbents [22]. They synthesized two HCPs, namely polystyrene (HCP-S) and benzene (HCP-B), from cost-effective monomers and suspended these polymeric in MDEA solutions to form a novel slurry solvent. They discovered that by employing HCP-B and HCP-S in MDEA solution, the CO₂ absorption rate was increased by 130 and 253%, respectively.

3.2. KMALC

The Kerr-McGee/AGG Lummus Crest (KMALC) is an emerging amine-based adsorption technology to capture CO₂ from flue gases [23,24]. This technology utilizes 15–20 wt% MEA solution for CO₂ absorption, and the low cost of MEA makes this approach more applicable for CO₂ capture. Researchers reported that a maximum of 800 tons/day of CO₂ can be absorbed via KMALC processes, whereas 8000 tons/day of CO₂ was emitted from the reported fossil fuel power plant [25].

3.3. Fluor EFG + Process

The Fluor Economic FG PlusSM is an experimentally proven technology that can be employed to capture CO₂ from flue gases. For capturing CO₂ from coal-based power plants' flue gases, Fluor has been improved to further reduce the energy consumption, operating and capital costs, and environmental influences of CO₂ capture plants in commercial applications. This technology has the license to be employed in 28 plants around the world. In EFG⁺ technology, a chemical solvent that absorbs CO₂ via an exothermic reaction has been used. NRG Energy designed, constructed, and operated a carbon capture demonstration plant at WA Parish Electric Generating Station, and in this project, they demonstrated the ability to capture 90% inlet CO₂ from a 240 MW equivalent flue gas slipstream that was exhausted from a coal-fired boiler [26]. Among recent Fluor FG⁺-based projects, the Electric Power Research Institute (EPRI), along with California Resources Corporation (CRC) and Fluor Corporation, has investigated Fluor's economic FG OlusTM-based carbon capture technology on a natural gas-fired combined cycle power plant in California. This carbon capture technology was integrated with the Elk Hills Power Plant (EHPP), which is located near Kern County, California. Flue gas can be divided in two ways: in one way, 79% of flue gas moves through Fluor's EFG⁺ unit, and in another way, 21% of flue gas is ventilated via the stack. The CO₂ capture unit can capture 90% inlet CO₂ from the flue gas with 97+% CO₂ purity, and 4000 tons of CO₂/day can be captured through this carbon capture technology in this plant [27].

3.4. KM-CDR Process

Mitsubishi Heavy Industries, Ltd. (MHI) and the Kansai Electric Power Co., Inc. (KEPCO, Osaka, Japan) have developed a CO₂ capture technology based on the KM-CDR (Kansai Mitsubishi Carbon Dioxide Recovery) process and have integrated the carbon capture plant with the Petra Nova Project, which is considered the largest CO₂ capture plant. In this project, a new solvent for CO₂ capture was prepared, and this new solvent showed better performance compared to KS-1TM in terms of solvent degradation, emissions, and steam consumption rate. The new solvent possessed 50% less solvent degradation, 50% less solvent emission, and approximately 5–10% less steam requirement compared to KS-1TM [28]. MHI and the research and development activities of the Nanko Pilot Plant have started the CO₂ capture operation at a 25 MW coal-based power plant at Southern Company's Plant Barry, which is operated and developed by Alabama Power. This plant is considered the world's first carbon capture technology integrated with a coal-based power plant. It was estimated that approximately 150,000 tons (500 tons/day) of CO₂ can be captured annually with a CO₂ capture rate of 90+% [29]. MHIENG's (Mitsubishi Heavy Industries Engineering, Ltd., Singapore) latest process, the KM-CDR process with KS-1TM,

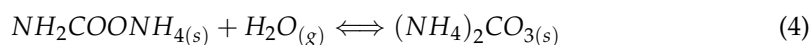
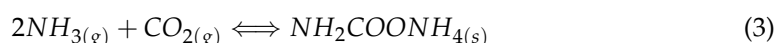
investigated the near-zero emission and CO₂ ratio and found a 99.5% CO₂ capture ratio. With their default system, it was found that at a 99.5% CO₂ capture ratio, the reboiler steam and solvent rate increased by 15% and 25%, respectively, whereas by employing 50% more absorption packing and maintaining the operating expenditure (OPEX) (\$/tonne CO₂) as the base case, a 50% reduction of reboiler steam and solvent rate can be achievable [30].

3.5. Chilled Ammonia Process (CAP)

Eli Gal has patented his research on the chilled ammonia process (CAP) that can absorb CO₂ at much lower temperatures, and this technique also minimized the density of moisture and volatile and acidic elements existing in the gas. CAP also minimizes NH₃ slip at a lower amount and controls the NH₃ loss to less than 6% of the solvent compared with the conventional aqueous ammonia process [31]. Daniel Sutter et al. developed an advanced ammonia-based CO₂ capture technology that controlled the solid formation chilled ammonia process (CSF-CAP). A comparison of CSF-CAP was carried out with conventional CAP (L-CAP) technology since a solid handling section, and from the scrutinized comparison it was found that in the CSF-CAP process reduction of steam, the requirement was minimized by 30% for CO₂ desorption and the SPECCA (Specific Primary Energy Consumption for CO₂ Avoided) by 17% [32]. There are some existing limitations of CAP technologies, including low absorption rates, the requirement of multiple absorber vessels, and the volatility of ammonia [33].

3.6. Aqueous Ammonia Scrubbing

Ammonia is considered a potential alternative to MEA, as it possesses higher availability, higher corrosion resistance, lower solvent degradation, lower expense, and higher CO₂ absorption capacity compared to MEA. Aqueous ammonia can capture CO₂ with higher purity, and it also captures other coexisting elements in flue gases such as SO₂, NO_x, HCL, HF, and different acidic gases. This process can minimize the cost of a plant by eliminating the acidic gas clean-up system, and the SO_x and NO_x can be converted to fertilizer that can make money and reduce the plant's cost. The CO₂ absorption by ammonia is carried out following Equations (1)–(3), where in the first step, ammonia reacts with CO₂ and produces ammonium carbamate in dry conditions (Reaction (3)). After adding some moisture, ammonium carbonate is formed from ammonium carbamate (Reaction (4)), and then it is converted into ammonium bicarbonate (Reaction (5)).



Aqueous ammonia scrubbing is more advantageous than amine-based processes, as ammonia-based solvents consume a lower amount of energy for solvent regeneration and are less expensive than amine-based processes [34]. There are also some limitations of aqueous ammonia solvents compared to amine-based solvents, including the requirement for a larger absorber area, higher initial capital cost, and lower CO₂ absorption capacity [35]. Moreover, a higher loss of ammonia causes higher uses of wash water, which results in a higher recovery cost of ammonia. To solve the problem of ammonia loss, Hamed Rashidi et al. developed an ammonia-glycerol hybrid solvent to capture CO₂ glycerol, which is a byproduct of biodiesel has hydroxyl groups which can bind ammonia molecules and hence the vaporization of ammonia reduces. Their experimental output reveals that applying glycerol with aqueous ammonia causes an increase in the mass transfer coefficient and a reduction in the vapor pressure of ammonia that results in lower losses of ammonia in the CO₂ capture system [36].

3.7. Amino Acid Absorption

The usability of amino acids in CO₂ capture systems makes them a potential alternative to amine-based absorption systems. There are some crucial limitations in conventional amine-based solvents, such as the volatility of solvents [37,38], degradation of solvents [39], lower corrosive resistance [38,39], higher energy requirement for regeneration [38,40], and lower CO₂ loading capacity [41]. On the other side, amino acid solvents possess some attractive features, such as a higher corrosion resistance, higher degradation resistance, lower volatility [37,38], and lower energy requirements compared to amine-based solvents. Moreover, the utilization of amino acids in CO₂ is also preferable due to their natural availability and biodegradability, and so, these solvents can minimize environmental hindrances. Additionally, hydrophilic amino acids are capable of operating under a wide range of temperatures and pressure conditions required for carbon capture [42]. Cheng et al. reported an ion pair arginine-arginine carbamate derived from L-arginine (amino acid) to capture CO₂ from gases, and their study expanded the understanding behavior of L-arginine and other amino acids for CO₂ absorption [43]. The application of amino acid anions in CO₂ absorption can enhance the CO₂ uptake twofold for some amino groups, and possible reactions were reported by Stefano et al. [44]. Maria Castro analyzed the use of sodium (Na) salts of aqueous solutions of different amino acids such as glycinate and proline for CO₂ capture via chemical absorption, and they experimented with this solution in a bubble column reactor under various testing conditions such as flow rates of flue gas and solvent concentrations [45]. Carboxylic groups have caused the major differences in reactions and absorption rates, and it has also been reported that glycinate possessed greater CO₂ loading than mono-ethanolamine (MEA) due to higher destabilization of carbamate of glycinate. To minimize the energy requirement for solvent regeneration, different crystallization processes can be employed with aqueous amino acid solvents. The crystallization of bis-iminoguanidines (Glyoxal-bis-iminoguanidine or GBIG) employed with aqueous amino acids is being developed as a potential technology to reduce the energy penalty from a CO₂ capture plant by minimizing the energy consumption for solvent regeneration, and the CO₂ loading capacity was reported as 1.36 mol per mol of GBIG [46].

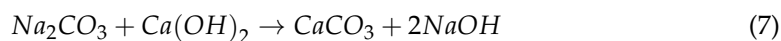
3.8. Dual Alkali Absorption (DAA)

Alkali metal carbonate solvents are a potential alternative to the conventional solvents applied in CO₂ capture technologies, and these alkali-based solvents can be employed through dual alkali absorption (DAA) processes. There are some attractive advantages to applying this CO₂ process, including lower degradation, lower emissions, and lower costs, whereas the limitations are a lower rate of CO₂ mass transfer and a lower and slower rate of reaction. To overcome these limitations, Yang Li et al. developed a dual alkali solvent (DAS) that is different from the conventional solvents in terms of phases as DAS has two aqueous phases. In the first phase, an organic alkali 1-(2-hydroxyethyl) piperazine (HEP) was employed for CO₂ absorption, while in the second phase, a mixture of K₂ CO₃/KHCO₃ aqueous solution and KHCO₃ precipitate was employed for CO₂ stripping. From their experimental investigation, they revealed that by implementing DAS to capture CO₂, 55.7% of energy can be saved without lowering the CO₂ absorption efficiency from 90% [47]. This novel system has faster CO₂ absorption kinetics and a low energy need for solvent regeneration, which are advantages of both amine and alkali metal carbonate, respectively.

3.9. Alkaline Solvent Absorption

Alkaline solvents such as sodium hydroxide or potassium hydroxide are potential solvents that are widely applied for CO₂ from the air. When air meets such absorbents, then CO₂ is captured via a chemical reaction following Reaction (6), where CO₂ reacting with NaOH forms sodium carbonate. Normally, the regeneration of this type of solvent (NaOH) is carried out by dosing another alkaline solvent (Ca(OH)₂), and calcite forms due to this Reaction (7). For further treatment, CaCO₃ is heated at 700 °C to form calcium oxide

(CaO) and CO₂ through Reaction (8), and then, by rehydrating CaO, regenerated Ca(OH)₂ can be obtained through Reaction (9) [48].



Alkali absorption is advantageous in terms of solvent availability and the cost-effectiveness of the solvent, but the treatment of CaCO₃ is much more expensive, which hinders the economic feasibility of these absorbents.

4. Different Types of Absorbents

4.1. Polymeric Solvent

In recent times, polymeric solvents have attracted much attention for further research due to their applicability in CO₂ capture technologies. There are some potential conveniences of these technologies, including lower viscosity, thermal stability, hydrophobicity, lower capital and operation costs, simplified installation and maintenance, and lower volatility. Among several polymeric solvents, a few that have emerged, such as polydimethylsiloxane (PDMS), polyesters, and polyethers (Pes), are remarkable. Miller et al. experimented with several solvents to compare their performances regarding the selectivity of CO₂, and these solvents included polypropylene glycol dimethyl ether (PPGDME), polyethylene glycol dimethyl ether (PEGDME), polydimethyl siloxane (PDMS), perfluoropoly ether (PFPE), polybutylene glycol diacetate (PBGDAc), and polypropylene glycol diacetate (PPGDAc) [49]. Their experiment revealed that PDMS and PPGDME were the most promising alternative for CO₂ capture from a mixed stream. Xingguang et al. prepared novel absorbent amine-infused hydrogels (AIHs) by adding hydrogels with organic amine solutions, and they found where hydrogels ensure the increased interfacial area to capture the higher amount of CO₂. Their result also showed that the CO₂ uptake capacity of AIHs is higher than that of aqueous amine solutions operating under the same conditions. Kim et al. prepared AIH in a disparate way than before by just adding a monoethanolamine (MEA) solution with dried hydrogel particles, and their results showed that AIHs showed higher CO₂ uptake capacity and selectivity than MEA solutions [50]. Dimethyl ether of polyethylene glycol (DMEPEG) is a novel polymeric solvent that offers potential conveniences such as being suitable for both carbon and sulfur contents, less corrosion, and a lower power consumption rate. In recent times, researchers have developed several integrated systems where they prepared carbon capture technologies by adding several polymers and copolymers with membrane-based materials. Tao et al. prepared such technologies to examine the effect of several copolymers by adding them during membrane fabrication time; they applied commercially available poly(2,6-dimethyl-1,4-phenylene oxide) (PPE) and additives including polyethylene glycol (PEG) and a PEG–PDMS copolymer (commercially known as IM22). After the experiment, they compared with pure PPE membrane, and they found that CO₂ permeability rose nearly 5 times after adding 50 wt% IM22 and rose 4 times after adding 40 wt% PEG. Table 2 summarizes the merits and demerits of different polymeric solvents.

Table 2. Merits and demerits of different polymeric solvents.

Polymeric Solvent	Merits	Demerits	Ref.
Hydrophobic polymeric solvents (PPGDME & PDMS)	Selective CO ₂ absorption.	Requires higher temperature.	[49,51]
Amine-infused hydrogels (AIHs)	Solid sorbents, can be easily manufactured at a large scale, fast kinetics, minimal performance degradation after recycling.	Tendency to agglomerate with each other without mixing, which resulted in decreased CO ₂ absorption capacity.	[50,52,53]
Di-Methyl-Ether of poly-Ethylene-Glycol (DMEPEG)	Suitable for both CO ₂ and H ₂ S. Less corrosive than chemical solvents. Consume a lower amount of power. Lower heat duty for gas desorption.	Varieties in solvent processing ability within a specific tower.	[54,55]
Low-viscous branched polymers	High capacity for CO ₂ . Large selectiveness.	For post-combustion CO ₂ capture, poly ethers are not suitable.	[56–58]
PEG-PDMS copolymer	Well-suited for precombustion carbon capture. Selective CO ₂ capture.	The existence of flowing gas may cause severe foaming,	[59,60]
PDMS solvents	Selective uptake of CO ₂ from different gases (H ₂ S, H ₂ O). Higher solubility and thermal stability.	A fall in CO ₂ solubility may be caused due to increased temperature. High cost for operational processes.	[61,62]

4.2. Poly-Ionic Liquid

Poly-ionic liquids (PILs) are a class of ionic liquids (ILs) that are effective as CO₂ absorbents. These liquids are characterized by the presence of multiple ionic groups in the molecule, which allows for a high level of CO₂ binding. PILs have been studied extensively in recent years due to their potential use in carbon capture and storage (CCS) technologies. One of the main advantages of PILs as CO₂ absorbents is their high CO₂ binding capacity. This is due to the presence of multiple ionic groups in the molecule, which can form multiple complexation sites for CO₂. Additionally, PILs are more effective at binding CO₂ than traditional amine-based absorbents, as they can form stronger complexes with CO₂. Another advantage of PILs is their thermal stability. Unlike traditional amine-based absorbents, which can degrade at high temperatures, PILs can maintain their CO₂ binding capacity even at high temperatures. This makes them well-suited for use in CCS technologies that involve high-temperature processes, such as post-combustion capture. PILs have also been found to be highly selective for CO₂, which means that they have a low affinity for other gases, such as N₂ and O₂. This is important in CCS applications, as it allows for a higher concentration of CO₂ to be captured. Additionally, PILs are non-corrosive, which is a significant advantage over traditional amine-based absorbents that can be corrosive to certain metals. Chau et al. developed a novel cyclic -5-valve pressure swing membrane absorption where they applied ionic liquid (1-butyl-3-methyl-imidazolium dicyanamide) as an absorbent, aiming to separate CO₂ from lower temperature syngas [63]. Their experimental results revealed the potentiality of their system, and 95.5% CO₂ can be yielded via that mechanism. Ionic liquid membranes are potential elements for CO₂ absorption, and these can be classified into supported ionic liquid membranes (SILMs) and

quasi-solidified ionic liquid membranes (QSILMs) [64]. Two approaches to utilize ionic liquid as membrane material for CO₂ absorption are shown in Figure 4.

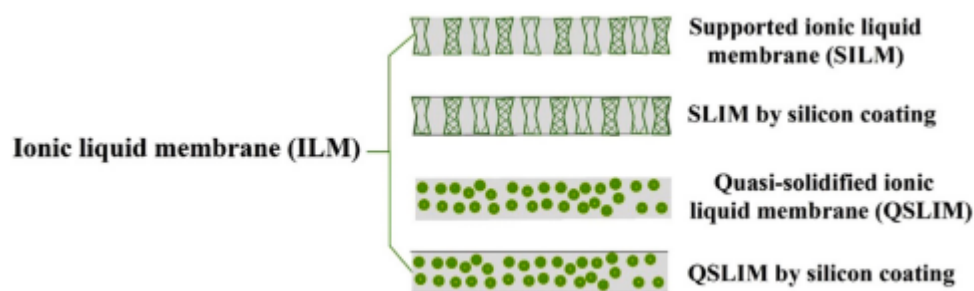


Figure 4. Utilizing ionic liquid as membrane material [64]. © 2016, copyright permission, Elsevier.

In addition, PILs are highly reusable, which is a major advantage over traditional amine-based absorbents that must be replaced after a certain number of usages. PILs can be regenerated by heating them to release the absorbed CO₂, which can then be captured and stored. This process can be repeated multiple times, which makes PILs a cost-effective option for CCS. Several different types of PILs have been studied for use as CO₂ absorbents. These include quaternary ammonium-based PILs, phosphonium-based PILs, and imidazolium-based PILs. Each of these types of PILs has its unique properties, and researchers are working to optimize the CO₂ binding capacity and selectivity of each type.

4.3. Nano Sorbent

4.3.1. Nanofluids for CO₂ Absorption

Nanotechnology is a novel technology that is broadly utilized in numerous energy systems to produce energy in an energy-friendly, economical way. In recent years, CO₂ absorption via nanofluids has attracted much attention due to this method having a higher capacity for CO₂ absorption. The concept of nanofluids was first proposed by Choi, and he defined nanofluids as dispersed nano-sized materials into the soluble base material. Numerous nanomaterials, such as nanorods, droplets, nanowires, nanoparticles, and nanofibers, can be applied to prepare nanofluids, whereas water-soluble or non-water-soluble liquids (Al₂O₃, TiO₂, SnO₂) can be employed as base materials [65].

4.3.2. Nano-Emulsions for CO₂ Capture

Nano-emulsions are a new class of materials that have recently been proposed as potential absorbents for carbon dioxide (CO₂) capture. These materials are composed of small droplets of one liquid suspended in another liquid, and they have unique properties that make them well-suited for CO₂ capture applications. One of the main advantages of nano-emulsions as CO₂ absorbents is their high CO₂ uptake capacity. The small droplets of the nano-emulsion have a large surface area to volume ratio, which allows them to efficiently capture CO₂. Additionally, nano-emulsions can be formulated to have a high selectivity for CO₂, meaning that they can effectively capture CO₂ while leaving other gases such as N₂, O₂, and CH₄ behind. Another advantage of nano-emulsions is their stability. These materials are thermodynamically stable and can remain stable over a wide range of temperatures and pressures. This makes them well-suited for use in CCS applications, which often involve capturing CO₂ at high temperatures and pressures.

Nano-emulsions can be prepared by a variety of methods, including high-pressure homogenization, ultrasonication, and micro-fluidization. The properties of the nano-emulsion can be tailored by adjusting the composition and concentration of the different components, such as the type of oil, surfactant, and co-surfactant used. One of the most common types of nano-emulsion used as CO₂ absorbent is oil-in-water (O/W) nano-emulsion, which is composed of small droplets of oil suspended in water. The oil droplets can be formulated to have a high CO₂ uptake capacity, and the water can act as a solvent

for the CO₂. Research has shown that O/W nano-emulsion can adsorb up to 40 times more CO₂ than bulk oil, due to the high surface area to volume ratio of the droplets [1]. Another type of nano-emulsion that has been proposed as a potential CO₂ absorbent is the water-in-oil (W/O) nano-emulsion, which is composed of small droplets of water suspended in oil. These nano-emulsions have a higher density than the O/W nano-emulsion, which makes them more suitable for use in CCS applications where the CO₂ is being captured at high pressures. W/O nano-emulsions have been reported to have a high CO₂ adsorption capacity and stability at high pressures and temperatures. A third type of nano-emulsion that has been studied for CO₂ absorption is the multiple emulsion, which is composed of droplets of one liquid (typically water) suspended within droplets of another liquid (typically oil), which are then suspended in a third liquid (typically water). These emulsions have been found to have high CO₂ adsorption capacity and stability, as well as the ability to separate CO₂ from other gases, making them promising candidates for CCS applications.

Despite the promising properties of nano-emulsions for CO₂ absorption, there are still some challenges that need to be overcome before they can be used in real-world applications. One of the main challenges is the cost of producing nano-emulsions on a large scale. The methods used to prepare nano-emulsions are often energy-intensive, which can make them more expensive than other CO₂ absorbents. Additionally, nano-emulsions can be difficult to separate from the captured CO₂, which can also add to the cost of the overall process.

4.4. Amino Acid Solution

Amino acid salt solutions are being recognized as promising absorbents to be used in CO₂ capture technologies due to their several amenities, such as higher surface tension, minor absorbent loss, lower oxidative degradation, and evaporation rate while being environmental [37–39]. AASs are normally produced through the reaction of alkaline substances and amino acids, while there are more than 20 standard amino acids for which diverse AASs can be observed. The most common amino acids that are employed to produce AASs include arginine, glycine, glutamine, lysine, and taurine, while potassium is the most common ingredient used to produce the AAS solution. Potassium lysine was recognized as a more effective absorbent solution due to having a higher CO₂ loading capacity compared to MEA and other AASs. In the case of AASs, the environmental pollution is lower because of the easy disposal of absorbed solutions due to their natural reaction, ionic nature, and extraordinary biodegradation possess. Ramazani et al. experimented with a MEA+PL solution to investigate the effect of the addition of PL and MEA on CO₂ loading capacity and found that with an increasing PL/MEA ratio, the loading capacity and corrosion rate of the blend solution increased [66].

4.5. Hydroxide Absorbent

4.5.1. Potassium Hydroxide

The aqueous solutions of alkali metal hydroxides have gathered much attention from scientists and researchers for employing CO₂ capture technologies due to their lower energy consumption and minimal negative influence on the environment and ecosystem. Rastegar et al. [67] experimented with aqueous KOH to investigate the effects of stirring and temperature on CO₂ absorption, and their results revealed that just by increasing the stirring of the mixer from 50 to 150 rpm, the absorption rate raised by 32%, whereas when they increased the temperature from 22 °C to 65 °C, CO₂ absorption dropped by 2.4%. Mourad et al. experimented with different effects on CO₂ absorption, such as CO₂ inlet concentration, KOH concentration, temperature, gas flow rate, pressure, and found that KOH concentration did not influence CO₂ absorption [68]. However, Firman et al. found different results from their experimental investigation, and their results revealed that an increment occurred in CO₂ absorption when KOH concentration was increased [69].

4.5.2. Sodium Hydroxide-Based Hybrid Absorbents

Sodium hydroxide (NaOH) has been an extensively studied topic for CO₂ absorption since the 1940s; however, at that time, NaOH was not studied for CO₂ capture [70,71]. Sodium hydroxide is considered an alkaline absorbent of acidic gases due to its ability to capture CO₂ at ambient temperature as well as its fast kinetics, availability, and reasonable price [72]. Traditional procedures followed a water wash with caustic solutions of NaOH (5–15 wt%). Since the wasted caustic creates a disposal problem as expected, it must first be neutralized with acid before being properly disposed of following current environmental and hazardous waste requirements. Aside from that, the annual production of hundreds of millions of tons of sodium carbonate and sodium bicarbonate makes the CO₂ absorption from flue gases commercially relevant. However, NaOH is generated as waste in some chemical processes, such as the manufacturing of chlorine, which lowers the price of CO₂ removal from flue gases [73]. According to study findings, increasing the concentration of NaOH reduces energy loss but increases corrosion rate and solution viscosity. Alkali metal hydroxides such as sodium hydroxide are considered a well-established technology for CO₂ capture; however, the major drawbacks of it are its high corrosion rate and energy loss. In this regard, glycerol can be applied as a potential element in aqueous NaOH solutions which intensifies the mass transfer performance as well as minimizes the offensive wastes and related pollutions. Sheyda et al. experimented with such NaOH-Gly solution to investigate the effect of glycerol on the CO₂ capture performance of aqueous NaOH solution and found that the presence of glycerol in the solution caused CO₂ absorption efficiency of more than 97%, as shown in Figure 5 [74].

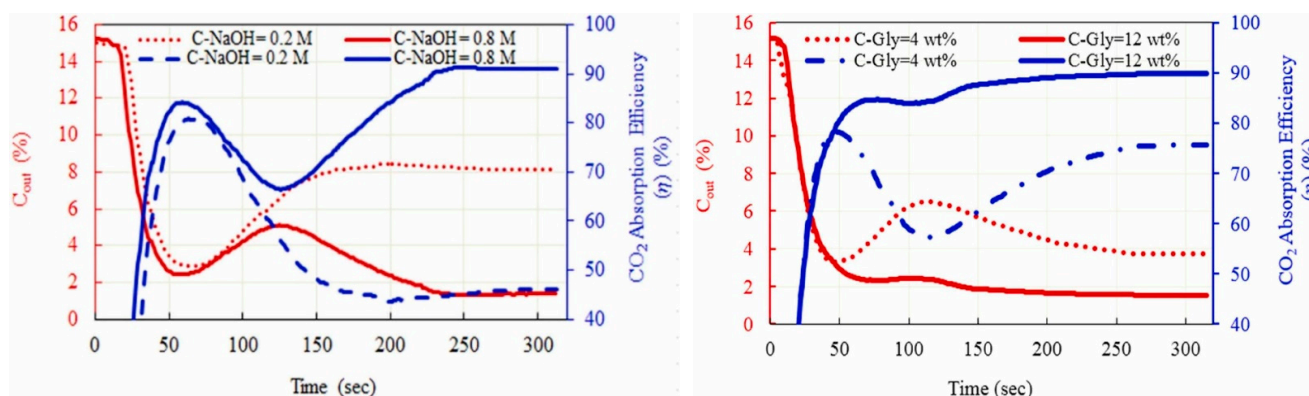


Figure 5. CO₂ outlet concentration and CO₂ absorption efficiency versus time under different NaOH concentrations ($Q_g = 200$ mL/min, $C_{\text{Gly}} = 8$ wt%, $T = 25$ °C) and glycerol concentration at ($Q_g = 200$ mL/min, $C_{\text{NaOH}} = 0.5$ M and $T = 25$ °C) [74]. Copyright permission © 2022 Published by Elsevier Ltd.

4.6. Carbonate Absorbent

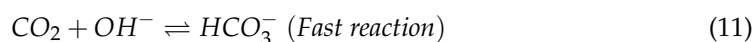
4.6.1. Potassium Carbonate

Potassium carbonate (K₂CO₃) is a favorable CO₂ absorbent due to it having some attractive properties such as relevant cost, low degradation rate, minimal toxicity, solubility in carbonate/bicarbonate solution, and less energy consumption. Zhao et al. caused the formation of sesqui-hydrated potassium carbonate crystal (K₂CO₃·1.5H₂O) for the lower energy requirement of K₂CO₃ [75]. Moreover, Thee et al. stated that 37% of the energy requirement can be minimized by utilizing potassium carbonate during regeneration processes [76]. Despite having such advantages, this absorbent also brings a limitation, which is its poor mass transfer rate. To overcome this limitation, researchers have carried out several experiments to investigate the effect of different promoters that can be applied with K₂CO₃ to increase its performance.

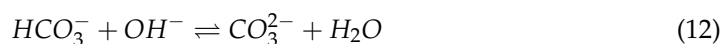
The overall reaction of CO₂ and potassium carbonate is as follows:



Bicarbonate formation:



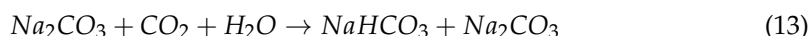
Carbonate formation:



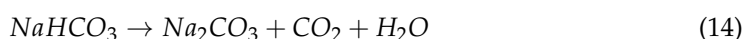
Hu et al. discussed detailed information on different promoters for potassium carbonate to be applied in CO₂ capture technologies [77]. Zheng et al. proposed a novel [Cho] [Pro] + K₂CO₃ absorbent for CO₂ capture and experimented with different weights of the solution to investigate CO₂ absorption and desorption performances [78]. Choi et al. experimented with K₂CO₃-based absorbents for CO₂ absorption to study the influences of promoters, evaluating the mass transfer coefficient for a specific absorbent [79]. Their experimental results revealed that the mass transfer rate was highest for K₂CO₃+CL-4 among other promoted K₂CO₃ solutions, and it was quite similar to commercial MEA solutions.

4.6.2. Sodium Carbonate

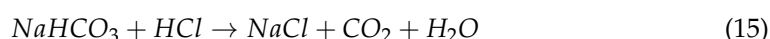
Sodium carbonate, also known as soda ash, is a chemical compound that has been used as a CO₂ absorbent in various industrial processes. Sodium carbonate has been found to be an effective and low-cost option for removing CO₂ from gas streams. The CO₂ capture process using sodium carbonate typically involves the reaction of CO₂ with sodium carbonate to form sodium bicarbonate and carbonate ions. This reaction is exothermic, which means it releases heat, and it can be represented by the following equation:



Na₂CO₃ is a strong base, and it can effectively capture CO₂ from flue gas, biogas, and other sources. It has been found to be highly selective for CO₂ over other gases, which makes it an efficient absorbent. Additionally, sodium carbonate can be easily regenerated for reuse, which makes it an attractive option for CO₂ capture. Research has shown that it can capture up to 90% of CO₂ from flue gas and biogas. It has also been found to be stable and durable, with a service life of up to 10 years. There are several ways to regenerate sodium carbonate after it has been used to capture CO₂. One method is to heat the sodium bicarbonate, which releases CO₂ and regenerates the sodium carbonate. This process is known as thermal regeneration, and it can be represented by the following equation:



Another method for regenerating sodium carbonate is to treat it with an acid. This process is known as chemical regeneration, and it can be represented by the following equation:



Both methods are effective for regenerating sodium carbonate, but thermal regeneration has been found to be more energy-efficient. Sodium carbonate has also been used in combination with other absorbents to enhance its CO₂ capture capabilities. For example, research has shown that sodium carbonate can be used in combination with amines to capture CO₂ from flue gas. The use of amines in combination with sodium carbonate has been found to increase the CO₂ capture capacity and improve the efficiency of the process. Valluri et al. [80] carried out experiments to investigate the performance of several reagents with frother-assisted NaCO₃ slurry in a pilot gas–liquid column. The added surfactant

increased the surface area of NaCO_3 to absorb more CO_2 . Hornbostel et al. experimented with CO_2 absorption with Na_2CO_3 -filled capsules and compared them with the amine solvent capsules [81]. They found that for similar dimensions, Na_2CO_3 -filled capsules caused less energy penalties, and they also revealed that carbonate-based solvents could compete with fast-reacting amine-based solvents.

4.6.3. Calcium Carbonate

Calcium carbonate (CaCO_3) is a naturally occurring compound that is commonly found in rocks such as limestone, marble, and chalk. It has recently been proposed as a potential CO_2 absorbent for carbon capture and storage (CCS) technologies. The use of calcium carbonate as a CO_2 absorbent is attractive due to its low cost, non-toxicity, wide availability, and environmentally friendly characteristics. Another advantage of calcium carbonate is its high CO_2 uptake capacity. Calcium carbonate can effectively capture CO_2 through a process known as carbonation. When CO_2 comes into contact with calcium carbonate, it reacts to form calcium bicarbonate and water. This reaction is exothermic, meaning it releases heat, which can be recovered and used to generate electricity. Moreover, the reaction is reversible, which means that the captured CO_2 can be released from the calcium carbonate by heating it, making it a potential option for CO_2 utilization. Hong et al. [82] studies CaCO_3 polymorphs to evaluate their performance as CO_2 absorbents and compared this absorbent with several amine-based absorbents such as MEA, MDEA, and DEA. They found that CaCO_3 had a 100% recovery rate in the MEA solution. They reported that when amine solutions came into contact with the CaCO_3 surface, they restricted crystal growth. Calcium carbonate can be used in different forms as a CO_2 absorbent. The most common form is precipitated calcium carbonate (PCC), which is made by reacting calcium oxide (CaO) and CO_2 . PCC can be used in a variety of industrial applications, including as a filler and coating material, and it can be produced in a variety of particle sizes and shapes. Additionally, there are other forms of calcium carbonate, such as ground calcium carbonate (GCC), which is made by grinding natural limestone and marble, and nano calcium carbonate (NCC) which is made by grinding PCC to a very fine powder. Each form has its unique properties and applications.

One of the main challenges in using calcium carbonate as a CO_2 absorbent is its low reactivity and solubility compared to some other absorbents. This means that it requires a longer contact time and higher concentrations of CO_2 to effectively capture the gas. Researchers are working to overcome this challenge by developing new methods to increase the reactivity of calcium carbonate, such as by modifying its surface or adding catalysts. However, CaCO_3 takes many acids for CO_2 absorption. To find out a suitable solution for this limitation Chen et al. reported adding a molten carbonate electrolyzer to capture CO_2 without using other additives such as lithium salts [83]. They also stated that their study provided a guideline to utilize CaCO_3 as a mediator to get pure O_2 from CO_2 in an enviro-economically friendly way.

4.7. Amine-Based Absorbents

4.7.1. Primary Amines

Primary amines have been studied as a potential solution for capturing carbon dioxide (CO_2) from industrial flue gases. These amines are a class of organic compounds that contain a nitrogen atom with a lone pair of electrons and at least one hydrogen atom bonded to it. They are effective CO_2 absorbents due to their chemical reactivity towards CO_2 . One of the main advantages of using primary amines for CO_2 capture is their high capacity for CO_2 absorption. They can effectively remove CO_2 from gas streams at low concentrations, making them suitable for use in industrial settings. Additionally, primary amines are relatively low-cost and easily available, making them a cost-effective option for CO_2 capture. The process of CO_2 capture using primary amines typically involves the use of an amine solution, such as monoethanolamide (MEA), which is passed through the flue gas stream. As the flue gas comes into contact with the amine solution, the CO_2 reacts

with the amine, forming a carbamate species. This carbamate species can then be separated from the flue gas stream, allowing the CO₂ to be captured. The captured CO₂ can then be further processed and utilized for various industrial purposes. Akram et al. studied a 30% MEA solution and found the absorption efficiency to be 90%, which was decreased to 89.6% due to an increase in the MEA at 40 wt% [84]. They also reported that the energy requirement was increased by 12.3%, and the solvent degraded thermally due to increasing the regeneration temperature.

One of the main challenges in using primary amines for CO₂ capture is their tendency to degrade over time. This can lead to a decrease in their effectiveness as CO₂ absorbents, as well as the formation of byproducts that can be harmful to the environment. To mitigate this, research is ongoing to develop more stable amine solutions and to improve the overall process of CO₂ capture using primary amines. Another challenge is the energy consumption associated with the regeneration of the amine solution. Amine solutions used in CO₂ capture are typically heated to high temperatures to release the CO₂, which can be energy-intensive. However, researchers are exploring various methods to reduce energy consumption, such as the use of membrane separation or pressure swing adsorption.

4.7.2. Secondary Amines

Secondary amines, like primary amines, have been studied as a potential solution for capturing carbon dioxide (CO₂) from industrial flue gases. These amines are a class of organic compounds that contain a nitrogen atom with two hydrogen atoms or alkyl groups bonded to it and they are effective CO₂ absorbents due to their chemical reactivity towards CO₂ [85]. One of the main advantages of using secondary amines for CO₂ capture is their high selectivity towards CO₂. They can selectively remove CO₂ from a gas stream containing other gases such as nitrogen, oxygen, and water vapor. Additionally, secondary amines have higher thermal stability compared to primary amines, which means they are less prone to degradation and can have longer lifetimes. The process of CO₂ capture using secondary amines typically involves the use of an amine solution, such as diisopropanolamine (DIPA) or methyl diethanolamine (MDEA), which is passed through the flue gas stream. As the flue gas meets the amine solution, the CO₂ reacts with the amine, forming a carbamate species. This carbamate species can then be separated from the flue gas stream, allowing the CO₂ to be captured. The captured CO₂ can then be further processed and utilized for various industrial purposes. For example, it can be used as a feedstock for producing chemicals and fuels, or for enhanced oil recovery. Wang et al. carried out experimental investigations to compare the performance of n-methyl-2-hydroxy ethylamine (MAE)+H₂O with several water-soluble alcohols [86]. They reported that the MAE/n-butanol/H₂O system with a ratio of 3:4:3 possessed great potential to be an attractive phase change absorbent for CO₂ capture, and they found excellent absorbent stability during CO₂ absorption.

One of the main challenges in using secondary amines for CO₂ capture is their relatively high cost compared to primary amines. However, secondary amines are more selective and have better thermal stability, which can lead to reduced costs associated with amine degradation and fewer emissions of byproducts. Another challenge is the energy consumption associated with the regeneration of the amine solution. Amine solutions used in CO₂ capture are typically heated to high temperatures to release the CO₂, which can be energy-intensive. However, researchers are exploring various methods to reduce energy consumption, such as the use of membrane separation or pressure swing adsorption. A comprehensive list depicting the advancements of alkanol amines during the period from 1970 to 2022 can be observed from Table 3.

4.7.3. Tertiary Amines

Tertiary amines have been studied as a potential solution for capturing carbon dioxide (CO₂) from industrial flue gases. They are a class of amines that contain a nitrogen atom with three alkyl or aryl groups bonded to it and these amines are effective CO₂ absorbents due to their chemical reactivity towards CO₂ [87]. One of the main advantages of using

tertiary amines for CO₂ capture is their high selectivity towards CO₂. They can selectively remove CO₂ from a gas stream containing other gases such as nitrogen, oxygen, and water vapor. Additionally, tertiary amines have higher thermal stability compared to primary and secondary amines, which means they are less prone to degradation and can have longer lifetimes.

The process of CO₂ capture using tertiary amines typically involves the use of an amine solution, such as trimethylamine (TMA), which is passed through the flue gas stream. As the flue gas comes into contact with the amine solution, the CO₂ reacts with the amine, forming a carbamate species. This carbamate species can then be separated from the flue gas stream, allowing the CO₂ to be captured. The captured CO₂ can then be further processed and utilized for various industrial purposes. For example, it can be used as a feedstock for producing chemicals and fuels or for enhanced oil recovery.

Sharif et al. [88] conducted a study to compare the intermolecular reaction of single DMAE, 2EAE, and blended solvent (2DMAE/PZ, 2EAE/PZ) with CO₂. They used a material studio application to carry out molecular dynamic simulations, and their results revealed that the mixture of secondary and tertiary amines showed better intermolecular reaction with CO₂ compared to single amines where PZ acted as a promoter on 2DMAE and 2EAE with carbon dioxide.

One of the main challenges in using tertiary amines for CO₂ capture is their relatively high cost compared to primary and secondary amines. However, the higher selectivity and thermal stability of tertiary amines can lead to reduced costs associated with amine degradation and fewer missions of byproducts. Another challenge is the energy consumption associated with the regeneration of the amine solution. Amine solutions used in CO₂ capture are typically heated to high temperatures to release the CO₂, which can be energy-intensive. However, researchers are exploring various methods to reduce energy consumption, such as the use of membrane separation or pressure swing adsorption.

Table 3. Development of several alkanol amines as CO₂ absorbents (from 1970–2022).

Year	Alkanolamine	Temperature, K	The Partial Pressure of CO ₂ , kPa	Amine Concentration, %	CO ₂ Loading, α	Ref.
1972	DEA	323	7–3370	19.2	0.45–1.13	[89]
1976	DEA	338.5–366.9	32–767	25	0.4–0.79	[90]
1977	DIPA	313–373	2.7–5888	33.63	0.07–1.11	[91]
1978	DGA	323–373	1.58–4720	60	0.13–0.62	[92]
1988	AMP	313.2	1.25–144	28	0.4–0.9	[93]
1990	AMP	313, 343	0.16–5279	18.8	0.03–1.65	[94]
1991	AMP	293–353	1.59–94	18.76, 28.14	0.13–0.94	[95]
	MDEA	313	0.18–92.8	22.9	0.04–0.84	[96]
1992	MDEA+MEA	313.15–373.15	1.12–2080	MDEA: 12–24/MEA: 6–18	0.188–1.015	[97]
1996	AMP	313–353	3.94–336.6	30	0.28–0.9	[98]
	DEA	313–353	4.85–357.3	30	0.4–0.73	[98]
1998	DEA+AMP	313.15–373.15	22–2838	DEA: 20–25/AMP: 5–10	0.337–1.2	[99]
	DEA+MDEA	313.15–393.15	0.4–2833.6	DEA: 10–32.5/MDEA: 10–35	0.038–1.119	[99]

Table 3. Cont.

Year	Alkanolamine	Temperature, K	The Partial Pressure of CO ₂ , kPa	Amine Concentration, %	CO ₂ Loading, α	Ref.
2000	MDEA	297.7	0.02–1.64	23.63	0.02–0.26	[100]
	PZ	313–343	0.03–40	4.7	0.16–0.96	[101]
		313–343	29–40,200	4.7	0.6–0.96	[101]
2001	MDEA	298–373	0.78–140.4	50	0.01–0.49	[102]
2004	MDEA	298–348	2.7–4559.5	48.88, 25.73	0–1.3	[103]
	DEA	298–348	4.85–357.3	47.78	0–1.09	[103]
2006	DEA	323–366	0.4–3798	25	0.1–1.13	[104]
2010	AMP	313.2	0.89–151.9	28	0.4–0.9	[105]
	MDEA	313	0.28–89.9	22.9	0.06–0.80	[106]
		323	6–434	50	0.1–0.89	[106]
	PZ	313	5800–7500	15–60	0.34–0.86	[107]
	TEA	313–353	1.43–153.4	26.5	0.03–0.53	[106]
2011	PZ	354–464.8	28–2583	29.8–40.59	0.23–0.45	[108]
	AMP	298–328	0.41–1449	23.5–46	0.19–1.1	[109]
		303–328	0.31–1472	40,50	0.24–1.04	[109]
2012	MEA	303–323	0.9–335.9	6.7–19	0.35–1.16	[110]
	AMP	313–393	6–983.5	30	0–0.97	[111]
2013	AEEA	303–323	1.11–794.67	15	0.06–1.4077	[112]
2014	DIPA	313–343	107–4064	45	0.52–1.05	[113]
2017	NH ₃	335–395	0.01–1000	20.4	1	[114]
	DIPA	313–343	91.2–3826.6	30	0.89–1.14	[113]
	DIPA + AEEA	313.15–343.15	105–3819.7	DIPA: 20.25/AEEA: 5–10	0.5837–1.251	[113]
	MDEA + PZ	313–375.15	0.033–95.78	MDEA:22.6–47.6/PZ: 0.4–21.3	0.027–0.37	[115]
	DIPA + AMP + PZ	313.15–343.15	112.9–3709.7	DIPA: 24–36/AMP: 7–13/PZ: 2–8	0.502–1.091	[113]
2019	MEA	303–353	0–50.65	12–15	0.017–0.577	[116]
	AMP + PZ	293.15–323.15	0.127–140.4	AMP: 8.9–38/PZ: 0.87–8	0.1511–0.9405	[117]
	MEA + DAP	315.15–333.15	13.24–215.46	MEA: 10–12.5/DAP: 2.5–5	0.22–0.711	[118]
2021	MEA	307.9	-	24.9	2.5–32.5	[119]
	MEA + DEA	308	-	24.8	2.5–32.5	[119]
	MEA + TEA	308	-	25	2.5–32.5	[119]
2022	DA2MP/AMP/PrOH	313.15–383.15	-	20	0.91–0.95	[120]

4.8. Triethylenetetramine (TETA)/Ethanol Solution as Absorbent

Triethylenetetramine (TETA) is a type of tertiary amine that has been studied as a potential CO₂ absorbent as when dissolved in ethanol, it forms a solution that has been found to be effective at capturing CO₂ from industrial flue gases. One of the main advantages of using TETA/ethanol solution for CO₂ capture is its high selectivity towards CO₂ [121]. The TETA/ethanol solution can selectively remove CO₂ from a gas stream containing other gases, such as nitrogen and oxygen [122]. Additionally, the TETA/ethanol solution has a high absorption capacity for CO₂ and can be regenerated easily by heating, which

allows for the captured CO₂ to be released and reused. The process of CO₂ capture using TETA/ethanol solution typically involves passing the flue gas through a TETA/ethanol solution. As the flue gas encounters the TETA/ethanol solution, the CO₂ reacts with the TETA, forming a carbamate species. This carbamate species can then be separated from the flue gas stream, allowing the CO₂ to be captured. The captured CO₂ can then be further processed and utilized for various industrial purposes, such as being used as a feedstock for producing chemicals and fuels. Additionally, TETA/ethanol solution has a high potential for enhanced oil recovery. From several experiments, it was found that TETA/ethanol solution having lower concentration polyamine showed better CO₂ desorption and cycle loading compared to higher concentration polyamines [123].

One of the main challenges in using TETA/ethanol solution for CO₂ capture is its relatively high cost. However, the high selectivity and absorption capacity of TETA/ethanol solution can lead to reduced costs associated with amine degradation and fewer emissions of byproducts. Another challenge is the energy consumption associated with the regeneration of the TETA/ethanol solution. TETA/ethanol solutions used in CO₂ capture are typically heated to high temperatures to release the CO₂, which can be energy-intensive. However, researchers are exploring various methods to reduce energy consumption, such as the use of membrane separation or pressure swing adsorption. One typical challenge for applying this technology is the generation of gelatinous products during absorption. To provide a potential solution to this problem, Zhifang et al. introduced an amine AMP into the TETA-based SLPCAs which successfully ignored such solid byproducts via yielding crystalline powders that could be easily separated [124].

4.9. Amino Acid Salt as Liquid-Solid Phase Changes Absorbent

Amino acid salt as a liquid-solid phase change absorbent of CO₂ is a novel technology that utilizes amino acid salts as a material for CO₂ capture [125]. These absorbents can capture CO₂ through a liquid-solid phase change process. When in contact with CO₂, the absorbent changes from a solid state to a liquid state, allowing for the absorption of CO₂. Amino acid salts have been found to have high selectivity and capacity for CO₂ capture. They can also be regenerated and reused, making them a sustainable option for CO₂ capture. The absorbents can capture CO₂ at a lower energy cost compared to traditional absorbents, which can lead to a more cost-effective CO₂ capture process. One of the advantages of using amino acid salts as liquid-solid phase change absorbents is that they can be used in a wide range of applications, such as power plants, industrial facilities, and transportation. Additionally, they can be used in post-combustion CO₂ capture processes, which is a common method for capturing CO₂ from power plants and other large emitters [126].

Li et al. [127] developed novel biphasic absorbent based on water-lean amino acid salt to enhance CO₂ capture performance and energy efficiency. They employed potassium proline and potassium sarcosinate with a secondary amino group as active elements, while 2-alkoxy ethanol possessing low specific heat, volatility, and viscosity were employed as physical antisolvents and accelerated the generation of the solid phase during CO₂ absorption. They used ¹³C NMR and XRD to characterize the phase change behavior and separation of CO₂ in the solid and liquid phases and to identify the product species in CO₂-rich solid phase. Their experiment revealed that 50–80% CO₂ could be captured via the solid slurry with 2.5 to 3.5 mol kg^{−1} CO₂ loading.

Amino acid salts have also been found to have high thermal stability, which allows them to be used in high-temperature CO₂ capture processes [128,129]. They are also non-toxic and biocompatible, making them a safe and environmentally friendly option for CO₂ capture. In addition, amino acid salts can be produced from renewable sources such as waste or byproducts of agriculture, food, and the chemical industry. This makes them a sustainable alternative to traditional absorbents, which are usually produced from fossil fuels. Research on amino acid salt as liquid-solid phase change absorbents is ongoing, and further advancements are expected in the future. For example, researchers are working

on developing new amino acid salts with improved properties and finding new ways to integrate them into CO₂ capture processes [130,131].

4.10. Encapsulated Absorbents

Encapsulated absorbents for CO₂ capture are technologies that involve enclosing an absorbent material within a protective shell or capsule. The main benefit of this technology is that it improves the stability, selectivity, and overall performance of the absorbent material by protecting it from degradation and chemical reactions. This can lead to a more efficient and cost-effective CO₂ capture process. Encapsulation can be achieved through a variety of methods, such as coating, impregnation, and entrapment. Coating involves applying a thin layer of protective material on the surface of the absorbent, impregnation involves filling the pores of the absorbent with a protective material, and entrapment involves enclosing the absorbent within a protective shell or capsule. The selection of any approach from these usually depends on the application and the properties of the absorbent. Polesso et al. experimented with a novel CO₂ absorption system where they investigated the performance of encapsulated poly-ionic liquids (PIL) as green solvents [132]. From this experiment, by employing the nano spray dryer B-90, encapsulated ionic liquids Emim [X], and capsules of water-based PIL P[DADMA][BF₄] were achieved, and the stability of this system and high CO₂ selectivity emphasized its potentiality for CO₂ absorption. Other encapsulated PILs were also compared, and P[DADMA]/BF₄ showed the highest performance based on CO₂ absorption rate and CO₂/N₂ selectivity, which is clear from Figure 6.

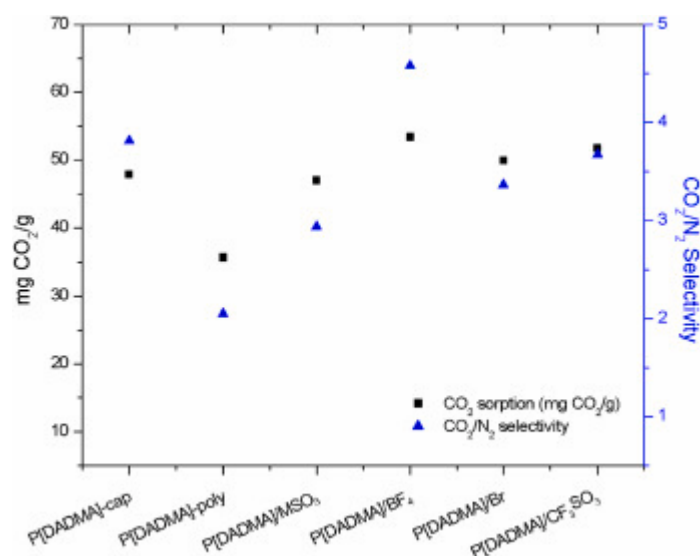


Figure 6. CO₂ sorption (mg CO₂/g) and CO₂/N₂ selectivity [132].

One of the significant advantages of encapsulated absorbents is that they can improve the stability of the absorbent. The protective shell or capsule can shield the absorbent from environmental factors, such as heat and light, which can cause degradation. This can increase the service life of the absorbent and reduce the need for frequent replacement. Additionally, encapsulation can also protect the absorbent from chemical reactions that may occur during the absorption process, which can improve its performance. Encapsulation can also improve the selectivity of the absorbent material for CO₂. For example, encapsulating amines within a porous material can increase their selectivity for CO₂ over other gases. This leads to a more efficient and specific CO₂ capture process. Some encapsulated absorbents are also designed to be regenerated and reused after the CO₂ is captured. This can reduce the cost of the CO₂ capture process and make it more sustainable.

4.11. Enzymatically Catalyzed Absorbent Systems

Enzymatically catalyzed absorbent systems for CO₂ capture are novel technologies that utilize enzymes to catalyze the capture and conversion of CO₂. Enzymes are biomolecules that act as catalysts, increasing the rate of a chemical reaction without being consumed in the process. This technology has been studied as a way to improve the efficiency and sustainability of CO₂ capture processes.

Enzymes that have been studied for CO₂ capture include carbonic anhydrase, which catalyzes the conversion of CO₂ and water to bicarbonate and protons, and formate dehydrogenase, which catalyzes the conversion of CO₂ and formate to carbon monoxide and water. These enzymes are typically immobilized on a support material, such as a polymer or a nanoparticle, to increase their stability and reuse. Hannaneh et al. proposed a hybrid enzymatic CO₂ absorption process integrated with carbonic anhydrase II enzyme in a membrane, and they found from their experiment that such enzymatic approaches improve CO₂ absorption [133]. In another article, Hannaneh reported a promising enzymatic CO₂ absorption approach in a packed bed reactor, and based on their experimental and theoretical approaches, they reported a packed bed bioreactor with immobilized carbonic anhydrase enzyme on magnetic nanoparticles and packing surface as an attractive process for green CO₂ capture process [134]. Several experiments have revealed that applying CA with absorbents (such as MDEA) can enhance absorption performance significantly [135]. Mthias et al. experimented with an enzyme-enhanced CO₂ absorption mechanism in which they incorporated CA in the biocatalyst delivery system to investigate with an aqueous MDEA solvent. Their result showed a sixfold improvement in the total absorbed CO₂ moles [136].

One of the advantages of enzymatically catalyzed absorbent systems is that they can improve the efficiency of CO₂ capture. Enzymes can catalyze the conversion of CO₂ to a more easily captured and stored form, such as bicarbonate or formate. This can lead to a more efficient and cost-effective CO₂ capture process. Enzymatically catalyzed absorbent systems can also improve the sustainability of CO₂ capture processes. Enzymes are biocompatible and can be produced from renewable sources, such as bacteria or plants. Additionally, enzymes can be recycled and reused after the CO₂ is captured, reducing the need for frequent replacement. Another advantage of enzymatically catalyzed absorbent systems is that they can be used in a wide range of applications, such as power plants and industrial facilities, and can be integrated into existing CO₂ capture processes. This technology is an active area of research, and further advancements are expected in the future.

The major barrier of this novel technology is the stability and activity of carbonic anhydrase enzyme under typical flue gas operating conditions. To propose a solution to this issue, Zhang et al. [137] proposed a novel CA/ZIF-L-1 composite by embedding CA into ZIF-L (zeolitic imidazolate framework). They found that the novel composite caused high enzyme activity retention and exhibited high thermal stability, which was improved by 100% at 40 °C, which can be observed from Figure 7.

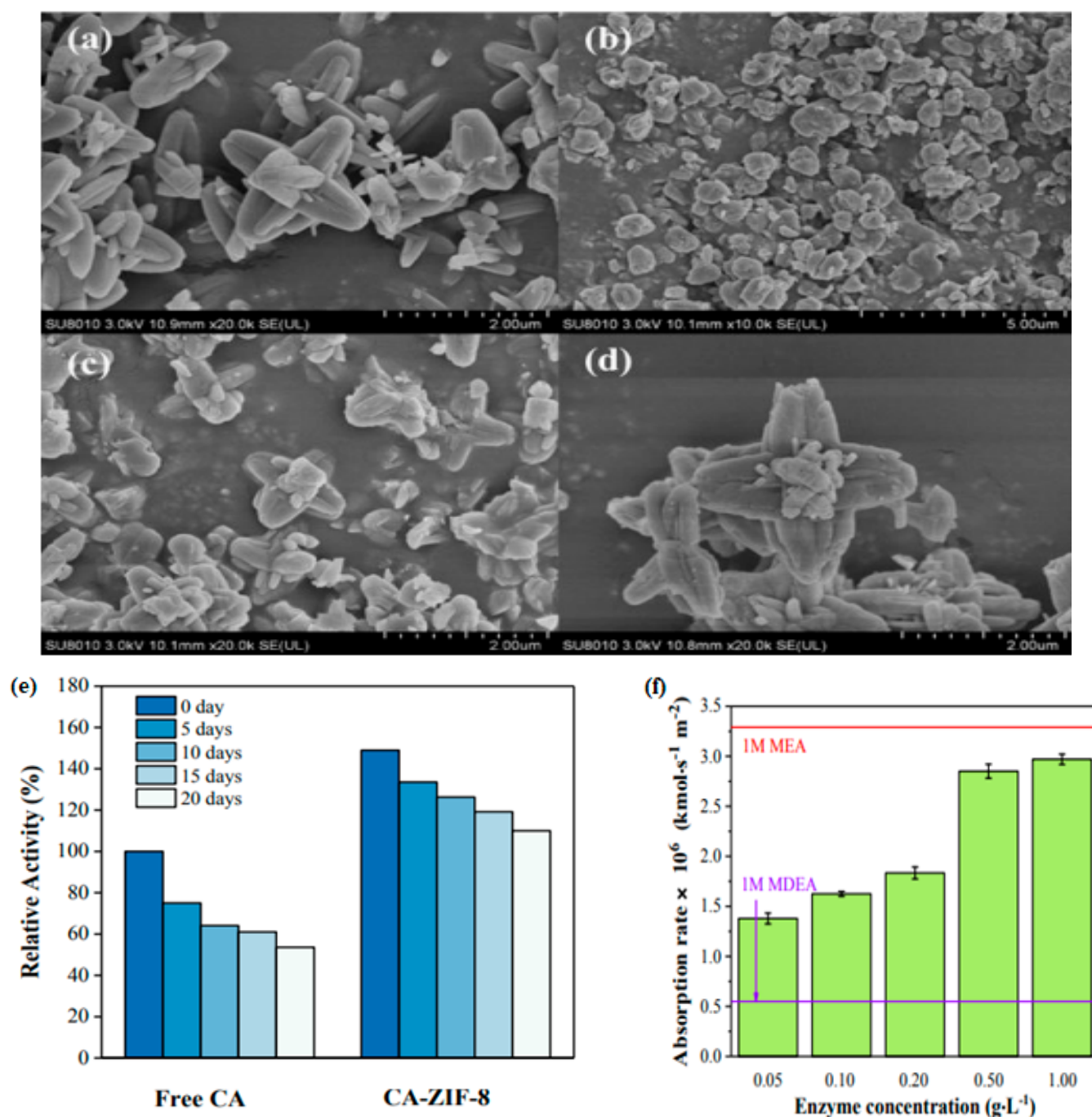


Figure 7. SEM images of (a) ZIF-L, (b) ZIF-L (5 min), (c) CA/ZIF-L-1, and (d) CA/ZIF-L-2. (e) The stability of the free enzyme and CA/ZIF-L-1 and reusability of CA/ZIF-L-1; (f) Performance of CO_2 absorption into 1M MDEA solution with different 604 concentrations of CA/ZIF-L-1 at 40°C and a CO_2 partial pressure of 15 kPa [137]. Copyright © 2018, American Chemical Society.

4.12. Deep Eutectic Solvents (DESs)

Deep eutectic solvents (DESs) are mixtures of two or more components that exhibit lower melting points and higher solubility compared to individual components. In recent years, they have gained attention as a potential solution for CO_2 capture and utilization due to their unique properties, such as low toxicity and high CO_2 solubility. Research advancements in the field of DESs for CO_2 absorption have focused on optimizing the composition and properties of DESs to increase their efficiency and cost-effectiveness. For example, studies have explored the use of different hydrogen bond donors and acceptors

to improve CO₂ solubility and selectivity. The Lewis or Bronsted acids and bases are used to create the DESs as novel ionic solvents that can contain a wide range of anionic and cationic species [138]. In more detail, DESs are created by combining a hydrogen-bond donor (HBD) and a hydrogen-bond acceptor (HBA) at the proper molar ratio. These materials are inexpensive, reliable, and simple to make from a variety of readily accessible beginning ingredients. The most typical and extensively utilized DESs are those based on cholinium chloride (ChCl). ChCl-based DESs are well known for sharing characteristics and behavior with traditional ILs, as well as having the same CO₂ order. capability for absorption [139–141]. Ruan et al. experimented with CO₂ absorption using DES, which was formed by superbase 1,5-diazabicyclo [4.3.0] non-5-ene (DBN) and 1,2,4-triazole (Tz), and they investigated the impacts of molar ratios of DBN and TZ for CO₂ absorption. Their experimental results revealed that DES [2DBN:Tz] showed the highest performance [142], which is clear in Figure 8.

DESs have potential applications in various industries, including the power generation and chemical industries, where they can be used to capture and utilize CO₂ emissions [138]. Additionally, they have been proposed to enhance oil recovery and as a solvent for chemical reactions. DESs work by dissolving CO₂ in the solvent mixture, forming a stable complex. This allows for the efficient separation of CO₂ from other gases, such as nitrogen and oxygen, in flue gas streams. The captured CO₂ can then be utilized or stored for later use. The advantages of using DESs for CO₂ capture include their low cost, low toxicity, and high CO₂ solubility. Additionally, they can be regenerated and reused multiple times, making them a sustainable solution for CO₂ capture. However, there are also limitations to the use of DESs for CO₂ capture. For example, the efficiency of CO₂ capture can be affected by temperature and pressure changes, and the stability of DESs can be impacted by impurities in the gas stream. Additionally, the production and use of DESs can also have an impact on the environment. Table 4 summarizes different absorbent materials with their advantages and disadvantages.

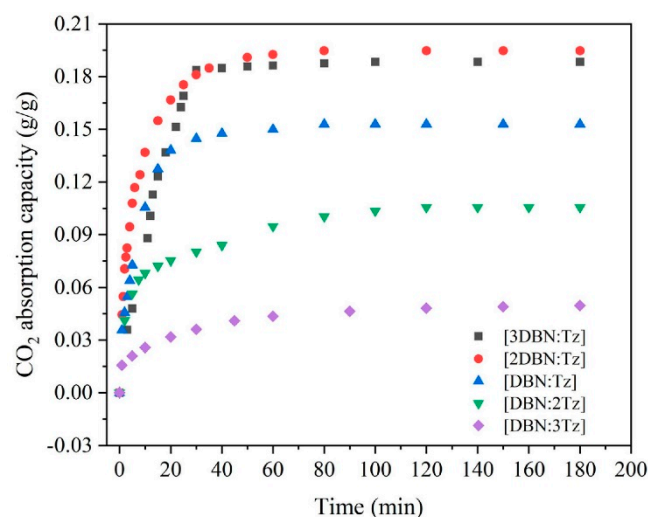


Figure 8. CO₂ gravimetric absorption capacity by DBN-Tz DESs under different molar ratios at 25 °C and 100 kPa [142]. Copyright permission © 2022 Elsevier.

Table 4. Different absorbent materials with their advantages and disadvantages.

Solvent/Absorbent	Advantages	Limitations/Disadvantages	Remarks
DEA	The absorption rate is high. Less expensive.	Lower capacity. Risk of corrosion due to the presence of atmospheric oxygen.	DEA is a liquid at room temperature, making it easy to handle and transport. It also has a high CO ₂ solubility, making it an attractive option for use in post-combustion CO ₂ capture and air purification applications.
K ₂ CO ₃	Degradation resistance is high, less expensive, and less enthalpy is needed for this solvent.	The mass transfer rate is low.	Organic/inorganic salts are mixed to enhance the mass transfer rate. Reactivity drops down at 40–200 °C.
AMP	Selectivity rate is high, simple regeneration, good absorption capacity, and degradation resistance.	The absorption rate is low.	Temperature decreases linearly with column height.
Di-isopropylamine (DIPA)	Less corrosion, cost-effective regeneration.	The absorption rate is low.	Dipa is a tertiary amine that can react with CO ₂ to form a stable carbamate, making it a viable option for removing CO ₂ from gas streams.
MEA	The cost-effective, high reaction rate	Lower capacity. Risk of corrosion due to the presence of atmospheric oxygen.	Among pilot, spray, and packed columns, pilot and spray columns show superior performance.
2PE	Rigid thermal and chemical behavior. Non-toxic and environmentally friendly.	Its high volatility can result in significant losses of 2PE during the CO ₂ capture process.	2PE has a high CO ₂ solubility and is a liquid at room temperature, making it easy to handle and transport.
PZ	Good corrosion resistance, less thermal degradation, cost-effective regeneration.	-	
AEP	The absorption capacity is high.	-	Include primary, secondary, and tertiary amines without formatting any carbamate.
Ionic liquids	Thermally and chemically stable. Cost-effective and high carbon capture selectivity.	-	By decreasing temperature and increasing concentration, an increase in density and viscosity is possible.
Ammonia	Low cost, high selectivity. Absorption capacity is high and available.	Slip	Pilot scale project.
MDEA	Good corrosion and degradation resistance. Low regeneration cost.	The absorption rate is low	Unlike primary and secondary amines, it does not bind.
AMP + PZ		-	A pilot plant, packed bed.
MDEA + PZ	Available, less corrosion, low cost.	High cost. High corrosivity.	MDEA is a tertiary amine that reacts with CO ₂ to form a stable carbamate, while PZ is an acidic compound that can enhance the reaction kinetics of the MDEA-CO ₂ reaction

Table 4. Cont.

Solvent/Absorbent	Advantages	Limitations/Disadvantages	Remarks
MDEA + glycerol	Concentration and pressure are low. Absorption capacity is high.	The solubility of carbon dioxide can be decreased due to high pressure and concentration of glycerol.	MDEA is a tertiary amine that reacts with CO ₂ to form a stable carbamate, while glycerol is a hydrophilic compound that can act as a solvent for the absorbent.
DETA	Huge loading of CO ₂ . Promote the absorption process.	-	
DETA/Sulfolane	A low volume required for regeneration. Low total heat duty, improved viscosity.	-	Novel absorbent to capture CO ₂ .
PEG-dicholine chlorides	CO ₂ intake increased with increasing pressure and temperature. Non-toxic. Fast kinetics and high absorption capacity.	Long-chain polymers have lesser mobility and CO ₂ loading. High cost. Form solid residue after absorption.	PEG (polyethylene glycol) is a hydrophilic polymer that is combined with a dicholine chloride molecule to form the PEG-dicholine chloride.
PEG-PDMS copolymer	Selective CO ₂ absorption: a copolymer with an imidazolium chromophore was shown to be an effective solvent for precombustion CO ₂ capture.	CO ₂ selectivity is moderate; severe foaming in the presence of flowing gas	The PEG component provides hydrophilic properties, while the PDMS component provides hydrophobic properties, making the copolymer an attractive option for CO ₂ removal from gas streams
AAM-co-AAC porous hydrogel copolymers	Excessive water content increased CO ₂ uptake capacity.	Water has a low CO ₂ solubility along polymer scaffolds.	The high swelling capacity of the copolymers allows for efficient CO ₂ absorption, and the porous structure increases the available surface area for CO ₂ absorption.
DMEPEG	Absorption of CO ₂ and H ₂ S from syngas; recovery of co-absorbed H ₂ ; and reduction of equipment size through solvent saturation.	Process performance variation; fluctuation in gas/solvent processing capability within a packed column.	DME-PEG copolymers are composed of a combination of dimethanolamine (DME), a tertiary amine that can react with CO ₂ to form a stable carbamate, and polyethylene glycol (PEG), a hydrophilic polymer that increases the solubility of DME in water.
Amino acid poly-ionic liquids (AAPILs)	Poly-ionic liquids based on [Arg] exhibited the maximum CO ₂ absorption and sorption capability.	Procedures execution on an industrial scale or for commercialization.	
Amine-infused microgels (AIMGs)	Increased CO ₂ intake and absorbing kinetics.	Long-term robustness, durability, and CO ₂ capturing capacity at high pressure and temperature are required for large-scale applications.	AIMGs are soft, hydrogel-like particles that are infused with an amine-containing chemical, such as a tertiary amine. The amine reacts with CO ₂ to form a stable carbamate, which is trapped within the gel structure of the AIMG.

Table 4. Cont.

Solvent/Absorbent	Advantages	Limitations/Disadvantages	Remarks
Novel Multiphase Systems of NOHMs	Because of the positive entropic impact, CO ₂ is readily available. At high pressure, and high CO ₂ capture; CO ₂ has a high selectivity over N ₂ O, O ₂ , and N ₂ .	The high temperature has a negative impact on CO ₂ absorption.	NOHMs are highly branched, organic molecules that contain nitroxide radicals, which can react with CO ₂ to form a stable carbamate.
POSS containing NOHMs	High thermal stability, enhanced CO ₂ molecule assimilation due to high canopy/core size ratio.	More physical research and polymer chain couplings are required to assess CO ₂ capture efficacy.	By incorporating POSS into NOHMs, the resulting materials can exhibit unique properties, such as high stability, low toxicity, and improved CO ₂ uptake.
Polydimethylsiloxane (PDMS)	Highly soluble and thermally stable; efficient CO ₂ extraction from H ₂ , H ₂ O, and H ₂ S.	Decreasing CO ₂ solubility with rising temperature causes high-cost process.	PDMS is often synthesized as a gel, which can be cut into small pieces to increase the surface area and therefore the CO ₂ absorption capacity.

5. Outlook and Prospects

Carbon capture and storage (CCS) is a technology that aims to capture carbon dioxide (CO₂) emissions from power plants and other industrial sources and store them underground. The use of CO₂ absorbents is a crucial component of CCS, as they are responsible for capturing the CO₂ from the emissions. The future of CCS and CO₂ absorbents is of great interest, as it is expected to play a significant role in reducing greenhouse gas emissions and slowing down global warming. One of the main prospects of CO₂ absorption and absorbents is the increased use of CCS in power generation. As countries around the world work to reduce their greenhouse gas emissions, the use of CCS in power generation is expected to grow. This will lead to an increased demand for CO₂ absorbents, and researchers are working to develop new and improved absorbents that are more effective and efficient at capturing CO₂.

Another prospect is the use of CCS in industrial processes. Currently, many industrial processes, such as cement and steel production, release large amounts of CO₂ into the atmosphere. CCS technologies, including CO₂ absorbents, can be used to capture and store these emissions, reducing their impact on the environment. As the demand for these technologies grows, researchers are working to develop new absorbents that are specifically designed for industrial applications. In addition, the use of CO₂ absorbents in direct air capture (DAC) is an emerging field. DAC technology captures CO₂ directly from the atmosphere rather than from industrial emissions [143]. This technology has the potential to significantly reduce the amount of CO₂ in the atmosphere and is seen as a promising solution for addressing climate change. The use of CO₂ absorbents in DAC is still in the early stages of development, but it is expected to grow in the future as researchers work to improve the efficiency and effectiveness of the technology [144].

Another prospect is the integration of CO₂ absorption and utilization. While traditional CCS technologies focus on capturing and storing CO₂, there is also a growing interest in utilizing the captured CO₂ for various applications such as producing chemicals, fuels, and even food. Researchers are working to develop new absorbents that can capture CO₂ for utilization, which would increase the value of CCS and make it more economically viable. Additionally, the development of sustainable and biobased absorbents is also an area of research. Traditional CO₂ absorbents are mostly based on fossil fuels, which are non-renewable and environmentally damaging. There is a growing interest in the development of absorbents that are based on renewable and sustainable resources such as biomass, which can reduce the environmental impact of CCS.

Another prospect for CO₂ absorption and absorbents is the development of hybrid absorbents. These absorbents combine two or more different types of absorbents to improve the overall efficiency and effectiveness of the CO₂ capture process. For example, a hybrid absorbent could consist of a traditional amine-based absorbent combined with a PIL (poly-ionic liquid) absorbent. The amine-based absorbent would provide a high CO₂ binding capacity, while the PIL absorbent would provide improved thermal stability and selectivity for CO₂. Researchers are also working on developing hybrid absorbents that integrate solid and liquid absorbents to achieve better performance.

Another important area of research is the development of more cost-effective CO₂ capture technologies. While CCS and CO₂ absorbents have the potential to significantly reduce greenhouse gas emissions, the cost of these technologies remains a major barrier to their widespread adoption. Researchers are working to develop new absorbents that are more cost-effective, such as those based on sustainable and biobased resources, to make CCS more economically viable. There is also growing interest in the use of CO₂ absorbents in carbon mineralization, which is a process that converts CO₂ into stable carbonates, such as limestone. Carbon mineralization has the potential to permanently remove CO₂ from the atmosphere and researchers are working to develop new absorbents that can capture CO₂ for mineralization. Lastly, the development of advanced monitoring and control systems for CCS facilities is also an important area of research. These systems would allow the real-time monitoring of the CO₂ capture process and would enable facilities to optimize the performance of their absorbents and improve the efficiency of their CCS systems.

6. Conclusions

In this paper, several absorption-based CO₂ capture approaches have been studied comprehensively, considering material and mechanism improvement as well as engineering aspects. The increased amount of CO₂ has been considered a curse in recent years, and researchers are working hard to develop materials for capturing CO₂ to protect the environment from its negative influences. Several catalysts can be utilized to ameliorate the performance of different absorbent materials. Researchers are working to develop different types of absorbents and technologies to synthesize absorbents while considering cost, safety, absorption rate, stability, and durability. Different novel technologies such as enzyme-based absorption and nanocomposite-assisted absorption, which improve the potentiality of carbon capture, have been developed. Power plants and other GHG emitters emit a massive amount of CO₂ regularly, which is harming the environment. However, these massive amounts of CO₂ can be utilized for energy production by applying CO₂ as feedstock material as well as CO₂ as a raw material to produce the alternative fuel methanol. To properly utilize and store of CO₂, it is necessary to have comprehensive knowledge of advanced CO₂ capture technologies, and as absorption is the most widely applied CO₂ capture technology, we reviewed and discussed previous research to assist researchers in further research.

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