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An exhaustive review of carbon dioxide capture through the utilization of chemical solvents via absorption

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HIGHLIGHTS

- The latest research on carbon dioxide capture through chemical absorption has been reviewed.
- This review helps in determining the optimal method for carbon dioxide capture .
- It discusses the impact of operating factors on the performance of absorption.
- The performance of absorption is determined by the mass transfer between the absorbent material and carbon dioxide.

Keywords:
Chemical absorption, CO_2 Capture, Global warming, Solvents, Post-combustion.

ABSTRACT

The release of carbon dioxide from the combustion of fossil fuels and chimney emissions has emerged as the primary catalyst for global warming. The significant increase in emissions is due to various factors, including power plants that rely on fossil fuels, different industrial processes, and many other factors, all of which are the main causes of environmental pollution. The need has arisen to invent an effective way to reduce carbon dioxide emissions into the atmosphere, where scientists have reviewed several methods, such as transitioning to renewable energy, improving energy generation stations, and capturing carbon dioxide emissions. However, the optimal and most realistic choice is carbon capture and storage to preserve a green environment. Currently, there are three methods: pre-combustion capture, post-combustion capture, and oxyfuel combustion. Post-combustion capture is the most common system; among its various methods, absorption is considered one of the most common processes for gas capture. Absorption involves contact between a gas-liquid mixture to remove one of the gas components by dissolving it in a suitable liquid. The purpose of this review is to clarify the techniques of CO_2 capture with a focus on the absorption process using the absorbent material (NaOH), as well as to identify other types of absorbent materials used in absorption processes and the effect of reactor structure on absorption performance in addition to the impact of reaction parameters on absorption efficiency.

1. Introduction

The significant emission of carbon dioxide from power plants, industrial facilities, and other sources is playing a critical role in the global climate, and Earth's life cycle CO_2 concentration has increased from 280 to 400 parts per million (ppm) with a 0.8 °C increase in global surface temperature [1]. The release of carbon dioxide into the atmosphere is widely acknowledged as the primary cause of climate change impacts, such as global warming, fluctuations in sea levels, intensified heatwaves, severe winters, and agricultural challenges. Given that fossil fuels will persist as a primary energy source in the foreseeable future, it is unavoidable that carbon dioxide emissions into the atmosphere will persist, exacerbating climate change's impacts. Hence, it is imperative to develop a cost-effective, sustainable, and ecologically sound approach to mitigate these impacts [2].

Numerous options exist to reduce CO_2 emissions from fossil fuel-fired power plants [3]: (1) Enhancing power plant efficiency, (2) Transitioning from hydrocarbon fuels to renewable resources, (3) Using natural gas as a substitute for coal, as it has lower carbon content, and (4) Carbon dioxide capture and storage.

Intensive efforts have been made worldwide to find technologies to address climate change, among which carbon dioxide capture and storage are promising technologies to reduce CO_2 emissions to the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC) reports, CCS can potentially decrease CO_2 emissions by 15 to 55% by 2100 [4].

Carbon dioxide capture and storage methods can be categorized into three primary groups: pre-combustion, oxy-combustion (oxyfuel), and post-combustion carbon dioxide capture [5]. Post-combustion CO_2 capture is the most common alternative process, and it is easier to implement as a retrofit option for existing plants than the other two approaches [6]. One of the most common and cost-effective technologies in the post-combustion method is chemical absorption or chemical solvent [7-9].

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Chemical absorption has several key advantages, such as high efficiency, low cost, and well-established technology, compared to other methods [7].

One of the most popular methods of chemical absorption is using solvents in carbon dioxide capture, but in contrast to its widespread use, it has some disadvantages. These solvents show strong corrosion to equipment, poor resource utilization of the product, high energy requirement for regeneration, and easy oxygen denization/degradation. To make the CO_2 absorption process more effective and financially viable, it is important to identify and design energy-efficient and environmentally friendly solvents specifically tailored for solvent-based CO_2 capture processes [8]. Numerous solvents have been developed since the first chemical absorption process was patented in the early 1930s. However, the implementation of CO_2 absorption at industrial processes such as cement production, iron and steel manufacturing, and fossil-fuel power plants requires novel solvent formulations that can address the main constraints limiting its deployment: the huge volume of treated gas, the low CO_2 concentration in the flue gas and the presence of trace components such as NO_x, SO_2 and particulate matter which degrade the solvents [9]. Due to chemical reactions between solvents and carbon dioxide, these solvents are well-known as "chemical solvents". Amines, salt solutions, and ammonia are examples of this type of solvent [10].

The review paper in section 4 discussed several types of chemical solvents and highlighted their advantages and disadvantages in a way that makes it easy for the reader to understand them. Given the global importance of this topic, we surveyed the number of research papers published on carbon dioxide capture using chemical absorption. Figure 1 shows an upward trend in research papers, specifically from 2015 to July 2024. The current review specifically aims to identify one of the main causes of global warming: carbon dioxide. It focuses on post-combustion carbon dioxide capture technology and the techniques for reducing its emissions into the atmosphere, as well as understanding the advantages and disadvantages of each method. The most commonly used chemical and physical solvents in the absorption process were reviewed, along with a summary of the effect of reactor structure on absorption performance. This paper also illustrates how it differs from previous studies by focusing on new angles as a review of most sorbents, which gives a broader view compared to research that may focus on only one substance or technology and provides a comprehensive understanding of carbon dioxide absorption techniques and the latest innovations and future trends in this field, which helps to identify future research priorities.

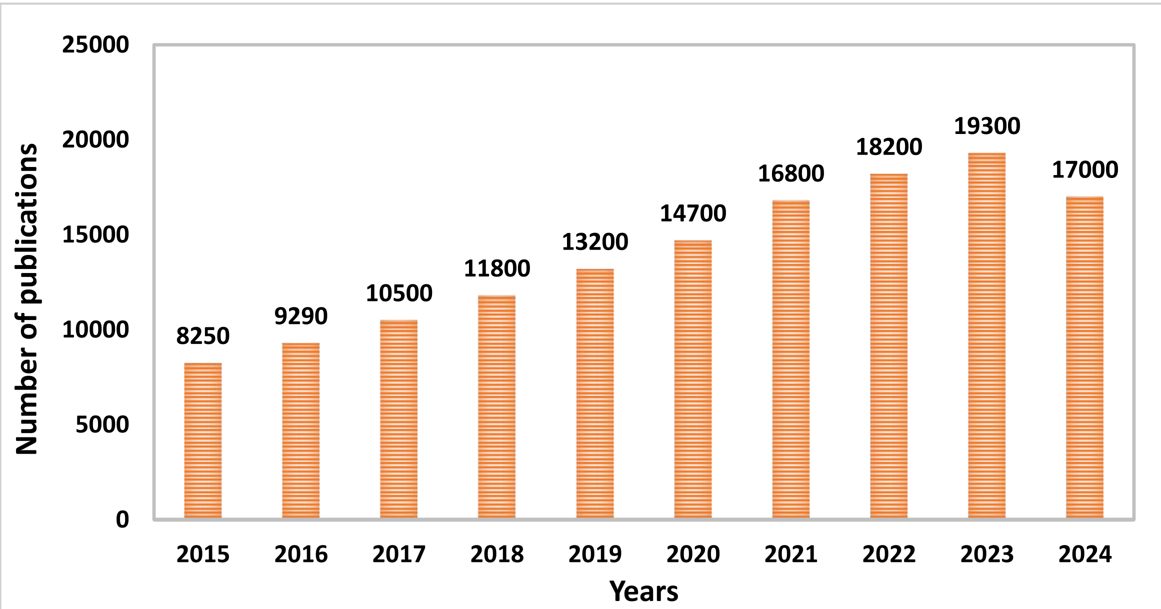


Figure 1: The number of published research studies on capturing CO_2 by absorption over the years (data for 2015 up to July 2024) (data from Google Scholar)

2. Carbon dioxide emissions

Greenhouse gas (GHG) emissions come from various sources, including the energy sector, buildings, landfills, transportation, industry, agriculture, forestry, and other land uses. The main greenhouse gases include CO_2, CH_4, N_2O, O_3, water vapor, and fluorinated gases (FG). As shown in Figure 2, the current atmospheric concentration of GHGs, particularly CO_2, CH_4, N_2O, and fluorinated gases (FG), is 76%, 16%, 6%, and 2%, respectively [11].

Different greenhouse gases persist in the atmosphere or the environment for extended periods due to their different absorption capacities and lifetimes in the atmosphere. The accumulation of trapped heat leads to a gradual increase in the Earth's temperature, resulting in alterations to the climate, as previously discussed. Greenhouse gases form a protective layer within the Earth's atmosphere, and carbon dioxide emissions warm the planet by trapping heat energy and increasing global temperatures. Emissions occur from both human activities and natural sources. Human activities like the processing, extraction, and combustion of fossil fuels, deforestation, and industrial manufacturing are the primary anthropogenic sources of CO_2 emissions. On the other hand, natural sources include ocean outgassing, the decomposition of organic matter, volcanic eruptions, and wildfires [12].

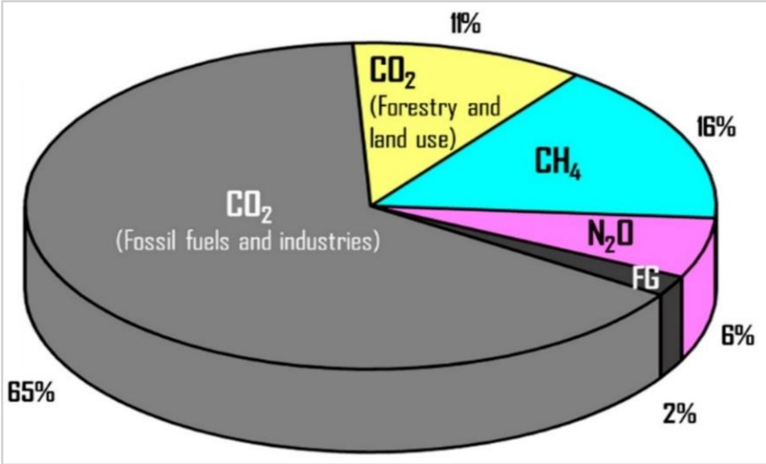


Figure 2: Global atmospheric concentrations of greenhouse gases [13]

Climate change, caused by the increasing levels of greenhouse gases (GHGs) in the atmosphere, is considered a significant problem in the 21st century. Scientists have demonstrated that it leads to environmental degradation and natural disasters that threaten human safety and health [14]. The sources and harmful health effects of CO_2 emissions are shown in Figure 3. Exposure to CO_2 at current levels in the environment can modify innate immunity, leading to increased inflammatory reactions to other air pollutants. Headaches, the most common symptom of Sick Building Syndrome in the workplace, have been closely associated with elevated levels of CO_2 [15]. To mitigate the potentially severe consequences of climate change, the Intergovernmental Panel on Climate Change (IPCC) has stressed the significance of constraining the rise in global average temperature to a maximum of 2 °C. The objective necessitates a decrease in worldwide greenhouse gas emissions, primarily (CO_2), of no less than 50% by 2050. This implies that the available room for future emissions will become exceedingly limited [16].

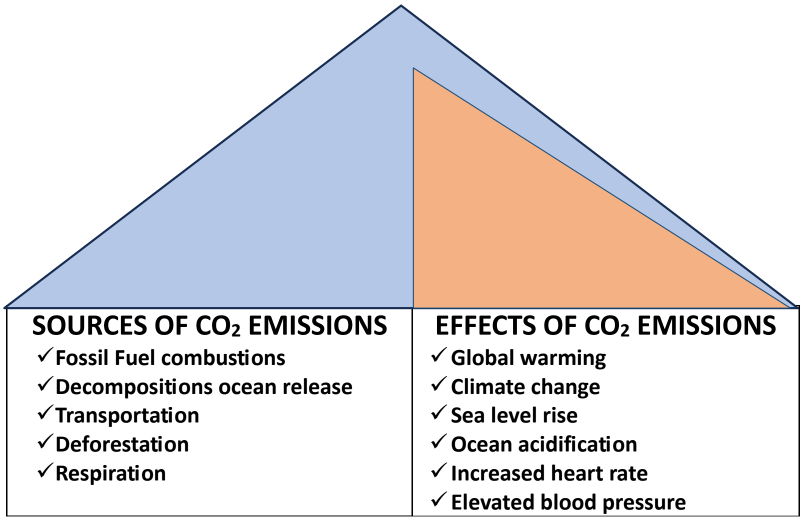


Figure 3: Sources and toxic health effects of CO_2 emissions [17]

3. CO_2 capture technology

CO_2 capture technologies are of global significance due to the substantial harm posed by carbon dioxide emissions from fossil fuels to the economy, environment, natural ecosystems, and human health. Progress in carbon capture and utilization technology has the potential to significantly decrease CO_2 emissions and contribute to achieving various United Nations Sustainable Development Goals, including Goal Six (Clean Water and Sanitation), Goal seven (Affordable and Clean Energy), Goal nine (Industry, Innovation and Infrastructure), Goal eleven (Sustainable Cities and Communities), Goal twelve (Responsible Consumption and Production), and Goal thirteen (Climate Action). Carbon capture, storage, and usage can be accomplished through four (4) distinct phases. The initial stage involves the extraction of carbon dioxide (CO_2) from the specific emission source.

Industrial operations create flue gases, which are considered a point source of pollution. These gases can be removed by chemical and physical absorption, membrane-based separation, adsorption, and other new technologies [18,19]. Compressed liquid carbon dioxide is a highly convenient storage and transportation medium. This compound can be permanently sequestered underground into porous rocks or beneath ocean beds, commonly called geosequestration [20]. The choice of sites depends on the presence of porous rock in the ground. Carbon dioxide (CO_2) is injected into the rocks' pores and trapped by an impermeable layer. This process is quite similar to how gas and oil are stored underground. CO_2 can be stored geologically in both onshore and offshore basins. The captured CO_2 is intended to be converted into valuable chemicals to improve oil recovery or for alkaline remediation. The combusted exhaust gas is used as the feedstock material for utilization. Carbon dioxide (CO_2) is utilized in the processing of food and beverages, as well as in the production of synthetic or hydrocarbon fuels when combined with hydrogen [21].

3.1 Carbon dioxide capture technology approaches can generally be categorized into three types

1) The pre-combustion carbon capture technique primarily aims to extract carbon dioxide (CO_2) from fossil fuel or biomass fuel before the energy-generating combustion processes. This pre-combustion capture technology is typically employed during coal, natural gas, and biomass gasification to produce syngas. It is also utilized in natural gas power plants [22].
2) The post-combustion approach involves the removal of CO_2 from the flue gas emitted by coal-fired power plants and other manufacturing businesses after the combustion process. Post-combustion technologies are the preferred choice for making modifications to current power plants. The main techniques utilized in post-combustion carbon capture include membrane separation, chemical looping, chemical absorption, and physical adsorption [23].
3) Oxy-fuel combustion involves using high-purity oxygen (O_2) to burn carbon sources, creating flue gas that does not contain undesirable pollutants (such as NO_x). This makes it easier to store carbon dioxide (CO_2) [24]. Like pre-combustion, its potential for retrofitting into existing plants is not promising due to the need for additional equipment, such as an air separation unit and an oxidizer before a combustion unit [25]. The oxy-fuel approach involves firing the fuel in the presence of oxygen, similar to the post-combustion process. Adding CO_2 increases flue gas concentration, improving its capture efficiency [26]. The constraints of specific materials and environmental conditions necessary to meet high-temperature demands have limited the research and development of pre-combustion and oxy-fuel combustion capture technologies. By contrast, post-combustion capture has emerged as a well-established and sophisticated technique within the industry [27]. It has garnered the most interest because it can easily be retrofitted into existing plants [28].Table1 compares the three CO_2 capture technologies described above.

Table 1: The Advantages and disadvantages of the various carbon dioxide capture technologies

Capture process	Application area	Advantages	Disadvantages	Ref.
Post-combustion	Coal-fired and gas-fired plants	Technology is more advanced than other options and can be integrated into existing plants.	The efficiency of capturing is affected by low CO_2 concentration.	[29]
Pre-combustion	Coal-gasification plants	Increased carbon dioxide concentration improves sorption efficiency. This technology is already completely developed and used commercially in certain industrial sectors. It is also potential to retrofit existing plants with this technology.	The heat transfer problem is related to temperature changes and the decrease in efficiency when using hydrogen-rich gas turbine fuel. Additionally, the current sorption systems have significant capital and operational costs.	[30]
Oxyfuel combustion	Coal-fired and gas-fired plants	Reduced flue gas and nitrogen emissions (NO_x elimination through pure oxygen utilization), improved boiler energy conversion efficiency, higher carbon dioxide concentration with the potential for direct CO_2 sequestration, and utilization of smaller combustors due to lower gas volume.	The requirement for a more intricate and regulated procedure, dependence on a substantial recycling flow from the flue gas to the combustor to avoid excessively high-temperature combustion, and, most notably, the energy-intensive separation unit necessary for removing N_2 from air to generate very pure O_2.	[31] [32] [33]

3.2 Cost-benefit analysis

Cost-benefit analysis of CO_2 capture technology reveals a complex landscape of economic viability, influenced by various factors, including technology type, project scale, and operational context. The following points summarize key insights from recent research:

1) The cost of CO_2 capture can range from €30-45 per tonne for new coal installations by 2030, while early projects may incur costs of €60-90 per tonne [34].
2) Oxyfuel combustion and post-combustion capture technologies show significant cost variations, with post-combustion systems achieving high CO_2 purity at competitive costs [35].
3) A membrane reactor system can increase electricity costs by approximately 30%, with a CO_2 avoidance cost of about €30 per tonne [36].
4) The cost of electricity for oxy-combustion and amine scrubbing technologies can increase by 60% and 79%, respectively, compared to non-capture plants [37].
5) A common economic model indicates potential cost reductions exceeding 50% for certain capture technologies, emphasizing the importance of site-specific evaluations [38].

While CO_2 capture technologies present significant upfront costs, their long-term benefits in mitigating climate change and potential cost reductions through technological advancements warrant further exploration.

4. Carbon dioxide separation techniques in post-combustion separation

4.1 Separation techniques

Several methods are used to capture or absorb CO_2 gas, including membrane, cryogenic, and absorption. However, the most commonly used method is chemical absorption [39]. Chemical absorption systems are currently the most commonly used method for capturing carbon dioxide after combustion. These systems have been used since the 1930s to capture CO_2 from ammonia plants for food applications and are a commercially realized technology [40]. The advantages and limitations of each option are summarized in Table 2.

Table 2: Advantages and limitations of carbon dioxide separation technologies [41][21][42][43]

CO_2 Separation technologies	Advantages	Limitations
Absorption	• Versatile and adaptable to various processes. • Exceptionally high efficiency in capturing carbon dioxide •Advanced technology	• Solvent regeneration may require a lot of energy. • Solvent deterioration and environmental pollutants are possible.
Algae systems	• Utilizes photosynthesis to convert carbon dioxide into biomass or biofuels • Well-suited for treating wastewaters that include high levels of nutrients • Economical in certain instances	• Harvesting and dewatering algae can be quite challenging. • Variable efficiency due to environmental factors • Requires extensive land areas for cultivation
Adsorption	• Could produce high-purity carbon dioxide • Regeneration requires lower temperatures and less heat compared to absorption. • It can be utilized in temperature or pressure swing processes.	• High cost of material for some adsorbents • Requires adsorbent regeneration
Cryogenic separation	• Can achieve very high-purity carbon dioxide • The technology has reached a stage of commercial maturity and has been proven effective.	• The process is highly energy-intensive because it requires extreme cooling. • High-purity carbon dioxide is expensive and usually only cost-effective in specific applications.
Membrane separation	• The majority of membrane systems do not necessitate heat energy, resulting in a decrease in energy requirements. • The design of these systems is compact and modular. • These systems can produce continuous separation.	• Prone to deterioration and fouling of membranes. • Highly selective and permeable membranes are needed for cost-effective operation.

4.2 Absorption

Absorption is a separation process in which one substance in a gas mixture is absorbed through contact with a liquid, where one component is absorbed while the other is not [44]. This method is commonly used in the chemical and oil industries to capture carbon dioxide and also used to absorb carbon dioxide (CO_2) from exhaust gases and incorporate it into solutions containing amine-based substances, which react with and capture the CO_2, forming dissolved bicarbonates and carbonates through chemical means until equilibrium is reached. Solvent scrubbing typically entails using a chemical solvent in the flue gas that interacts with carbon dioxide and is then regenerated at higher temperatures, creating a purified carbon dioxide (CO_2) stream suitable for compression and storage.

Chemical absorption makes use of solvents like mono-ethanolamine (MEA), Diethanolamine (DEA), tri-ethanolamine (TEA), Diglycolamine (DGA), N-Methyldiethanolamine (MDEA), and 2-amino-2-methyl-1-propanol (AMP), as well as glucosamine (GA), to dissolve carbon dioxide. Alkanolamines are selected based on their ability to absorb CO_2 over other gases like oxygen, ammonia, or flue [45,46]. The absorption of CO_2 refers to capturing carbon dioxide from the atmosphere using various techniques. This can be achieved through physical or chemical means, such as utilizing absorbents such as NaOH, ionic liquids, alkanol amines, and aqueous amine solutions [47,48]. The process of the solute gas being taken in by the absorbent may be broken down into three parts, which can be represented using the resistance-in-series model. Figure 4 depicts the mass transfer process within an absorption column. The interaction between the gas and the liquid occurs at the surface of the packing components. It is defined by the process of CO_2 molecules diffusing through the gas film, being absorbed in the liquid phase, and then diffusing through the liquid film [49]. At a particular point of an absorber column, mass transfer occurs because of a chemical potential gradient between gas and liquid phases. The mass transfer ends when equilibrium is reached. In other words, when the net mass transfer becomes zero [50]. Absorption methods are crucial in reducing greenhouse gas emissions, particularly CO_2, which accounts for a significant portion of these emissions [51]. Studies have shown that factors like CO_2 flow rate, absorbent concentration, temperature, and the presence of ions in the solution can impact the efficiency of carbon dioxide absorption [52].

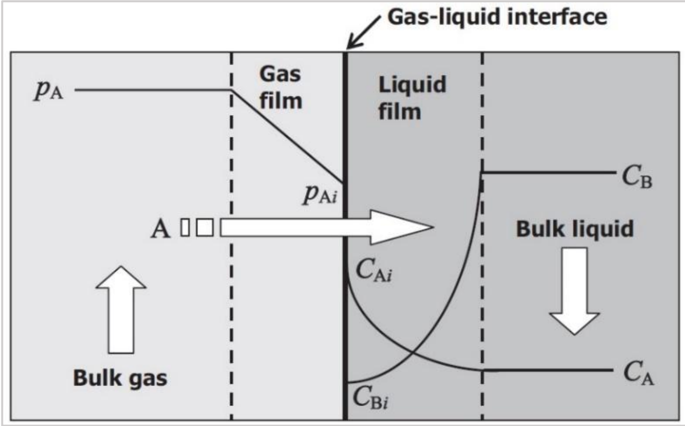


Figure 4: Reactive absorption modal based on the two-film theory [53]

5. Absorbent type effect on the absorption performance

The type of absorbent significantly impacts the absorption performance in CO_2 capture. Various absorbents like inorganic reagents, organic amines, ionic liquids, non-amine alkaline solutions, and sterically hindered amines have been studied for their effectiveness in CO_2 capture [54]. The chemical absorption method involves using a liquid solution, typically an alkaline solution, to selectively remove combustion flue gas components easily soluble in absorbent by chemical reactions [55]. Chemical absorption separation has the advantages of high efficiency, low cost, and easy availability of materials. The ideal carbon dioxide absorber should have a high absorption capacity, fast absorption rate, and low energy consumption for regeneration, as well as the characteristics of safety and stability, environmental friendliness, low equipment corrosion, and good economy [56]. The absorbent serves as the central component in the chemical absorption technique for CO_2 removal. Chemical absorbents commonly employed include inorganic reagents, organic amines, and ionic liquids, among other most common substances. The various kinds of CO_2 absorption and their respective advantages and disadvantages are presented in Table 3.

Table 3: Chemical absorbents and their advantages and disadvantages

Chemical absorbent	Type	Advantages	Disadvantages	Ref.
Inorganic absorbent	$Ca(OH)_2$, Na_2CO_3, $NH_3.H_2O$, NaOH, k_2CO_3, etc	Low cost, non-volatile	Some reagents have low solubility and the rate of absorption slow	[54]
Organic amine absorbent	Monoethanolamine (MEA), Methanol amine, etc.	cheap solvents, strong CO_2 absorption capacity, fast absorption rate	Degradation equipment corrosion, High energy consumption, and easy foaming	[57]
Ionic liquid	Cations: pyridine, imidazole, quaternary amine and pyrrolidine, etc. Anions: halogens, carboxylic acids boric acids, etc.	High solubility and selectivity of CO_2, Low regenerative energy demand, No equipment corrosion problem	High viscosity and low mass transfer rate of CO_2, Only used in the laboratory	[10] [58]

Chemical absorption by alkanolamine solvents is a well-established commercial process for capturing CO_2 in various industrial applications. This method is known for its high absorption efficiency and capability to enhance power plants' performance [59]. The primary amine (MEA) is the most well-known and widely utilized absorbent in the industry of CO_2 capture [60- 62]. MEA has a fast absorption rate, cheap solvent, high selectivity, and removal efficiency [53].

Methyl diethanolamine (MDEA) has good chemical stability, the solvent is not easily degraded, and the absorption volume is large, but the absorption time is long. MEDA plays a catalyst-like role in the absorption of CO_2. Still, when reacting with CO_2, MEDA must be hydrolyzed before slowly reacting with CO_2 and generating sub-stable bicarbonate, which can lead to a slower absorption rate of MDEA, which is its biggest defect [63]. The amine scrubbing process is extensively utilized in the carbon dioxide capture industry due to its mature process, convenience of operation, rapid carbon dioxide absorption rate, high absorption capacity, and ability to be recycled, occupying more than 60% of the market share in carbon capture [64-66]. Although amine scrubbing is widely accepted as a technology worldwide, its commercial application is significantly hindered by water evaporation from the absorption tower, the escape of amines, and the high heat required for desorbing amine and carbon dioxide mixtures. These problems lead to significant energy losses during the amine absorption process and pose potential environmental risks [67-70].

ILs are effective molecular and/or environmentally friendly solvents that can be utilized instead of routinely employed volatile organic solvents [71]. Specific biological, chemical, physical, and thermal properties are associated with them. Typically, ILs refers to liquids that exist only in ionic form. However, it is also recognized in its classical form as room temperature or below ≤100 °C ILs, fused salt, molten salt, organic salt liquids, and numerous more and composed of anions and cations [72]. Ionic liquids have extremely low saturation vapor pressure, good thermal stability, and a customizable structure. They cause minimal environmental pollution through volatilization and can be easily separated from other substances for recycling. Ionic liquids primarily capture carbon dioxide through their basic group, directly capturing it with their structure [73]. ILs are still not preferred commercially due to their high viscosity and low absorption capacity [74,75].

Commonly used CO_2 inorganic adsorbents are $Ca(OH)_2$, K_2CO_3, Na_2CO_3 , $NH_3.H_2O$ and NaOH, etc. $Ca(OH)_2$ reacts rapidly with CO_2 within a wide temperature range. The $Ca(OH)_2$ concentration influences the absorption of CO_2, with saturated solutions capable of absorbing more CO_2 than the theoretical amount. However, the energy consumption for Ca $(OH)_2$ preparation is high, and the preparation process releases CO_2, which limits the application of this method. K_2CO_3 is a cost-effective, non-volatile, and less toxic alternative to organic amines. Nevertheless, its solubility is low at lower temperatures, leading to a slower absorption rate of CO_2. Furthermore, the $KHCO_3$ produced by the reaction of K_2CO_3 and CO_2 is highly corrosive, necessitating the addition of corrosion inhibitors such as V_2O_5, As_2O_3, etc. $NaCO_3$ is commonly utilized to absorb carbon dioxide from flue gases, yielding highly pure CO_2, up to 99%. However, its high cost and substantial water consumption pose disadvantages. $NH_3.H_2O$ enables fast and efficient CO_2 absorption, offering relative stability and resistance to degradation. Additionally, the by-products formed by $NH_3.H_2O$ and CO_2 can be repurposed as scrap [54]. The usage of sodium hydroxide for CO_2 absorption has been studied intensively for the past eighteen years. However, most studies focused on academic endeavors like absorption mechanisms and system performance rather than carbon dioxide capture [76,77].

Sodium hydroxide exhibits superior carbon dioxide absorption capabilities compared to MEA absorbent. According to Yoo et al. [78], the theoretical ability of NaOH to absorb CO_2 is 1.11 tons per ton of NaOH, whereas MEA has an approximate capacity of 0.72 tons per ton of MEA. Furthermore, NaOH is more plentiful and cost-effective than MEA. Additionally, metal oxides like calcium oxide and magnesium oxide to amine absorbents have been shown to enhance CO_2 absorption rates and decrease saturation times to clarify this further, Nie et al. [79], explored the effect of metal oxides on absorbent materials by analyzing the process of carbon dioxide absorption using N-methyl diethanolamine (MDEA) after adding both calcium and magnesium oxides to the MDEA solution. The effects of each metal oxide on CO_2 retention by the MDEA solution were evaluated. Adding these oxides in certain proportions was found to accelerate the carbon dioxide absorption rate and shorten the MDEA solution's saturation time by 9% - 17%. These findings underscore the importance of selecting the appropriate sorbent type to optimize carbon capture efficiency.

6. The effect of reactor structure on absorption performance

Many researchers have used various reactors to capture carbon dioxide gas, and the chemical method can improve carbon dioxide absorption efficiency. Various researchers have compiled the absorption characteristics of multiple reactor designs in Table 4.

Table 4: Comparison of typical reactors for carbon dioxide carbon dioxide absorption

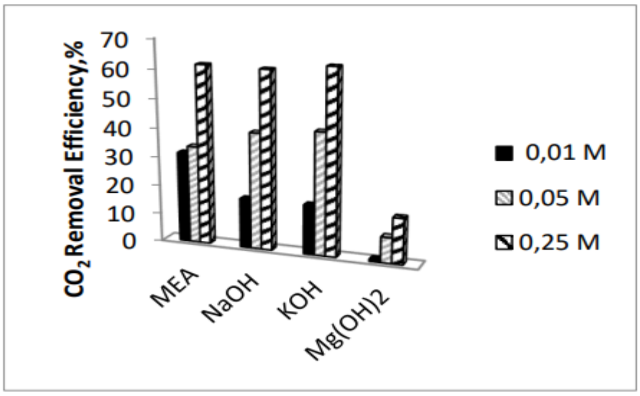
Reactor type	Absorbent type	Concentration absorbent	The flow rate of absorbent	Concentration of CO_2	The flow rate of gas	Reaction temperature	Ref.
Packed column	Aqueous ammonia	1.16-8.81 mol/L	0.13,0.2,0.26, 0.33 and 0.4 L/min	15%	10,16,20, 24,28 L/min	20-55 °C	[80]
Microchannel reactor	MEA	0.165 mol/L 0.331 mol/L 0.496 mol/L	0.01,0.02,0.03 L/min		3,5,7 L/min	25,35,45 °C	[81]
Tubular reactor	NaOH	0.00728 mol/L	20.6-53 L/min	30% v/v CO_2/air	2.9-17.66 L/min	-	[82]
Internal-loop airlift reactor	NaOH	0.1 mol/L	0.17-0.38 L/min	20-80%	4-10 L/min	25 °C	[83]
Packed column reactor	NaOH	0.5-1 mol/L	1-7 L/min	10-15%	40-180 L/min	-	[84]
Pyrex reactor	NaOH	0.026-0.13 mol/L	0.5 L/min	31.5%	3 L/min	25 °C	[78]
Rotating packed bed (RPB)	Novel non-aqueous absorption AMP-AEEA-NMP	3.6 mol/L	-	14%	33.3 L/min	25-60 °C	[85]
Bubble Column Reactor	Different solvents (MEA, NaO)H, KOH,and $Mg(OH)_2$)	0.01 mol/L 0.05 mol/L 0.25 mol/L	0.5 L/min	5%	4 L/min	A troo mtemperature	[86]

7. Operating conditions affect the absorption efficiency

Besides reactor structure, reaction parameters significantly impact CO_2 absorption performance by different solvents. These parameters usually include absorbent concentration, absorbent flow rate, CO_2 concentration, gas flow rate, and operating temperature.

7.1 Absorbent concentration

The concentration of the absorbent plays a crucial role in the efficiency of carbon dioxide (CO_2) capture in different capture processes. Research indicates that increasing the absorbent concentration generally leads to higher absorption rates, overall mass transfer coefficients (K_Ga), and carbon dioxide removal efficiency [43]. For instance, in the study conducted using a bubble column reactor and different types of solvents (MEA, NaOH, and KOH) solvents at a flow rate of 500 ml/min. The absorption rates and carbon dioxide removal efficiency were maximized at high concentrations of these solvents with values exceeding 60% of the efficiency by increasing the concentration of absorbent materials from (0.01-0.25 mol/L) Figure 5 (a,b) [86]. Similarly, experiments conducted by Kazemi et al. [87], on aqueous piperazine solutions and stirred reactor using different concentrations of the absorbent material, where it was noted that the absorption efficiency increased from 70 to 95% when the concentration was raised from 0.5 to 1.5 mol/L at different pressure and temperature Figure 5c.



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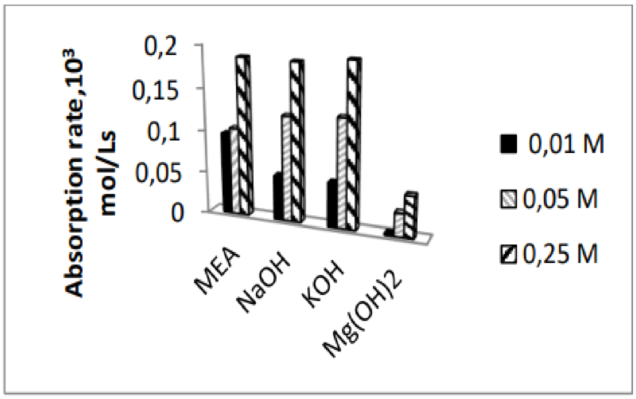

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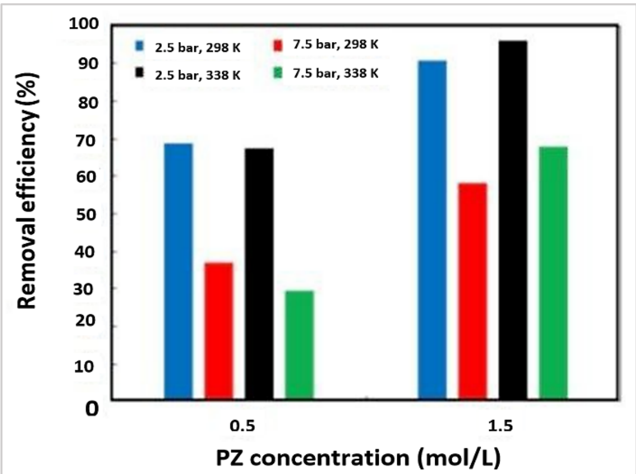

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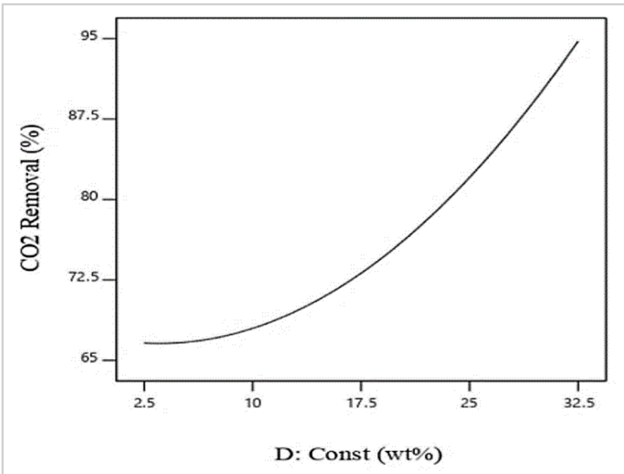


(d)

Figure 5: The effect of absorbent concentration on carbon dioxide absorption performance. (a,b) The effect of different concentrations on CO_2 removal efficiency and absorption rate [86], (c) The effect of concentration on removal efficiency [87], and (d) The effect of concentration on CO_2 removal% [91]

Liao et al. [88], conducted empirical investigations on the CO_2 absorption process using a mixed solution of DEEA and MEA at various amine concentrations. The investigation revealed that the most effective chemical concentration was 2.75 (mol/L). A study found that the K_Ga value increased from 0.55 to 1.08 kmol/m^3.hr kPa when the chemical concentration was raised from (2 to 2.75) mol/L. The increase in the mass transfer coefficient with an increase in the concentration of the absorbent material. Once the chemical concentration was above 2.75 mol/L, the K_Ga fell to 0.8 kmol/m^3.hr kPa. This is due to the saturation of the active sites of the absorbent material, which leads to a decrease in the reaction rate when the concentration increases further. Ma et al. [89], discovered that a concentration of 0.6 mol/L of [Apmim][BF4], resulted in the greatest k_L value of 20.7×10^{-4} m/s. To determine the optimal concentration for CO_2 reduction, a study was conducted on the effect of Na_2CO_3 solvent concentration on the absorption process (1.42,1.89,2.36,2.83 and 3.30 mol/L). This study found the optimal concentration for CO_2 reduction was (2.36 mol/L) because the reaction between Na_2CO_3 and CO_2 is an equilibrium reaction, so at high concentrations (2.83 mol/L and 3.30 mol/L), absorption leads to a turning point in the reaction. The absorption process becomes less ideal than the (2.36 mol/L) concentration [90]. Janati et al. [91], conducted a study on carbon dioxide (CO_2) absorption using (MEA+DEA or MEA+TEA) in a T-junction microchannel (d_h=600 µm; Lc=25 cm). They found that for the MEA+DEA solvent, the carbon dioxide removal efficiency increased with both amine concentration and volume percentage. In the case of the MEA+TEA solvent, these effects appeared to be more sensitive and complex, exhibiting a parabolic trend. The optimal values were 21.5 wt% for amine concentration and 4 vol/vol% for volume percentage, respectively Figure 5d.

7.2 Absorbent flow rate

The effect of the absorption material flow rate on the efficiency of carbon dioxide gas absorption was reviewed using different absorbent materials and different types of reactors. Several researchers have conducted studies on the absorption of CO_2. In a study conducted by several researchers, 40 grams of sodium hydroxide were dissolved to obtain a sodium hydroxide solution with a concentration of 0.1N. A high absorption rate was achieved with an increase in the flow rate of the absorbent material [92]. Xu et al. [93], studied the absorption process using 3 kmol/m^3 of DEEA solution for 0.1 and 0.3 mol/mol of lean CO_2 loading at different liquid flow rates (3.9 to 11.7 m^3/m^2.hr). The absorption of CO_2 into DEEA was carried out under a CO_2 partial pressure of 15 kPa. At increasing liquid flow rates, the K_Ga (mass transfer coefficient) for amine solution with a CO_2 addition of 0.1 mol/mol increased marginally from (0.15 to 0.18) kmol/m^3.hr.kPa. The solution with a CO_2 input of 0.3 mol/mol had a maximum K_Ga value of 0.13 kmol/m^3.hr.kPa. Therefore, the system demonstrated that CO_2 absorption at a lean CO_2 loading of 0.1 mol/mol with the greatest K_Ga value of 0.18 kmol/m^3.hr.kPa was effective.

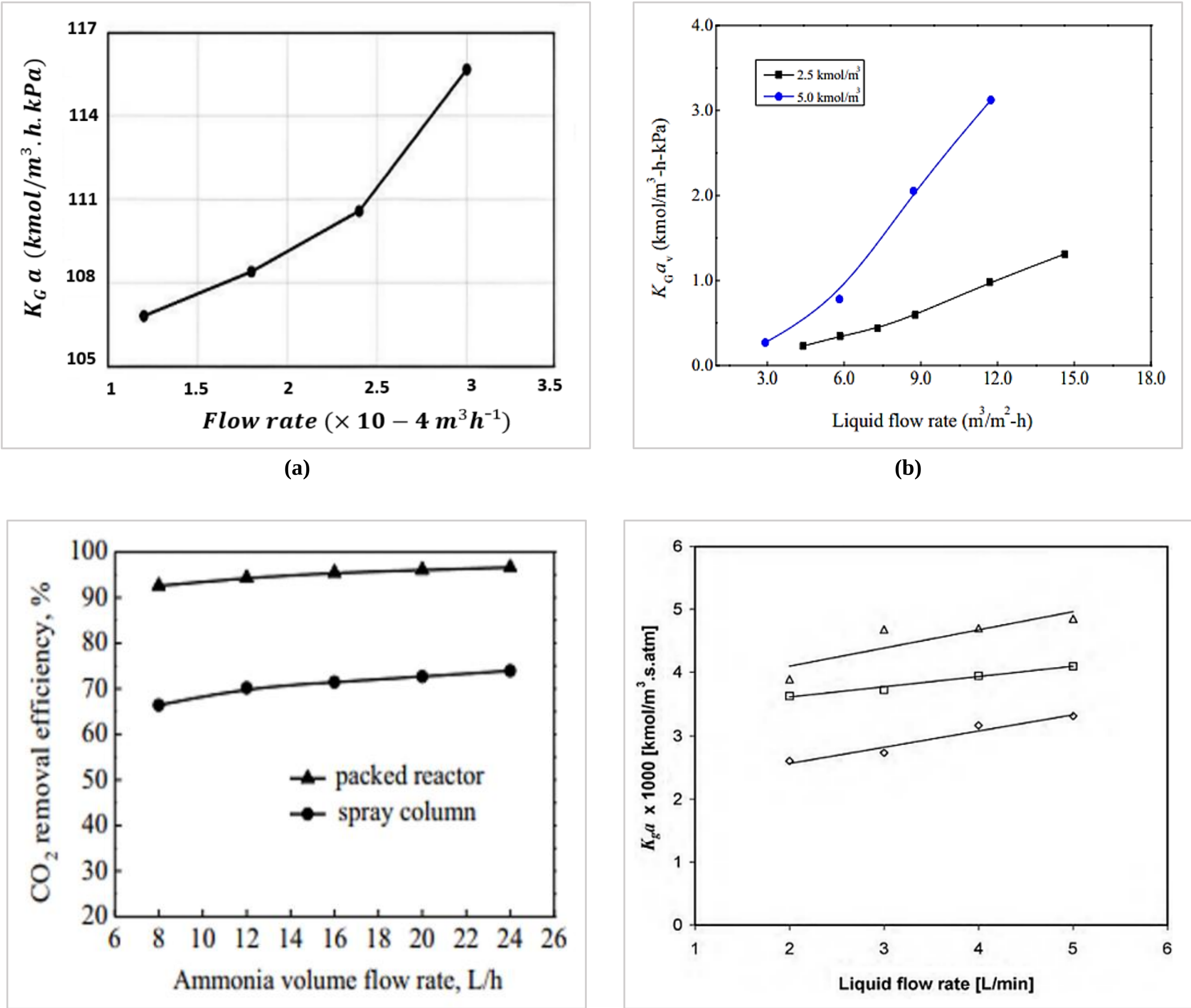


Figure 6: The effect of absorbent flow rate on CO_2 absorption performance, (a) the effect of absorbent flow rate on K_Ga [94], (b) the effect of the liquid flow rate on K_Ga [95], (c) The effect of ammonia flow rate on the CO_2 removal efficiency [97], and (d) the effect of liquid flow rate on K_Ga [98]

Cheng et al. [94], tested a CO_2/ammonia solution system in a T-type microchannel (500 µm×500 µm×60 mm) and showed a 10% increase K_Ga with the increasing Q_L (0.12-0.3 ml/h) Figure 6a. Fu et al. [95], observed that the K_Ga (mass transfer coefficient) rose as the liquid flow rate increased, ranging from 2.92 to 14.63 m^3/m^2.hr. This was observed for two different concentrations of MEA-MeOH blended solution (2.5 and 5.0 kmol/m^3) during CO_2 absorption at a carbon dioxide partial pressure of 13.4 kPa. The K_Ga value increased from (0.3 to 3.2) kmol/m^3.hr.kPa when the solvent concentration was 5.0 kmol/m^3. Similarly, the K_Ga value increased from 0.29 to 1.4 kmol/m^3.hr.kPa when the solvent concentration was 2.5 kmol/m^3 Figure 6b. The percentage of CO_2 gas absorption is affected by the flow rate of the absorbent. The higher the flow rate, the greater the mol K_2CO_3 and H_2O, resulting in more carbon dioxide gas reacting. Therefore, the percentage removal of carbon dioxide gas from the gas phase to the liquid phase increases [96].

One of the studies conducted by Qing et al. [97], found that the flow rate of aqueous ammonia solution significantly impacts the efficiency of carbon dioxide removal. It was found that increasing the flow rate of aqueous ammonia from (8 to 24) L/h increased the efficiency of carbon dioxide removal from 66.38% to 73.92% in the spray column, thus increasing the absorption capacity Figure 6c. Another study showed that the interfacial surface area per unit volume inside the column increased by increasing the waste flow rate from 2 liters/minute to 5 liters/minute in the CO_2 absorption process using a spray column Figure 6d [98]. Meanwhile, Ling et al. [99], conducted CO_2 absorption experiments employing a blended solution of MEA+1DMA2P at a CO_2 partial pressure of 13.4 kPa. The liquid flow rate ranged from (2.92 to 5.85 m3/m2.hr). According to the authors, the rise in KGa from (0.4 to 1.8 kmol/m3.hr.kPa) was attributed to an augmented effective contact area for the reaction at elevated liquid flow rates.

7.3 Temperature

The relationship between temperature and the efficiency of carbon dioxide absorption is intricate and influenced by factors such as reactor structure and other operational procedures [100]. Aghel et al. [101], compared the efficiency of carbon dioxide in three different absorbents (MEA, DEA, and a-MDEA) in a circular microchannel where the hydraulic diameter (d_h) was 600 µm and the length of the channel (Lc) was 25 cm. The tests were conducted at various temperatures. The results shown in Figure 7a indicate that at temperatures below 300 K, the mass transfer flux of CO_2 exhibited a decreasing trend, primarily due to physical absorption, especially for a-MDEA. In contrast, both MEA and DEA exhibited a peak in mass transfer due to chemical absorption. Gul and Un [102], explained the effect of temperature on the absorption capacity of carbon dioxide in a bubble column, where the absorption capacity showed a clear decrease from (0.456 mol CO_2/ mol MEA to 0.32 mol CO_2/ mol MEA) with increasing temperature (25 ℃ to 45 ℃ when using 20% MEA solution Figure 7b. This resulted from the thermodynamics of the exothermic CO_2 absorption system, which could lead to reversible reactions under high temperatures.

Raising the temperature can elevate the CO_2 vapor pressure above the solution, resulting in a reduction in the physical solubility of CO_2 in the solvent [103]. Xu et al. [93] found that the absorption of CO_2 into a DEEA solution with a concentration of 3 kmol/m^3 increased K_Ga when the inlet temperature was raised from 273 K to 333 K. The enhanced mass transfer can be attributed to the decrease in solvent viscosity at higher inlet liquid temperatures, leading to a higher solubility of CO_2 [93], in studies by Sayar et al. [48], the absorption method was used to determine the overall process of carbon dioxide removal, where the effect of several variables on the carbon dioxide absorption rate was studied, including temperature. It was found that temperature is one of the most influential factors on the absorption rate, as illustrated in Figure 7c. It can be concluded that high temperatures are required to achieve the highest absorption rate.

The best conditions for optimal absorption are at T=40, where the absorption rate was 0.077 mol/Kg.min [48]. Several studies have shown that absorption efficiency increases with temperature, while others have shown a decrease in absorption efficiency with higher temperatures. For example, the study by Kazemi et al. [87], observed that the absorption flux, removal efficiency, and loading of CO_2 increased with decreasing temperature by stirred reactor. Monde et al. [104], found that the loading capacity and CO_2 removal increased with the increase in temperature Figure 7d . In general, the optimum reaction temperature cannot be determined except based on a comprehensive study of the absorption reactor and operating conditions [105].

7.4 CO_2 concentration

The concentration of carbon dioxide in the gas feed significantly impacts the absorption efficiency in CO_2 capture processes. For instance, potassium carbonate promoted with glycine as a green solvent showed varying carbon dioxide removal efficiencies based on the CO_2 concentration in the gas feed. CO_2 removal efficiency decreased from 79.24 to 65.79 % as the CO_2 concentration in the gas feed increased from 15 mol% to 30 mol% Figure 8a [106]. Qing et al. [97], studied the CO_2 absorption into an ammonia aqueous solution using a packed reactor and a spray column. They evaluated the removal efficiencies over a range of main operating variables, including carbon dioxide inlet concentration, which was increased from 5% to 15%. According to the two-film theory, increasing CO_2 partial pressure increases the gas-phase driving force and the gas-phase mass transfer coefficient. This increase is advantageous for enhancing the absorption rate. Increasing the CO_2 partial pressure facilitates the movement of additional CO_2 molecules from the gas bulk to the gas-liquid interface, improving removal efficiency. The molar ratios of ammonia to carbon dioxide (CO_2) decreased from 13.78 to 4.59, with an increase in the inlet concentration of carbon dioxide from 5% to 15%. This decrease in ratios resulted in a loss in removal efficiency. Therefore, the effectiveness of CO_2 removal somewhat decreased as the concentration of carbon dioxide entering the packed reactor and spray column increased Figure 8b [97].

The study conducted by Rajiman et al. [107], on removing carbon dioxide through chemical absorption from biogas in a packed absorption column using 30% MEA (Monoethanolamine) determined the effect of gas concentration on the efficiency of carbon dioxide removal. Two different concentrations (30% and 40%) were used, and the efficiency was evaluated along the length of the column. The results showed that 30% carbon dioxide in the feed gas had a higher removal efficiency than 40%, which could remove 94% of CO_2 Figure 8c. In addition, Wu et al. [108], designed a spray tower with varying diameters and a new spray mode using dual nozzles to improve the efficiency of the CO_2 absorption process. They also investigated the impact of CO_2 concentration on the rate of CO_2 removal and the overall mass transfer coefficient Figure 8d. The experimental data indicates that as the CO_2 content increases from 8 vol% to 18 vol% at a fixed liquid flow rate of 80 $L.h^{-1}$, the CO_2 removal rate decreases from 92.2% to 84.0%. The total mass transfer coefficient decreases from 0.427 to 0.292 $kmol\cdot m^{-3}.h^{-1}.kPa^{-1}$. According to the two-film hypothesis, increased CO_2 concentration increases the driving force and mass transfer coefficient in the gas phase.

This, in turn, enhances the absorption process. Studies have shown that as the CO_2 concentration in the gas feed increases, the CO_2 removal efficiency tends to decrease due to limitations in the liquid phase's ability to absorb high CO_2 concentrations [86].

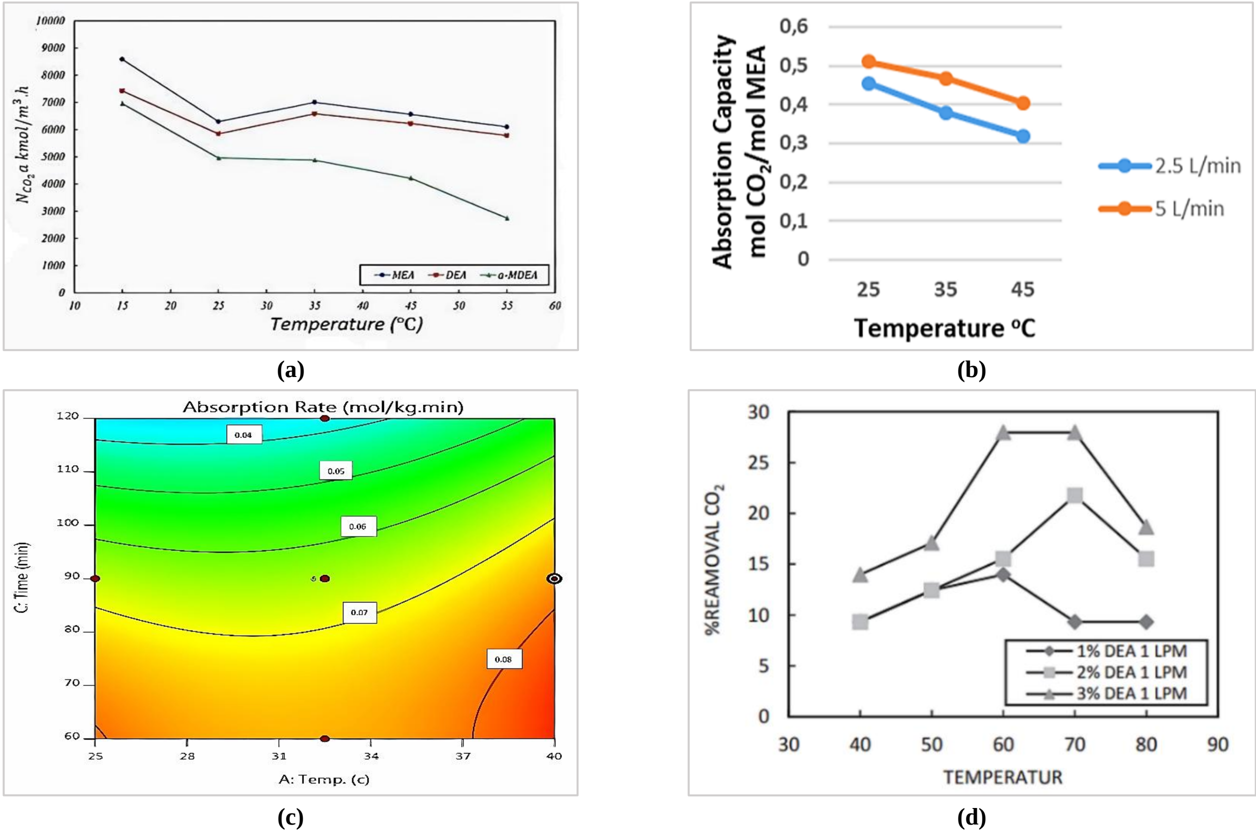


Figure 7: The effect of temperature on CO_2 absorption performance, (a) effect of temperature on CO_2 mass transfer flux [94], (b) the effect of temperature on the absorption capacity [102], (c) the effect of the temperature and time on the absorption rate [48], and (d) the effect of temperature on CO_2 removal efficiency [104]

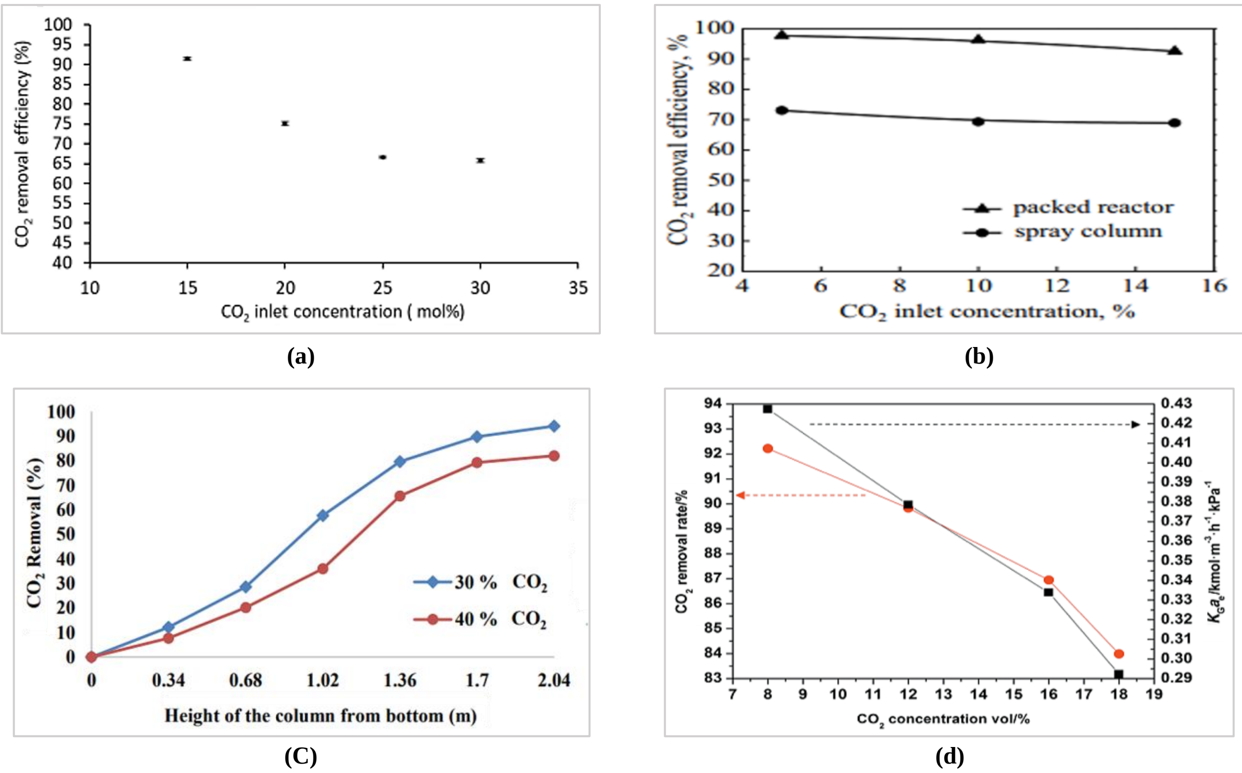
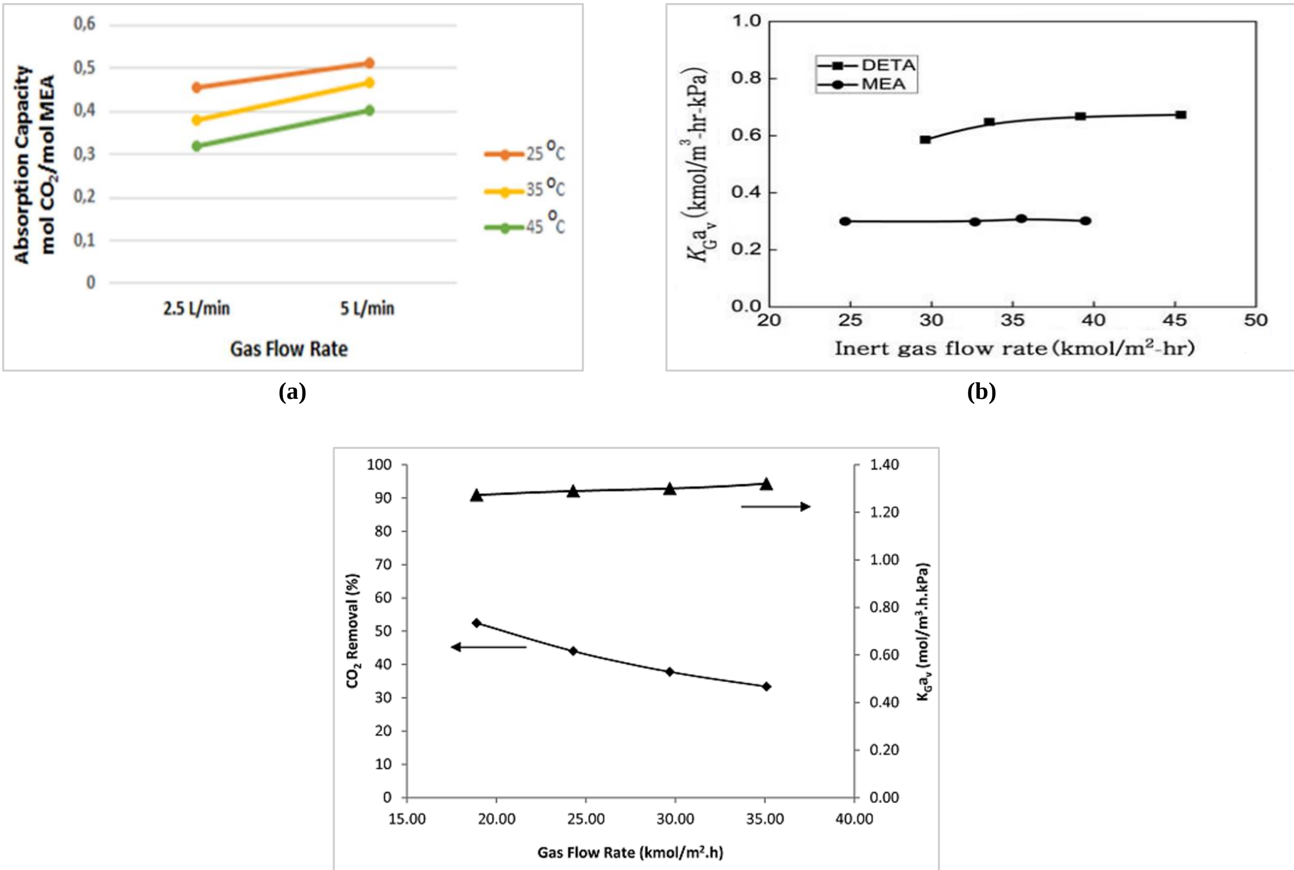


Figure 8: The effect of carbon dioxide concentration on CO_2 absorption performance. (a) CO_2 removal efficiency over various carbon dioxide concentrations [106], (b) The effect of inlet concentration of CO_2 on carbon dioxide removal efficiency [97], (c) The impact of different CO_2 concentrations on carbon dioxide removal [107], and (d) effect of CO_2 concentration on the CO_2 removal rate and K_Ga [108]

7.5 Gas flow rate

Carbon dioxide gas has a flow rate that significantly impacts the absorption process when using different absorbents. Higher CO_2 flow rates can decrease the absorption factor due to reduced contact time between CO_2 gas and the absorbent, as observed in the CO_2 absorption process with NaOH [47]. The researchers Ayse Gul et al. [102] examined the impact of the flow rate of CO_2 on its ability to be absorbed, measured in terms of the absorption capacity (in grams of CO_2 per kilogram of solvent and in moles of CO_2 per mole of MEA). This investigation was conducted in a bubble column reactor using a semi-batch operation, with a 20% MEA solution employed as the solvent.

The CO_2 capture efficiency per solvent unit improves as the gas flow rate increases. The CO_2 absorption capacity per solvent unit increased from 66.27 g CO_2/kg solvent to 74.71 g CO_2/kg solvent. The CO_2 absorption capacity per unit of MEA increased from 0.456 mol carbon dioxide (CO_2)/mol MEA to 0.51 mol carbon dioxide (CO_2)/mol MEA when the gas flow rate was increased from 2.5 L/min to 5 L/min. As the gas flow rate increased, the time the gas spent in the solution reduced. Nevertheless, an increased flow rate induces turbulent conditions within the column, which promotes efficient mass transfer. As the gas flow rates increase, the force that drives the transfer of carbon dioxide molecules from the gas phase to the gas-liquid boundary layer is enhanced. This leads to the rise in the mass-transfer coefficient Figure 9a [102]. Fu et al. [109], discovered that when using different flow rates of inert gas, there were minimal changes in the absorption of CO_2 in diethylenetriamine (DETA) and MEA solutions at a constant CO_2 partial pressure of 15 kPa as the inert gas flow rate increased from 25 to 45 kmol/m^2.hr, they observed insignificant changes in K_Ga values for both solvents due to the gas phase having negligible resistance (see Figure 9b). Gul et al. [110], studied the absorption process using a bubble column reactor and MEA absorbent. This study showed the effect of the inlet gas flow rate change at the range of (4–6) L/min on the absorption capacity and the overall mass transfer coefficient at a temperature of 25 °C. The gas flow rate positively affected the K_Ga, whereas higher flow rates improved K_Ga. There was almost a 53% increase in K_Ga when the flow rate was increased from 4.0 to 6.0 L/min at higher absorbent concentrations. No significant change was observed in the absorption capacity [110]. Abdul Halim et al. [111], conducted experimental research on the absorption of CO_2 into a MEA solution with a concentration of 2 mol/L. The experiments were carried out at a CO_2 partial pressure of 1010 kPa, and the process was completed at various gas flow rates ranging from 18.89 to 35.08 kmol/m^2.hr. The K_Ga rose slightly from 1.27 to 1.32 mol/m^2.hr.kPa due to the increased gas flow rate. The result was determined by the liquid phase's control over the absorption process, meaning that any alterations in the gas phase did not impact the process Figure 9c. Khan et al. [112], in a packed column using a means of aqueous (MDEA + PZ) as an absorbent for post-combustion carbon dioxide capture technology, it was observed that the removal efficiency of carbon dioxide gradually decreases as the gas flow rate increases from (5 to 8) L/ min at CO_2 partial pressure of 15 kPa.



(a) (b)

(c)

Figure 9: The effect of gas flow rate on CO_2 absorption performance. (a) The effect of gas flow rate on the absorption capacity [102], (b) The effect of inert gas flow rate on K_Ga [109], and (c) The effect of total gas flow rate on CO_2 removal% and K_Ga [111]

8. Future work

Despite abundant research worldwide on carbon dioxide capture by absorption, more efforts are needed to develop new mechanisms for CO_2 capture. Some future suggestions could significantly reduce carbon emissions, address climate change, and ensure a sustainable future.

1) A new reactor and additional development to increase the capacity for absorbing carbon dioxide gas can enhance mass transfer between the gas and liquid phases. This could achieve CO_2 removal rates that have not been previously attained. Therefore, developing the reactor should be a focus of future efforts in the near term.
2) Converting carbon into valuable products such as synthetic fuels, plastics, and other chemicals can reduce dependence on fossil fuels and provide an economic solution to carbon emissions.
3) Develop new absorbent solutions that combine the advantages of traditional amines with modern chemicals to increase carbon capture efficiency and reduce equipment corrosion problems caused by amine solutions.

9. Conclusion

With the increasing environmental disasters related to weather due to the rapid growth of carbon dioxide (CO_2) emissions from human activities across various industrial sectors, reducing CO_2 emissions is imperative to alleviate global warming. Consequently, many carbon capture processes have been developed, including absorption, adsorption, and others mentioned in the current review. As an innovative contribution, we collected and classified the most important sorbents into three basic divisions and clarified their advantages and disadvantages. In addition, a comprehensive study was presented for the most efficient bioreactors in absorption. Despite several capture technologies, post-combustion capture is the most widely used globally due to its economic and technological advantages. This review discussed various operational factors affecting absorption efficiency and identified the most common types of absorbent materials used in chemical absorption. Despite their many advantages, these materials have significant drawbacks, including thermal degradation, oxidation, equipment corrosion, and high energy consumption. The eighth section of this review also compared the most well-known bioreactors globally in terms of absorbent concentrations, temperature, type of absorbent material, CO_2 gas flow rate, and other factors. It also suggests the most important future work in this field that can help develop carbon dioxide capture processes. Thus obtaining a green environment free of pollution. This paper is written in a way that allows the reader to easily access the most critical research related to CO_2 capture through chemical absorption

Author contributions

Conceptualization, H. Al-Maaine. and N. AlHaboubi; data curation, H. Al-Maaine. and N. AlHaboubi; formal analysis, H. Al-Maaine. and N. AlHaboubi.; investigation, H. Al-Maaine.; methodology, H. Al-Maaine. and N. AlHaboubi.; project administration, H. Al-Maaine. and N.AlHaboubi, resources, H. Al-Maaine. and N. AlHaboubi.; software, N. AlHaboubi.; supervision, N. AlHaboubi.; validation, H. Al-Maaine. and N. AlHaboubi.; visualization, H. Al-Maaine. and N. AlHaboubi.; writing—original draft preparation, H. Al-Maaine and N. AlHaboubi; writing—review and editing, H. Al-Maaine. and N. AlHaboubi. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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