AIMS Environmental Science

AIMS Environmental Science, 13(4): 797–827.
DOI: 10.3934/environsci.2026032
Received: 22 June 2026
Revised: 07 August 2026
Accepted: 16 September 2026
Published: 18 September 2026

http://www.aimspress.com/journal/environmental

Review

Insight into carbon dioxide gas (CO2) capturing technologies: A review

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Abstract: As global imperatives demand urgent climate action, carbon capture, utilization, and storage (CCUS), technologies stand at the forefront of industrial decarbonization. In this review, we provide a critical and comprehensive insight into the current landscape of carbon dioxide (CO_2) capturing methodologies, bridging the gap between foundational chemical processes and next-generation innovations. By systematically evaluating the technical efficiencies, economic viability, and scalability bottlenecks of diverse pathways, including absorption, adsorption, and advanced membrane systems, this paper offers a definitive roadmap to guide future research and accelerate the deployment of viable net- zero solutions. Concern about climate change has increased over the years from a global viewpoint. To date, the reduction of CO_2emissions remain aesthetic attention and consideration abroad the nations, owing to the toxicity of CO_2gas and the seriousness of its release into the air; it has become possible to collect it and sell it in hard currency in the global markets. With the renaissance of capturing CO_2 gas, there has been a steadily growing interest in this research field. Confirming the assertion, we

present a state-of-the-art review of CO_2 gas capturing, collection, and utilization by physical processes. There are several technologies, such as Absorption, Adsorption, Membrane, Cryogenic Distillation, and others, to capture and separate CO_2 gas to use it as a raw material in other industries or for storage on capture storage (CCS), carbon capture utilizing and storage (CCUS), and to obtain financial benefits from the Certificates of Emissions Reduction (CER) in carbon markets. Until now, only absorption technology has been applied in the industry, although it includes some problems and requires work to develop it to increase its advantages and reduce its disadvantages. For the other technologies, more research is needed to improve the technical procedure to reduce the problems in them and increase the benefits for everyone, such as the key advances of CO_2 capturing, its utilization principles, and comparisons of capturing and selling. Conclusively, this research paper will enhance the researchers' concept and fill the gap toward a green environment.

Keywords: carbon dioxide; capturing; global warming; climate change; carbon market; UNFCCC

Nomenclature	
CCS	Carbon Capture Storage
CCUS	Carbon Capture Utilizing & Storage
CER	Certificates of Emissions Reduction
AR	Assessment Report
AR1	First Assessment Report
AR2	Second Assessment Report
IPCC	The Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention for Climate Change
COP	Conference of the Parties
KP	Kyoto Protocol
PA	Paris Agreement
PPM	Part Per Million
NASA	National Aeronautics and Space Administration
TRL	Technology Readiness Level
TRL1	First Technology Readiness Level
TRL2	Second Technology Readiness Level
GHG	Greenhouse gases
CO_2	Carbon Dioxide gas
CH_4	Methane gas
N_2O	Nitrous Oxide gas
CFC_S	Chlorofluorocarbons gases
N_2	Nitrogen gas
O_2	Oxygen gas
GWP	Global Warming Potential
INDC	Intended Nationally Determined Contribution
NDC	Nationally Determined Contribution
MEA	Mono Ethanol Amine

MDEA	Methyl Di-Ethanol Amine
LNG	Liquefied Natural Gas
EPRI	Electric Power Research Institute
IEA	The International Energy Agency
PMR	Partnership for Market Readiness
CPLC	Carbon Pricing Leadership Coalition
MAAP	Mitigation Action Assessment Protocol

1. Introduction

Driven by atmospheric carbon dioxide (CO_2) concentrations exceeding 410 ppm and a global temperature rise of over 1.0°C [1], international frameworks like the UNFCCC and the Paris Agreement mandate urgent emission reductions [2]. Meeting these climate targets while leveraging financial mechanisms like Certified Emission Reductions (CERs) in carbon markets relies heavily on industrial decarbonization [3].

Consequently, extensive scientific research is focused on advancing Carbon Capture, Utilization, and Storage (CCUS) technologies to mitigate emissions from large-scale point sources like fossil fuel and energy plants. Several primary CO_2 separation technologies have been developed, namely absorption, adsorption, membrane separation, and cryogenic distillation [4]. While chemical absorption is the most established and widely used method for industrial capture, adsorption and membrane technologies are emerging as highly promising, energy-efficient alternatives. Cryogenic distillation, is utilized to achieve high-purity CO_2. Advancing and optimizing these capture processes is critical for isolating CO_2 efficiently, enabling it to be permanently sequestered or repurposed as a valuable raw material in other industries [5]. CO_2 is a gas emitted from natural processes and human activities, especially during the combustion of fossil fuels for energy production. All animals, fungi, and microorganisms that depend directly or indirectly on living or decomposing plants for food make CO_2 when they breathe [6]. CO_2 is a gas that could be used as a raw material to produce other materials. Some of its commercial uses are as a solvent for supercritical fluid extraction, a vasodilator, an anesthetic, an antagonist, a gas for food packaging, a propellant for food, and a gas for soda [7]. It is also a metabolite of the yeast *Saccharomyces cerevisiae*, which is used to make ethanol. Research trends have increasingly shifted toward the development of novel adsorbents aimed at optimizing process efficiency, minimizing material costs, and improving operational handling in large-scale carbon capture systems [8].

For a better understanding of how this gas could be used to help get carbon out of industrial and agro-industrial processes, especially power generation, several things must be taken into account, including technical parameters, kinetics of the process, thermodynamics, process integration, technologies and economic viability of projects, sustainability, green chemistry, and engineering principles [9]. Greenhouse gases (GHGs) are emitted from natural sources, but most of the gaseous emissions come from human activities, and CO_2gas is the most abundant of them. The accumulation of these gases in the atmosphere causes global warming and climate change worldwide, which increases the temperature of the Earth. This is caused by the greenhouse effect; therefore, the world is working hard to find tools that reduce the effects of GHGs [10]. In this case, our scope of this paper is narrowed to analyze the composition and concentration of gaseous emissions from the chimneys of thermochemical plants and ethanol plants (bioenergy). We also aim to showcase the key capture

technologies available on the market. A literature review is necessary due to the vast amount of CO_2emissions that cannot be halted. This review will help identify methods to effectively remove CO_2 from sectors of the global economy [11–13]. Our goal of this work includes several factors: contextualize the issue, present the impact, introduce international efforts, highlight technological development, and detail existing technologies.

2. Impacts of CO_2 gas emissions on the atmosphere

In accordance with the Emission Database for Global Atmospheric Research, the amount of CO_2 released into the atmosphere was 36.1 billion tons in 2022. This was 48% more than it was 20 years ago. During the past 100 years, the amount of CO_2 in the air has increased by more than 39%, from 280 ppm during pre-industrial times to a record of more than 400 ppm in May 2022. This has caused the temperature of the Earth's surface to rise by about 1.10°C. Without policies to stop climate change, it is thought that by 2030, world GHG emissions will be 25–90% higher than they were in 2000, and the amount of CO_2-equivalent in the atmosphere could reach 600–1550 ppm [14].

The Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment Report (AR5), which was published in 2013–2014 [15,16], confirmed the 4th Assessment Report's claim that global warming of our climate system is clear and is linked to the rise in greenhouse gas concentrations caused by humans [17]. Additionally, the 6th assessment report (2021 – 2022) says that the 40 years from 1983 to 2022 were possibly the warmest 40 years in the Northern Hemisphere in the last 1400 years. The same IPCC report (AR5) says that the worst effects of climate change can be avoided if the temperature rise stays below 2°C compared to pre-industrial levels, and CO_2 emissions are cut by 41–72% by 2050 and by 78–118% by 2100 compared to 2010 levels [18]. However, there was no binding agreement on reducing CO_2 emissions at the last United Nations Climate Change Conference (COP27), which was held in November 2022 in Sharm El Sheikh/Egypt [19]. All the countries that attended were looking forward to an economy that would lead to sustainable growth [20]. The IPCC conducted a study of the different CCS technologies, which researchers and policymakers can use as a guide when making plans to reduce GHG emissions [21]. Most of the information though is older, and a lot has changed since then. Moreover, studies on the CCS technology chain only look at one part at a time, focusing on either capture, transport, storage, or environmental effects [22,23]. Figure 1 presents the different sources of CO_2 in the atmosphere. The first objective is to give a comprehensive review of the current state of CO_2 capture technologies and other relevant topics. The second objective is to systematically dissect the mechanism, performance, and commercial readiness of diverse carbon capture pathways (including absorption, adsorption, membranes, and novel materials), critically assessing their energy penalties and environmental footprints to identify the most viable solutions for future large-scale deployment.

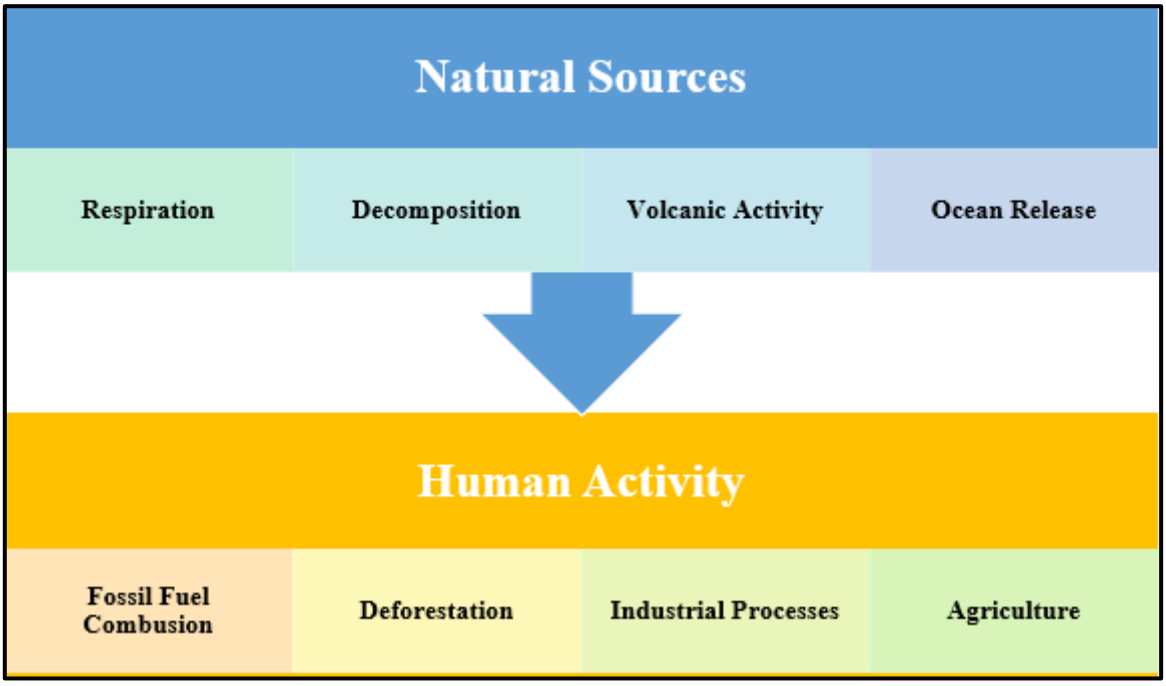


Figure 1. Sources of CO_2 in the atmosphere.

2.1. Global warming

As industries expanded, they emitted increasing amounts of GHGs into the atmosphere. According to a 2018 report by the Intergovernmental Panel on Climate Change, approximately 41 billion tons of CO_2 are released into the atmosphere annually [24]. Because of this, global warming is happening, which is caused by the uncontrolled release of greenhouse gases like CO_2, methane (CH_4), and nitrous oxide (N_2O) [25]. The climate of Earth has a natural process called the greenhouse effect. It is essential to the existence of life on Earth because it works as a blanket, absorbing energy from the sun to keep the average global temperature stable [19]. Because of the greenhouse effect, the heat that comes back to the atmosphere does not escape into space. Without this, the Earth's temperature would be so low that there would be no way for life to exist on the surface [26]. In turn, global warming happens because there is an abundance of GHGs in the atmosphere that keep heat there longer than the Earth needs [27]. GHGs, which are primarily CO_2, N_2O, and CH_4, are able to absorb heat due to their specific molecular structures. This ability causes global warming [27]. The factors below are the contributions of each one GHG on global warming, indicating how much each contributes: 53% is CO_2, 17% is CH_4, 12% are Chlorofluorocarbons (CFCs), 6% is N_2O, and the rest is 12% [28].

The large amounts of GHG released into the atmosphere by industrial and agro-industrial activities, such as combustion of fossil fuels to produce energy in thermoelectric plants and the fermentation of sucrose for producing ethanol in sugarcane plants, can worsen the greenhouse effect by enabling more infrared radiation from the electromagnetic spectrum to be absorbed. Thus, the processes that are making global warming worse are those that are caused by humans [29–32]. Since global warming is crucial for the economy, society, and the environment, the IPCC wrote the First Assessment Report (AR1) in 1990, and the United Nations legislated the Framework Convention on Climate Change (UNFCCC) in 1992, the Kyoto Protocol (KP) in 1997, and the Paris Agreement in 2015. Most countries have taken big steps to reduce GHGs [33], and it is important to understand,

track, and control climate change, especially global warming. This is shown by the fact that big world conventions, which include the Rio+202, have been set up to work together and identify international actions and policies to reduce GHG emissions [34]. Figure 2 shows the emissions of GHGs for every sector contributing to global warming and the increase in the average global temperature of the planet.

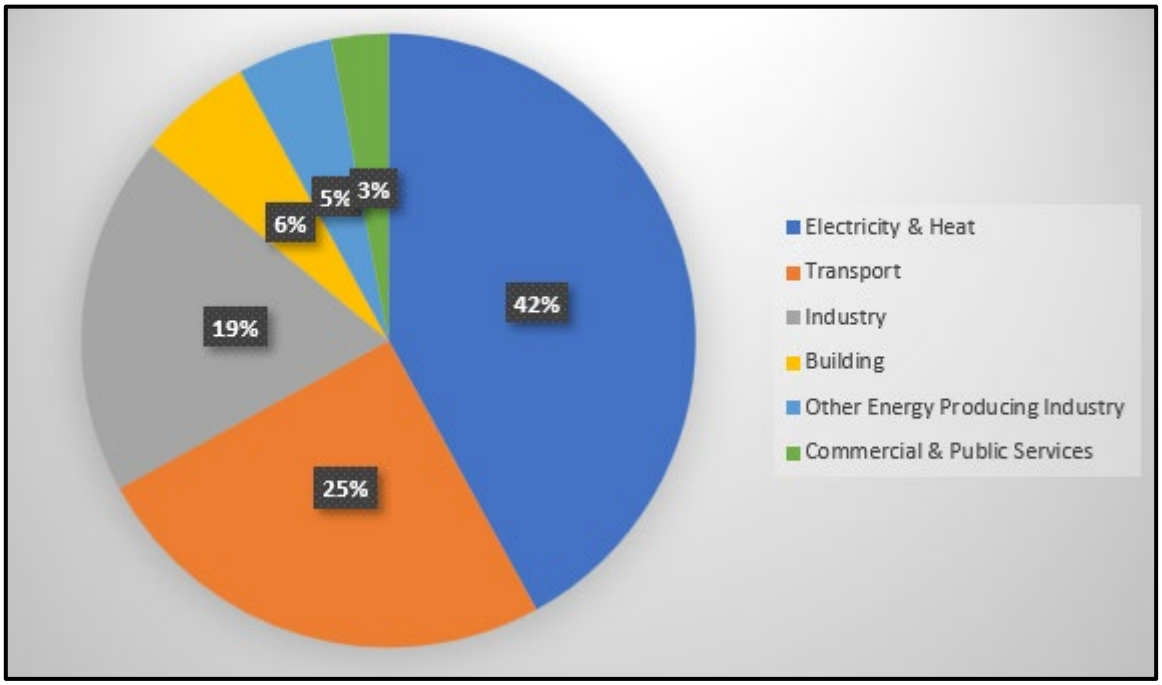


Figure 2. CO_2 Gas Emissions Worldwide [35].

Carbon dioxide is mostly produced by combusting materials and changing how forests are used. Other gases are compared to CO_2 as a reference gas when we want to know how much they might affect global warming. For example, N_2O, which is mostly made by burning things, has a warming power 310 times greater than CO_2. CH_3 is made from things like the decomposition of organic material, which happens mostly in landfills, and has global warming power 21 times greater than CO_2; however, According to the document by the Intergovernmental Panel on Climate Change (IPCC) published in (2014), GWP100 (100-year Global Warming Potential), which is used as a reference in decarbonization calculations, the relative effects of different gases on the global temperature are: CO_2 = 1, CH_4 fossil = 30, CH_4 biogenic = 28, and N_2O = 265 [36].

2.2. Climate change,UNFCCC, and PA as incentives for GHG reductions

Climate change refers to the Earth's long-term temperature, and other climate elements are called “climate change”. This will have major effects on rain and ocean currents and water resources, as well as on extreme weather and significantly increase in the average global temperature of the planet. The Paris Agreement on Climate Change says that the rise in global temperature should stay well below 2°C compared to the time before the Industrial Revolution. A limit of 1.5°C would be needed to keep the world's climate from worsening. To reach this goal, things, products, or actions that cause greenhouse gas emissions need to be reduced. Additionally, technologies and goods that emit or produce many GHGs should be replaced with natural ones that do not have any emissions. A third way

to help is to lower the amount of CO_2 already in the atmosphere [37]. This can be done by removing $CO_2$from the air and exhaust gas emissions by using an adsorption process [38–40]. For the 1.5°C limit to be met, the countries that signed the deal promised to cut down on uncontrolled GHG emissions and stressed that by 2050, there must be zero net CO_2 emissions [41]. The tools, sources, or sectors that countries are looking for are mostly for the energy, land use and change, and transport and traffic sectors. This is because, according to the Intergovernmental Panel on Climate Change (2018), these are the sectors that contribute the most to GHG emissions [42].

For parties participating in the 21th conference of the UNFCCC parties in 2015 (COP21), which was held in France/Paris (in which the Paris Agreement was legislated), every party of UNFCCC submitted the Intended Nationally Determined Contribution (INDC), which included what the country wants to do and what it wants to make to mitigate GHGs or CO_2 emissions and what the country wants to do to adapt to climate change impacts on the vulnerability sectors or those affected by climate change impacts. After the country is contracted with the Paris Agreement, it becomes a party to this agreement and can make modifications to the INDC to become a Nationally Determined Contribution (NDC) to reach the Paris Agreement goal [43].

3. Important technologies for CO_2 gas capturing

Countries are exploring and implementing different methods to capture their CO_2 emissions. These methods include: improving energy efficiency and encouraging energy conservation, using more low-carbon fuels, like natural gas, hydrogen, or nuclear power, using any type of renewable energy, using geoengineering technologies, like afforestation and reforestation, and CO_2 capture and storage (CCS) [44–46].

Some employ clean fuels and technologies such as clean coal techniques. Others emphasize environmental management and energy efficiency to decrease overall energy consumption, thereby saving energy. Each method carries its own set of advantages and weaknesses that influence its practicality and effectiveness. It is unlikely that any single pathway, approach, or strategy alone will achieve the IPCC goal of reducing CO_2 emissions by 50–85% by 2050 compared to 2000 levels. Therefore, effective CO_2 emission reduction strategies must encompass multiple pathways and approaches working together synergistically, with room for continual improvement. One such pathway is Carbon Capture and Storage (CCS), which can significantly reduce CO_2 emissions. CCS technology has the potential to reduce emissions by 85–90% from large sources such as power plants and energy-intensive industrial facilities like cement kilns. In CCS, CO_2 is first captured from fuel gases, separated from the sorbent material, transported, and either stored or utilized in industrial applications [47].

3.1. CO_2 gas capturing categories and stages in the plants

As activities that release CO_2 are expected to increase in the future, it is crucial for every country to implement environmental policies to reduce CO_2 emissions in accordance with the Paris Agreement on climate change. Numerous Research, Development, and Innovation (R, D, I) efforts are being made to reduce CO_2emissions and manage its impact [48]. These efforts can be categorized into four main groups, including making chemicals, such as polymers and carbonates, from raw materials [49], making fuel, like petrol and diesel, from raw materials [50], biological use, such as a source of carbon for microalgae to grow [51], and usage in everyday life, such as a cleaners.

Additionally, there are various methods to reduce CO_2 emissions, including using energy more efficiently, implementing energy-saving technologies and practices to lower overall energy consumption, replacing fossil fuels with lower-carbon alternatives, and adopting green energy solutions, such as utilizing renewable energy sources such as solar, wind, and hydroelectric power. Carbon storage includes capturing and storing CO_2in geological formations to prevent it from entering the atmosphere [52]. Moreover, CO_2can be utilized as a raw material, benefiting the economy and the environment. It can serve as an input in industrial processes to create new products and materials. CO_2 is an excellent raw material because it is readily available, non-toxic, and cost-effective [53]. The technologies are designed to capture CO_2 in the cleanest, most cost-effective, and least harmful way for industrial use. According to the Intergovernmental Panel on Climate Change (2005), CO_2 capture involves three steps: Capture: Extracting CO_2 from emissions. Transport: Moving the captured CO_2. Storage/Utilization: Storing CO_2 or using it in industrial processes [11].

The pre-combustion process is based on a method called gasification. In this process, the fuel is converted into synthesis gas, primarily composed of hydrogen and carbon monoxide. The next step involves converting carbon monoxide (CO) into CO_2 through the water–gas shift reaction while producing hydrogen (H_2), which then undergoes the gas separation process, as shown in Figure 3. Figure 4 illustrates the oxy-combustion process, which captures the gases released during fuel combustion. This process operates by burning fuel in an environment with a high concentration of oxygen. The post-combustion process is the final step before releasing combustion gases into the atmosphere. It is an effective method for removing CO_2 from plants that generate energy from waste, such as thermoelectric plants. After the combustion gases are emitted, appropriate technology is used to separate CO_2 from the other gases, as shown in Figure 5.

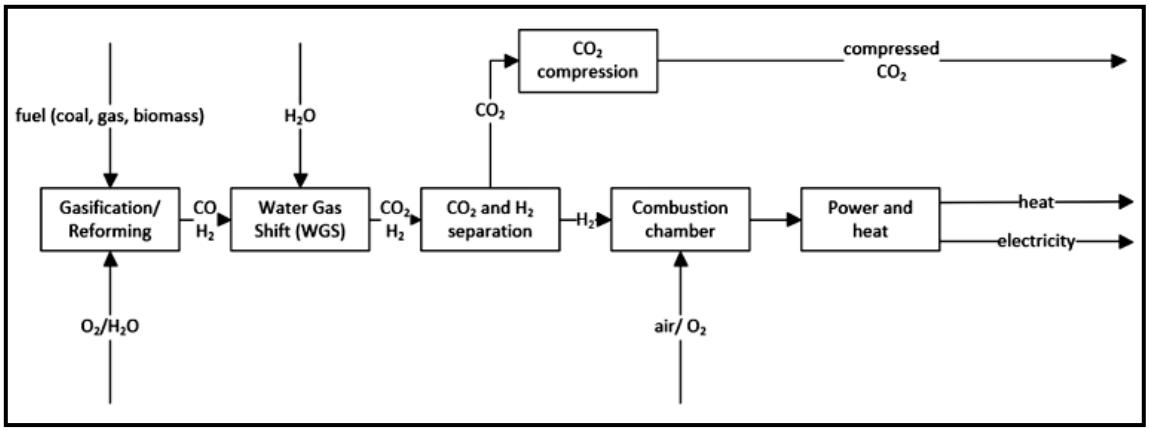


Figure 3. Pre- combustion CO_2 gas capturing [54].

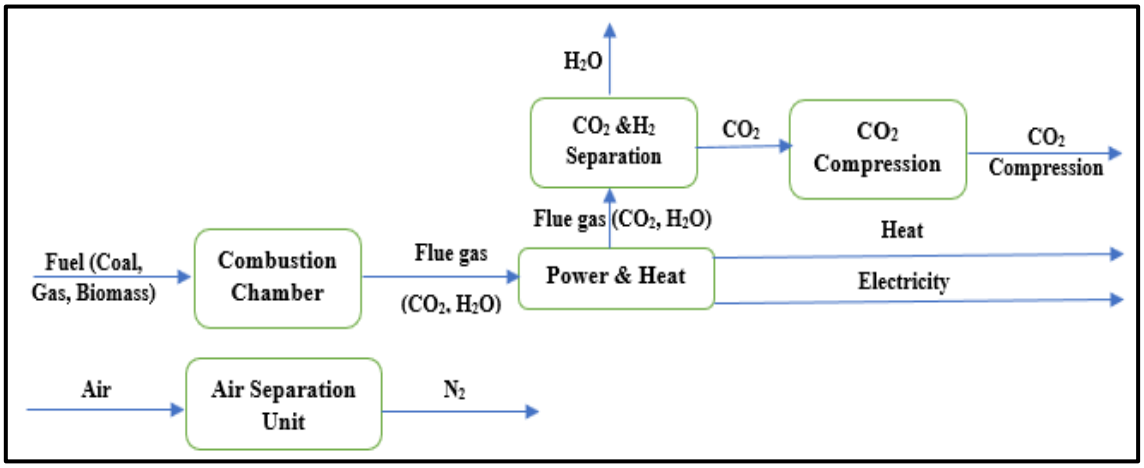


Figure 4. Oxy-combustion CO_2 gas capturing [55].

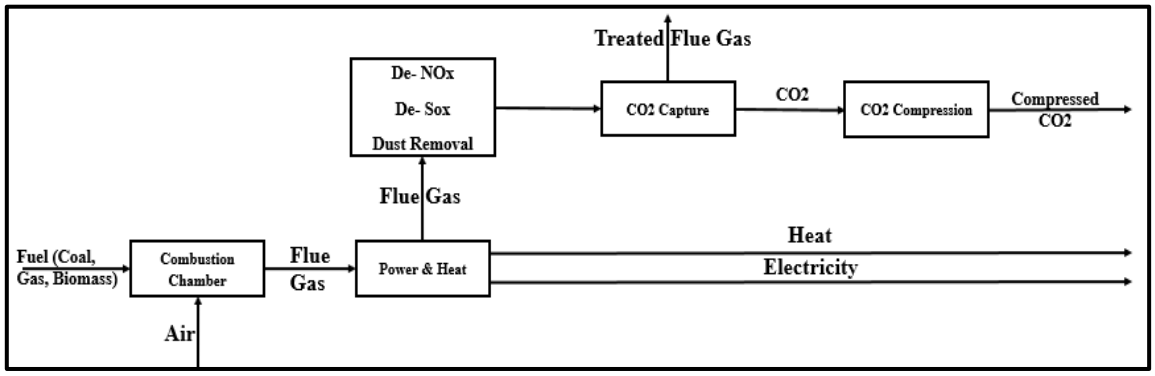


Figure 5. Post- combustion CO_2 gas capturing [56].

Comparing the three CO_2 capture methods reveals distinct applications and cost efficiencies. Pre-combustion, primarily used in coal-gasification plants, involves converting fuel into synthesis gas before combustion. Post-combustion is the most developed CO_2 capture technology and can be applied to coal and gas-fired plants. It involves capturing CO_2 after combustion. Oxy-fuel combustion is also applicable to coal and gas-fired plants; this method burns fuel in an oxygen-rich environment to facilitate easier CO_2 capture.

Cost comparisons indicate that pre-combustion technology for coal-fired plants has the lowest cost per ton of CO_2 avoided. In contrast, post-combustion and oxy-fuel technologies have similar costs for coal-fired units. For gas-fired plants, post-combustion capture is nearly 50% cheaper per ton of CO_2 avoided compared to the other two methods [57]. To address the quantity of CO_2captured [58], Eqs (1) and (2) are reported.

$$CO_2(\text{Captured})\ (g) = CO_2\ (\text{inlet})\ (g) - CO_2\ (\text{outlet}) \quad (1)$$

$$CO_2(\text{Captured})\ (\%) = CO_2(\text{Captured})\ (g)/CO_2\ (\text{inlet})\ (g) \times 100 \quad (2)$$

To define separation technologies, it is important to know at which point gas capture will happen. Since these two are linked, it is possible to find the best technology that meets the standards of cost,

deployment, time, purity, and amount of CO_2. Next, we will discuss the main types of technology used to capture and separate CO_2 from other gases [59].

3.2. Important technologies of CO2 gas capturing and separating

Due to the importance of CO_2capture techniques, we focus on the most significant methods. The key technologies for capturing CO_2 gas include: absorption technology, adsorption technology, cryogenic distillation technology, membrane capturing or separation technology, hydrate-based capturing or separation technology, and chemical capture of CO_2 gas technology.

3.2.1. Absorption technology of CO_2 gas capturing

In absorption processes, certain requirements and crucial steps enable the separation of captured CO_2. This is facilitated by materials used in the technology that can transfer the gas between phases. Here, $CO_2$is chemically absorbed by the liquid amine through reversible reactions, forming carbamate and/or bicarbonate species, thereby enabling its separation from the remaining gas components [60]. The absorbed CO_2 is subsequently released during solvent regeneration by heating [11]. In thermoelectric plants, for instance, the mixture of processed gases undergoes treatment in a system where it encounters amine solutions. During this stage, temperature is elevated to facilitate the separation of CO_2 from other components in the mixture. Absorption is regarded as one of the most promising technologies due to its effectiveness and economic viability. However, as discussed, this process also consumes a significant amount of energy [61]. Therefore, studies and research are being conducted to optimize the operation with minimal energy consumption, and tools and technologies are being developed to enhance absorption efficiency [62]. Researchers favor absorption technologies due to their practical utility, which has been refined over more than 70 years of study and development [63,64]. In absorption, a component of a gas is transferred into a liquid or solid phase with the objective of removing it from the gas phase efficiently using an absorbent. There are two main types of absorption processes: chemical absorption (chemisorption) and physical absorption (physisorption). The choice between these two types depends on factors such as the concentration of CO_2 in the gaseous mixture and other relevant parameters [65]. Although amine-based absorption is the most mature and commercially deployed technology for post-combustion CO_2 capture, it has several environmental and economic limitations [66]. Amine solvents are susceptible to oxidative and thermal degradation, as well as reactions with impurities such as SOx and NOx in flue gases, leading to solvent loss, reduced absorption efficiency, equipment corrosion, and the formation of potentially hazardous degradation products, including ammonia, nitrosamines, and nitramines [67]. These issues increase the need for solvent replacement and raise environmental concerns, necessitating appropriate solvent management and emission control strategies [68]. In addition, the cost of amine-based CO_2 capture strongly depends on the CO_2 concentration in the feed gas. For flue gases from coal- and natural gas-fired power plants containing approximately 10–15% and 3–5% CO_2, respectively, the capture cost is typically estimated at US$40–100 per ton of CO_2 captured, depending on the solvent, process configuration, and energy integration [69]. In contrast, capturing CO_2 directly from the atmosphere (approximately 420 ppm, or 0.042% CO_2) is significantly more energy-intensive because of the very low CO_2 concentration, resulting in substantially higher costs, generally in the range of US$250–600 per ton of CO_2, although ongoing technological advances aim to reduce these costs [70]. Consequently, improving solvent stability, minimizing degradation, and reducing regeneration energy

remain key research priorities for enhancing the sustainability and economic viability of amine-based CO_2 capture.

3.2.1.1. Chemical absorption technology of CO_2 gas capturing

Chemical absorption (chemisorption) technology is commonly employed in post-combustion capture processes. In this method, the gas component that needs to be captured undergoes a chemical reaction and is absorbed in the liquid phase to separate it effectively [71]. The most common technology used to capture and separate CO_2 from other gases in gaseous mixtures emitted from fossil fuel combustion is chemical absorption [72]. One of the primary advantages of chemical absorption is that the captured CO_2 is very pure, often exceeding 99% purity, eliminating the need for further purification steps. However, a significant drawback of chemical absorption is the energy-intensive process of regenerating the absorbent [73,74]. Amines such as Monoethanolamine (MEA) and Methyl Diethanolamine (MDEA) are commonly used as absorbents in chemical absorption processes to capture and separate CO_2 [75]. In this process, CO_2 is first dissolved in water and then chemically reacts with the amine, forming chemical compounds. The captured CO_2, now in a pure state, is then compressed into containers under high pressure, while the amine absorbent is recycled in small amounts [76,77]. During regeneration, the CO_2-amine solution is heated and depressurized, triggering a reaction that releases the CO_2. The regenerated amine can be reused in subsequent cycles of CO_2 capture [78]. Figure 6 shows the chemical absorption technology for CO_2 gas capture. Moreover, there are disadvantages of chemical absorption for CO_2 capture. The first disadvantage is the equipment and cost requirements due to the low percentage of CO_2 in the gaseous mixture; the capture equipment and absorbent materials (solvents) require extensive and costly infrastructure. The second disadvantage is energy intensity, where the process requires a significant amount of energy to regenerate and separate the captured CO_2 from the absorbent material (solvent) [79]. The third disadvantage is the high efficiency absorbent materials, in which achieving high efficiency in CO_2 absorption requires expensive absorbent materials, adding to the overall cost of the method. Additionally, there are losses associated with these materials, further increasing costs [73].

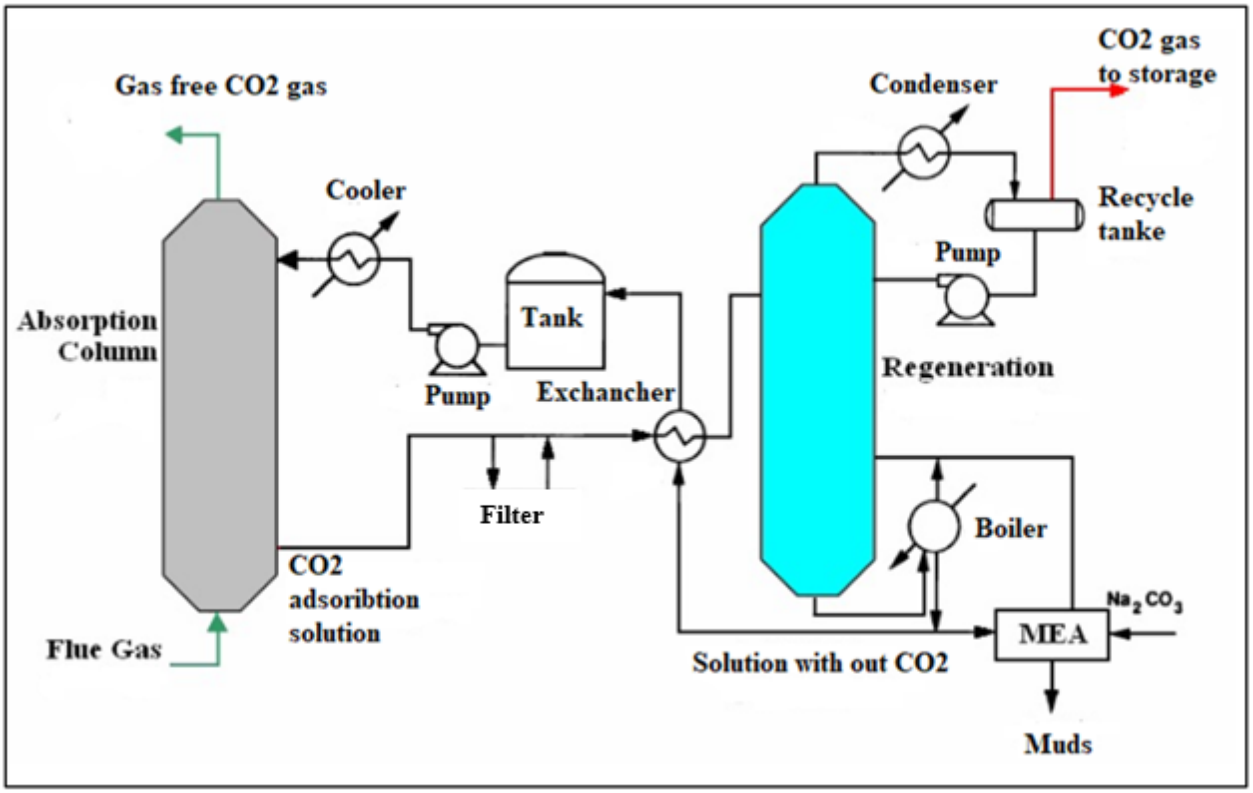


Figure 6. Chemical absorption technology for CO_2 gas capturing [80].

3.2.1.2. Physical absorption technology of CO_2 gas capturing

Physical absorption (physisorption) is a method commonly used to capture or absorb CO_2 gas. It relies on physical interactions and bonds such as Van der Waals forces. These interactions are relatively weak, allowing the absorption process to be reversible, known as desorption [80]. This is needed to enable changes in the pressure and temperature. For instance, to maximize gas capture or dissolution in a liquid, high partial pressures and low gas concentrations in the liquid are needed [81]. Furthermore, different solvents are used for physical absorption. For example, CO_2 can be captured at around 25°C, but using methanol, which is flammable and volatile, requires operations at -25°C [82]. In physical absorption, CO_2 molecules move into the solvent based on Henry's law, which states that gas solubility in a liquid increases with high pressure and a drop in temperature. This method is particularly effective when there is a high concentration of CO_2 in the emitted gas (high partial pressure). Common solvents for this process include dimethyl ether, polyethylene glycol, and cold methanol [83]. The reactivation process, similar to chemical adsorption, involves reducing pressure to release CO_2 from the solvent. This method, which is illustrated in Figures 7 and 8, is also used commercially [84].

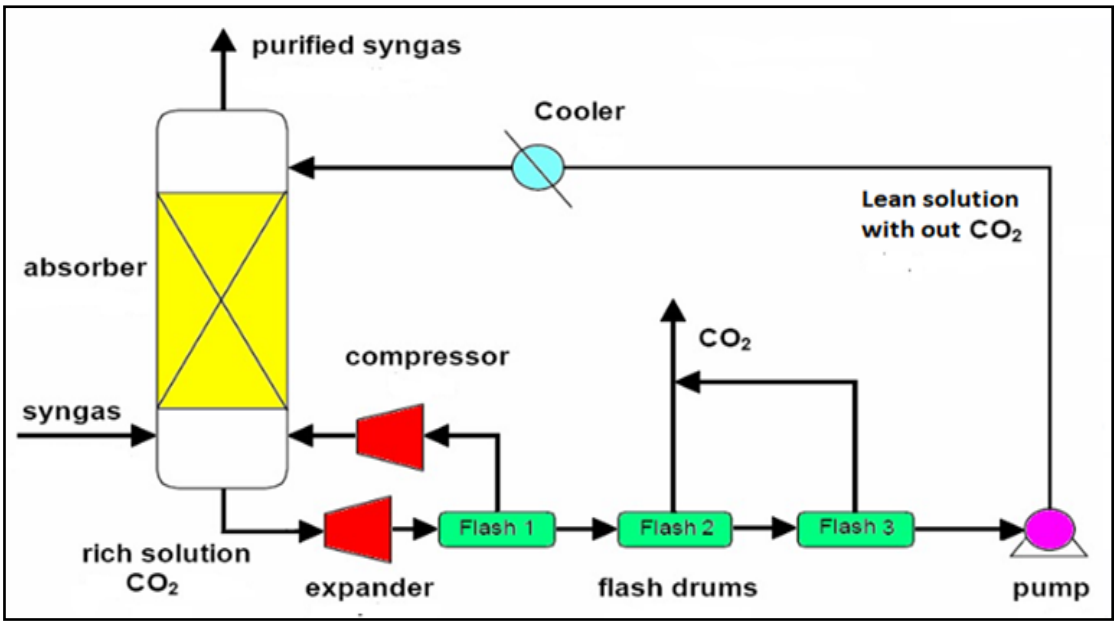


Figure 7. Physical absorption technology of CO_2 gas capturing.

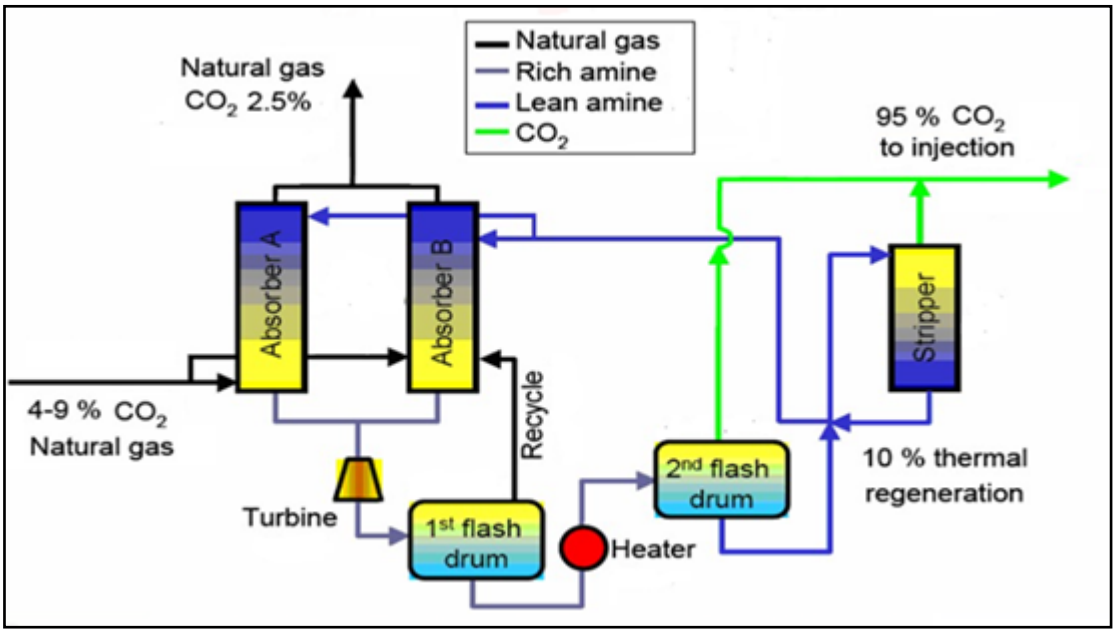


Figure 8. Physical absorption technology of CO_2 gas capturing [61].

3.2.2. Adsorption technologies of CO_2 gas capturing

Due to the challenges associated with absorption technology, such as the high cost of liquid absorbents (solvents like MEA and MDEA) and significant energy consumption, researchers have been exploring and developing alternative methods for capturing CO_2 gas [75]. One of these methods is the adsorption process. During adsorption, the gas comes into contact with porous particles that have the ability to capture or adsorb the gas due to their affinity for the surface, effectively separating CO_2 from the gas mixture [85]. Many researchers studying new technologies advocate for the future development of this process [86]. This method uses solid materials to capture CO_2 gas molecules,

which are attracted to specific sites on the adsorbent surface [87]. The CO_2 is separated from the gas mixture by passing the flue gas over the adsorbent material. When the material becomes saturated, the flue gas flow is stopped and redirected to fresh adsorbent, and the saturated material is reactivated by removing the CO_2 gas [88,89]. There are several ways to reactivate the adsorbent, such as heating it, washing it with a liquid stream, flushing it with a gas stream, or lowering the pressure [90]. The efficiency of these methods varies, with some being more effective than others depending on the application [91]. Some methods take more time and incur higher costs [92]. Zeolite, alumina, and carbon are the most significant materials used in the adsorption method. This method works well when the amount of CO_2in the flue gas stream is low [93]. During an adsorption process, parts of the gas phase adhere to the surface of the solid material. There are two types of adsorption processes: chemical adsorption and physical adsorption. Key properties of adsorbents include a large surface area relative to their mass, availability, selectivity for CO_2, stability, ease of cleaning (reactivation or regeneration), cost-effectiveness, simplicity, and high efficiency in adsorption capacity [94,95].

3.2.2.1. Chemical adsorption technology of CO_2 gas capturing

In chemical adsorption, the adsorbed gas molecules form chemical bonds (ionogenic or covalent) with the surface of the solid substance (adsorbent). Various solid materials are typically used as adsorbents, especially porous materials that can be functionalized with amines. Incorporating amine groups onto solid materials enhances their ability to adsorb gases. Polymeric amines, such as polyaniline, polyethyleneimine, polypropyleneimine, and hyperbranched polyamines, are being actively researched and studied for their potential use as effective adsorbents [95]. Activated aluminum oxide modified with sodium hydroxide can effectively capture or adsorb CO_2 gas under different temperatures, various durations, and varying concentrations of sodium hydroxide. This capability was demonstrated using a fixed bed column adsorption device [96]. CO_2 gas capture or adsorption can also be achieved using mesoporous alumina prepared through a sol-gel method. Mesoporous alumina offers numerous pores and a large surface area, with pores evenly distributed. These features provide ample sites on the adsorbent surface where CO_2 can be captured or adsorbed through chemical and physical adsorption mechanisms [97].

3.2.2.2. Physical adsorption technology of CO_2 gas capturing

Physical adsorption occurs when the gas component to be captured or adsorbed binds to the surface of the solid material through van der Waals forces [98]. This implies that the ideal solid material for capturing or adsorbing the gas component (CO_2 gas) from flue gas must possess high porosity relative to its mass, excellent stability, high selectivity for CO_2 gas, efficient adsorption capacity, affordability, simplicity, and be derived from waste materials [88]. Activated carbon, zeolites, and metallic oxides are suitable adsorbent materials for capturing CO_2 gas because they can bind to the surface of these solids. These materials have well-defined pore structures, and their pores are interconnected through a network of channels. Zeolites, particularly those containing sodium and calcium, have been extensively studied for capturing or separating CO_2 gas from flue gases, especially at high temperatures, yielding favorable results [99–101]. CO_2 possesses a significant quadrupole moment that enables interaction with the electron field produced by the structural cations of zeolites. However, the adsorption capacity of zeolites decreases when the gas to be captured contains moisture.

Therefore, it is essential to dry the gas of moisture before the adsorption process when using zeolites as adsorbents [102]. Figure 9 shows the Schematic diagram of the fixed column adsorption system.

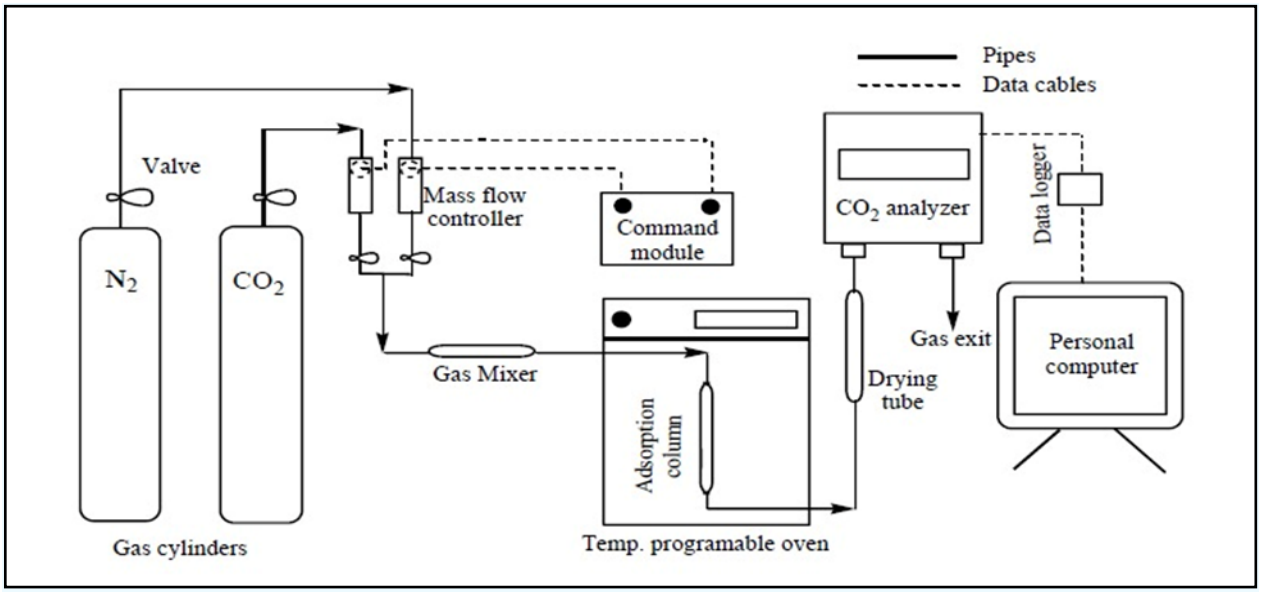


Figure 9. Schematic diagram of the fixed column adsorption system [103].

3.2.3. Cryogenic distillation processes of CO_2 gas capturing

Cryogenic distillation is a method for capturing or separating gases using distillation at extremely low temperatures and high pressures. Unlike traditional distillation of liquids, cryogenic distillation is used to separate gaseous components based on their freezing points. For CO_2 capture or separation, flue gas containing CO_2 is cooled to temperatures ranging from -100 to -135°C. The CO_2 gas solidifies and is separated from lighter gases, then compressed to pressures of 100 to 200 atmospheres. This process can remove up to 90–95% of the CO_2 from the gas stream. However, cryogenic distillation is energy-intensive due to the very low temperatures and high pressures required. It typically consumes between 600–660 kWh per ton of liquid CO_2 recovered. Despite its high energy costs, several patented processes and ongoing research aim to reduce these expenses [104,105].

During cryogenic distillation, $CO_2$is physically separated from flue gas by condensing it at very low temperatures. The process becomes more cost-effective with higher concentrations of CO_2 in the flue gas. Despite its energy intensity, systems producing liquid CO_2 through cryogenic capture are attractive due to lower energy requirements for pumping. A hybrid approach combining adsorption and cryogenic methods is often considered optimal. Commercially, cryogenic methods are used for flue gases with over 90% CO_2 concentration, where it is most cost-effective. Efforts continue to improve this technology and reduce its cooling costs [105,106]. Researchers have explored cryogenic methods that leverage the inherent cold energy of liquefied natural gas (LNG) to extract CO_2 from power plant flue gas. During LNG regasification, the liquid transitions to a gas, providing a substantial cooling source at approximately -162°C. This cold energy is transferred via multi-stage heat exchangers to cool the flue gas to temperatures as low as -140°C, causing the CO_2 to condense or desublimate [107,108]. However, the cold energy recovered from LNG regasification alone is thermodynamically insufficient to capture and release the CO_2 as a pure, pressurized gas. Additional mechanical and thermal energy is required to operate auxiliary refrigeration cycles to make up the

cooling deficit, separate the solid/liquid CO_2, and compress it into a pure gaseous state for transport. Literature estimates indicate that capturing one ton of CO_2 typically requires the cold energy from approximately 1.0 to 1.5 tons of LNG, alongside an additional energy input of roughly 1.0 to 1.5 GJ/t CO_2 for purification and compression. Because this method supplements the cooling load, the cost of CO_2 capture from point-source flue gases can be reduced to an estimated \$30 to \$50 per ton. Conversely, if this cryogenic approach were applied to Direct Air Capture (DAC), the required cooling volume would be drastically larger due to the ultra-low concentration of CO_2 in the atmosphere (~0.04%). This would require vastly more additional energy, pushing the capture cost well above \$300 per ton of CO_2. Figure 10 shows the Capturing of CO_2 gas by Cryogenic Distillation Technology.

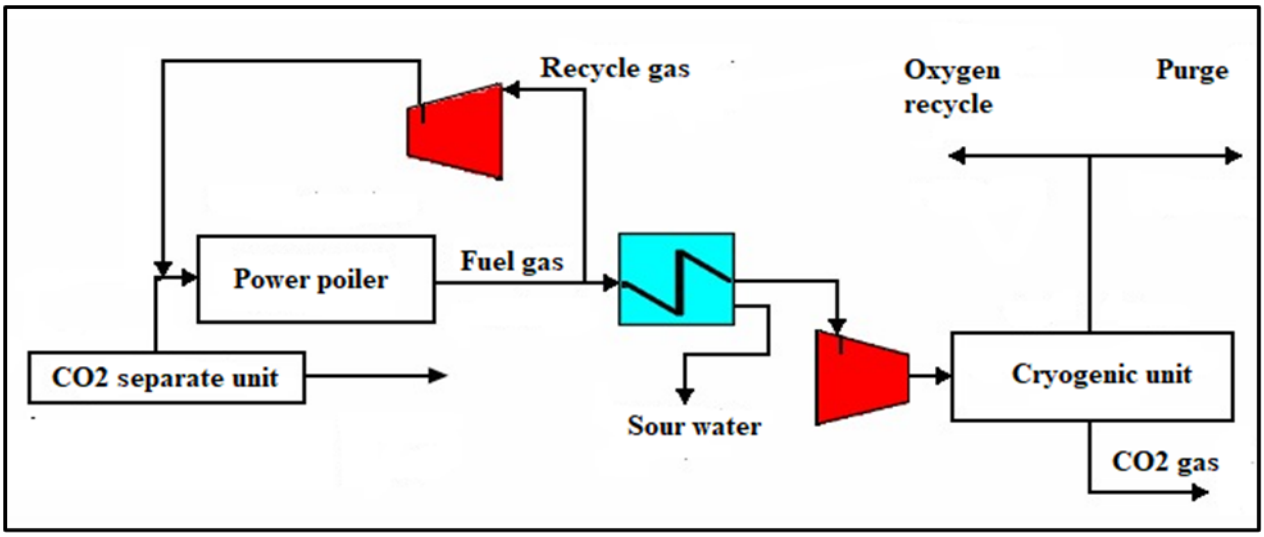


Figure 10. Capturing of CO_2 gas by Cryogenic Distillation Technology [109].

Advancements have expanded cryogenic capture beyond conventional distillation, introducing highly cost-effective desublimation techniques [110]. De and Oduniyi [111] patented a novel cryogenic technology (U.S. Patent No. 10,670,334) designed to capture industrial emissions without the need for chemical reagents. This system utilizes a closed-cycle nitrogen refrigerator to generate a cold nitrogen refrigerant, which enables the sequential fractional condensation and separation of various flue gas pollutants, including sulfur oxides, nitrogen oxides, and mercury, alongside CO_2 [111]. Crucially, the cost and specific cooling duty of this cryogenic separation are strong functions of the initial CO_2 concentration in the flue gas, as lower concentrations require processing a larger volume of bulk gas per ton of CO_2 captured. Further investigations into cryogenic desublimation have demonstrated its versatility for industrial point-source capture and Direct Air Capture (DAC). A detailed thermodynamic study by De et al. [106] introduced a Novel Low-Cost Carbon Capture Technology (NLCCT) that cools flue gas 10°C to 15°C below the thermodynamic desublimation temperature of CO_2 (approximately -140°C to -160°C) [106]. For low-concentration sources like Natural Gas Combined Cycle (NGCC) power plants, the technology achieved over 99% CO_2 capture efficiency with an exceptionally low energy penalty of roughly 631 MJ/t CO_2 and a water consumption of just 574 L/t CO_2 [106]. This efficiency drives the capture cost down to approximately \$12/t CO_2 [106]. While the energy consumption and overall cost remain heavily dependent on the CO_2 concentration in the feed gas, this reagent-free cryogenic approach offers a highly competitive

alternative to traditional chemical absorption, drastically reducing the water penalty and operating costs [112].

3.2.4. Membrane technology of CO_2 gas capturing

Membrane technology is capable of capturing or separating atoms and molecules based on their respective sizes. Larger particles are unable to pass through the membrane and become trapped. The effectiveness of membrane separation relies on its permeability and selectivity in separating materials or gases. This method utilizes the concentration gradient as the driving force for separation and does not require additional energy, making it environmentally friendly and cost-efficient for energy-related applications. Membranes are frequently employed for capturing or separating CO_2 gas, particularly in post-combustion processes [113–116]. Using membranes to capture or separate $CO_2$from flue gas poses challenges due to the low concentration of $CO_2$and low pressure in the emitted gas. For membranes to effectively capture or separate CO_2, they must possess several key characteristics [117–119]. The first key characteristic implies high selectivity, where membranes should selectively enable CO_2 molecules to pass through while blocking other gases in the flue gas, such as nitrogen. Durability is also important to ensure resistance to degradation over time (senility) and to maintain performance under various operating conditions. Another key characteristic is permeability, in which the membranes should exhibit high permeability to enable CO_2 to pass through at a sufficient rate, ensuring efficient capture. Cost-effectiveness is also an important key characteristic, where the materials and manufacturing processes used for membranes should be economically viable for large-scale deployment in industrial settings. Moreover, versatility also needs to be considered, as membranes should be adaptable for use in different parts of the capture system, offering flexibility in application.

Developing membranes that meet these criteria is crucial for enhancing the efficiency and effectiveness of CO_2 capture technologies, particularly in environments where the concentration of CO_2 is relatively low, such as flue gases from industrial processes. Some membranes naturally resist water and require modification for effective CO_2 capture. Enhancing chemical and thermal stability through material selection, thickness optimization, reliability, sustainability, resilience, permeability, and surface area can enhance membrane performance. Polymer membranes are commonly used in this technology to separate CO_2 from flue gas. There are two main approaches to membrane-based CO_2 separation [120–123]: Selective permeation is the first approach, which enables CO_2 molecules to pass through while blocking other gases like nitrogen. The second approach is pressure swing adsorption (PSA), which implies the utilization of membranes to facilitate the adsorption of CO_2 under pressure and its subsequent release under reduced pressure.

These advancements are critical for advancing membrane technology's role in CO_2 capture and reducing its environmental impact.

3.2.4.1. Gaseous absorption membranes

The gas-liquid absorption barrier involves two fluids flowing in opposite directions. The first is the flue gas containing CO_2, while the second is a liquid capable of capturing or absorbing CO_2. CO_2 molecules in the flue gas are attracted to the liquid on the other side of the membrane, where the membrane acts as a separation barrier preventing the mixing of the two fluids. The membrane selectively enables CO_2 molecules to pass through while blocking other components from crossing.

This selective permeation process facilitates the capture or absorption of CO_2 gas from the flue gas stream [124–126].

3.2.4.2. Gas separation membranes

Gas separation membranes operate by enabling CO_2 gas molecules to permeate through based on chemical interactions with the membrane's molecules. The movement across the membrane depends on the partial pressure difference of CO_2 gas between its two sides. These membranes are engineered to selectively permit only CO_2 while excluding other components of the emitted gas. The membrane plays a pivotal role in this process, typically composed of a composite polymer structure. This structure includes a thin, selective layer adhered to a thicker, non-selective, cost-effective layer that provides mechanical support to the membrane [127–129]. By optimizing membrane designs, this method has been extended to capture or separate other gases, such as O_2 from N_2 and CO_2 from natural gas. Researchers have achieved CO_2 separation efficiencies ranging from 82% to 88%. Advances in membrane technology include the development of ceramic and metal membranes, alongside polymeric membranes, for gas diffusion applications. These membranes demonstrate superior CO_2 separation capabilities compared to traditional liquid absorption methods. Comprehensive studies have reviewed the effectiveness of membrane-based CO_2 separation compared to other methods like adsorption and cryogenics [123,130,131]. The application of membrane systems is significantly hindered by flue gas conditions such as low CO_2 concentration and pressure, which are major challenges for this technology. Despite substantial advancements in gas separation membrane systems, studies indicate that they have not fully realized their potential [132,133]. Figure 11 illustrates the capture or separation of CO_2 gas using two membrane technologies.

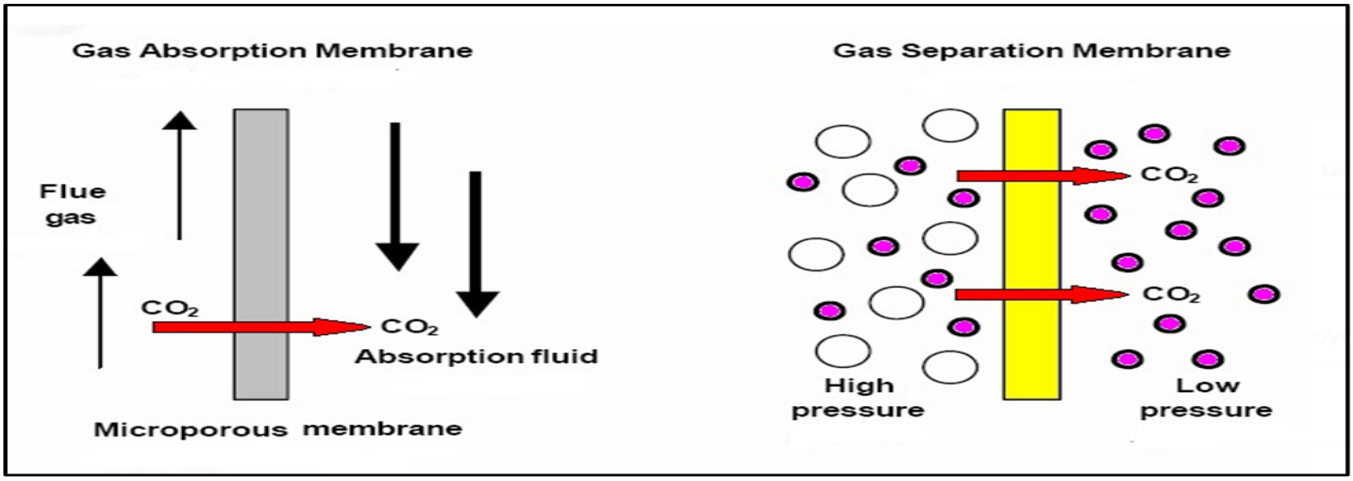


Figure 11. CO_2 gas capturing or separating by the two ways of membrane technology (gas absorption membranes and gas separation membranes) [134].

The commercial viability of CO_2 capture technologies is strongly influenced by their resource requirements, including capital and operating costs, energy consumption, and water demand, as well as the characteristics of the flue gas, particularly its CO_2 concentration. A comparison of these factors is presented in Table 1.

Table 1. Comparative analysis of CO_2 capture technologies based on resource consumption, cost, and flue gas conditions.

Capture Technique	Optimal CO_2 Concentration (%)	Energy Consumption (GJ/t CO_2)	Water Consumption (m^3/t CO_2)	Capture Cost ($/t CO_2)	Ref.
Chemical Absorption (e.g., Amine/MEA)	Low to Medium (3 - 15%)	2.5 – 3.6 (mostly thermal)	1.5 – 3.0 (high cooling needs)	(40 –80) $	[135]
Physical Absorption (e.g., Selexol)	High (> 20%)	0.5 – 1.5 (mostly electrical)	0.5 – 1.0	(20 –50) $	[136]
Solid Adsorption (PSA/TSA)	Medium to High (10–20%)	1.0–2.5	0.1 – 0.5 (very low)	(40 –100) $	[137], [138]
Membrane Separation	Very High (> 20%)	0.5 – 2.0 (compression)	~0 (minimal to none)	(30 –70) $	[139], [140]
Cryogenic Distillation	Very High (> 50%)	2.0 – 3.0 (cooling/compression)	0.1 – 0.5 (low)	(50 –100) $	[141], [142]

Values for cost, energy, and water consumption are broad estimates based on literature averages and depend heavily on plant configurations, integration methods, and the scale of the facility. The role of flue gas concentration is as follows: The thermodynamic minimum energy required for separation increases as the CO_2 concentration decreases. Therefore, capturing CO_2 from a natural gas combined cycle (NGCC) plant (~4% CO_2) is significantly more expensive and energy-intensive per ton than capturing it from a cement plant or a pre-combustion process (≥ 20% CO_2). The water-energy nexus highlights that chemical absorption (amines), while being the most mature and widely deployed technology, suffers from a severe water penalty. It requires immense amounts of cooling water to manage the exothermic reactions in the absorber and to condense steam in the stripper. In arid regions, this water consumption makes chemical absorption unfeasible. Alternative resource profiles point out that membrane separation and solid adsorption offer excellent alternatives regarding water conservation. While membrane technologies require significant electrical energy for gas compression, they consume almost no water, making them ideal for water-scarce environments provided the flue gas is highly concentrated.

In recent years, metal-organic frameworks (MOFs) have emerged as highly promising advanced solid sorbents for post-combustion CO_2 capture [143]. MOFs are defined by their highly porous crystalline structures, constructed by coordinating metal ions or clusters with organic linkers. The primary advantage of MOFs over traditional solid adsorbents, such as zeolites, xerogels, Chitosan, and activated carbon, lies in their exceptional modularity [93]. Researchers can synthesize MOFs with precisely tunable pore sizes to physically separate CO_2 based on molecular dimensions while incorporating chemically active sites-such as open metal sites or amine-functionalized linkers to enhance the selective binding of CO_2 over N_2 and other flue gas components. This combination of physical and chemical tunability enables MOFs to achieve extraordinarily high CO_2 uptake capacities with lower regeneration energy requirements compared to aqueous amines. However, applying MOFs to actual industrial flue gas streams faces practical challenges, particularly regarding their long-term

hydrothermal stability in the presence of moisture and the high material costs associated with large-scale synthesis.

4. Technology Readiness Level (TRL)

Technology Readiness Level (TRL) is a crucial metric in assessing the development stage of new technologies, particularly in sectors like energy, chemicals, and agriculture, which are major contributors to greenhouse gas emissions. Developed initially by NASA and adopted widely, TRL provides a systematic way to evaluate and compare technologies based on their progress and maturity. It helps stakeholders, including policymakers and business leaders, plan investments in research and development effectively by predicting timelines, costs, and environmental impacts. Despite its utility, the TRL scale lacks specific guidance on advancing from one level to the next, posing a challenge for technology developers seeking to navigate through its stages [144–151].

5. Carbon Market

The carbon market has emerged as a response to the increasing negative impacts of climate change globally, particularly driven by rising GHG emissions, notably CO_2. International agreements such as the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol (KP), and the Paris Agreement underscore the urgency of reducing these emissions. The carbon market operates through agreements among countries aimed at accelerating the adoption of mitigation technologies and enhancing global cooperation on GHG reduction efforts. It incentivizes countries to trade carbon credits, enabling those who exceed their emission targets to buy credits from those who have surplus allowances. This market mechanism not only encourages economic incentives for emission reductions but also fosters societal awareness of GHG mitigation. Understanding the dynamics of the carbon market from a business perspective is crucial for accurately assessing anthropogenic contributions to CO_2 emissions and strategizing for sustainability [152–156]. Over time, as the impacts of climate change worsen, the carbon market will increasingly incentivize countries to adhere to international agreements and conduct research on reducing or utilizing greenhouse gases. Carbon pricing methods are predominantly applied in industrial, energy, and land use change sectors [153,157,158]. Some examples of international efforts to establish carbon pricing mechanisms include: Partnership for Market Readiness (PMR), Carbon Pricing Leadership Coalition (CPLC), and Mitigation Action Assessment Protocol (MAAP).

6 Conclusions and recommendations

The review of CO_2 Gas Capturing Technologies highlights several key points regarding the current landscape and future prospects:

1. Complexity of the CO_2 Challenge: Addressing the high concentration of CO_2 in the atmosphere is a formidable challenge with no quick-fix solutions. Effective mitigation requires a combination of individual efforts and comprehensive international initiatives aimed at reducing anthropogenic emissions.

2. Evolution of Carbon Capture Technologies: Over time, significant advancements have been made in the development and enhancement of carbon capture technologies. Future research aims to

innovate further and optimize methods to improve cost-effectiveness and efficiency, thereby enabling broader implementation.

3. Diverse Technological Approaches: Adsorption processes show promise due to their efficiency in separating CO_2 from gas streams. Ongoing research focuses on reducing energy consumption and enhancing technical feasibility, particularly in post-combustion scenarios.

4. Advantages of Absorption: Absorption technologies, which involve the dissolution of CO_2 into a liquid phase, offer high efficiency and economic viability. They represent one of the most mature and scalable technologies available for large-scale deployment.

5. Optimizing Cryogenic Distillation: Despite its energy-intensive nature, cryogenic distillation remains effective in producing high-purity liquid CO_2. Continued efforts to optimize energy efficiency through technological advancements aim to reduce operational costs and environmental impact.

6. Hybrid Approaches for Efficiency: Combining adsorption and cryogenic processes in hybrid systems presents a promising solution. This approach leverages the strengths of both methods, enhancing overall process efficiency while minimizing energy requirements for CO_2 transportation.

7. Membrane Technology Potential: Membrane technologies depend on material selectivity and permeability to separate CO_2 effectively from gas streams. Overcoming technical challenges, such as optimizing membrane parameters, remains critical to maximizing their utility in CO_2 capture applications.

8. Technological Readiness and Impact Assessment: Monitoring and evaluating technology readiness levels (TRL) are crucial for predicting development timelines, costs, and environmental implications. This assessment framework aids in decision-making by benchmarking technological maturity and identifying areas for improvement.

9. Role of the Carbon Market: The carbon market plays a pivotal role in incentivizing emission reductions through carbon pricing mechanisms. Understanding its dynamics from a business perspective is essential for accurately assessing anthropogenic CO_2 emissions and shaping future strategies.

In conclusion, advancing CO_2capturing technologies is pivotal to mitigating climate change impacts. Continued innovation, supported by robust research and international collaboration, is key to realizing a sustainable and low-carbon future.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgment

The authors would like to express their sincere gratitude to Universiti Teknologi MARA (UiTM) for the financial support provided through the Industrial Grant (UITM.800-3/3/PRI (074/2025)). The authors also extend their heartfelt appreciation to Master Jaya Greentech Sdn. Bhd. for their valuable industrial collaboration, technical assistance, and continuous support throughout the successful completion of this research. Their contributions have been instrumental in advancing the objectives and outcomes of this study.

Conflict of interest

The authors declare no conflict of interest.

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