



Review article

Comprehensive review and assessment of carbon capturing methods and technologies: An environmental research

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ABSTRACT

A majority of the primary contributors of carbon dioxide (CO₂) emissions into the environment have really been out of human-made activities. The levels of CO₂ in the atmosphere have increased substantially since the time of the industrial revolution. This has been linked to the use of fossil fuels for energy production, as well as the widespread production of some industrial components like cement and the encroaching destruction of forests. An extreme approach is now necessary to develop the right policies and address the local and global environmental issues in the right way. In this regard, CO₂ capturing, utilization, and storage are reliable options that industrial facilities can initiate to overcome this problem. Therefore, we have evaluated the two leading technologies that are used for carbon capture: direct (pre-combustion, post-combustion, and oxy-combustion) and indirect carbon (reforestation, enhanced weathering, bioenergy with carbon capture, and agricultural practices) capturing to provide their current status and progresses. Among the considered processes, the post-combustion techniques are widely utilized on a commercial scale, especially in industrial applications. Technology readiness level (TRL) results have showed that amine solvents, pressure-vacuum swing adsorption, and gas separation membranes have the highest TRL value of 9. In addition, the environmental impact assessment methods have been ranked to evaluate their sustainability levels. The highest global warming potential of 219.53 kgCO₂ eq./MWh has been obtained for the post-combustion process. Overall, through this comprehensive review, we have identified some critical research gaps in the open literature in the field of CO₂-capturing methods where there are strong needs for future research and technology development studies, for instance, developing stable and cost-effective liquid solvents and improving the adsorption capacity of commercialized sorbents. Furthermore, some research areas, like novel process design, environmental and economic impact assessment of capturing methods with different chemicals and modeling and simulation studies, will require further effort to demonstrate the developed technologies for pilot and commercial-scale applications.

1. Introduction

Carbon emissions are referred to the release of carbon dioxide (CO₂) and other greenhouse gases into the atmosphere due to human activities in all sectoral activities, such as burning fossil fuels, deforestation, transportation, industrial processes, etc. (Raza et al., 2022). Global population growth and increasing sectoral activities result in ever-increasing carbon emissions. These emissions have become a matter of great concern due to their adverse effects on the environment and human health. The risks associated with carbon emissions are multifaceted. They contribute significantly to climate change, which is a

significant concern. Combined with other greenhouse gases, CO₂ traps heat in the atmosphere and causes global temperatures to rise. This phenomenon, known as global warming, has various adverse consequences, including melting ice caps, rising sea levels, and extreme weather events, such as hurricanes, droughts, and heat waves (see (Van Soest et al., 2021) for further details).

Air pollution poses serious health risks and is closely related to increased carbon emissions. Particulate matter, nitrogen oxides, and sulfur dioxide are released when fossil fuels are burned, particularly in vehicles and power plants. Some critical health conditions, such as asthma, bronchitis and cardiovascular diseases, may be exacerbated or

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caused by these pollutants. A prolonged exposure to high levels of air pollution may even lead to some premature deaths. Ocean acidification is another danger associated with carbon emissions. The absorption of CO₂ by seawater causes the oceans to become more acidic. Ocean acidification significantly threatens marine life, especially coral reefs and shellfish. As a result of higher acidity levels, these organisms cannot form and maintain their protective structures, leading to ecosystem degradation and biodiversity loss. Carbon emissions also cause depletion of natural resources and environmental degradation. Fuel extraction and combustion release greenhouse gases, damage ecosystems, pollute water sources, and disrupt habitats through destructive practices such as mining and drilling. In addition to contributing to carbon emissions, deforestation, often caused by farming and logging, deprives the planet of crucial carbon sinks. Overall, the effects of carbon emissions on the environment and human health are numerous. As a result of these emissions, climate change, air pollution, ocean acidification, and environmental degradation is occurring, all of which have far-reaching effects on the planet and its inhabitants. Mitigating these dangers and building a healthier and more resilient future requires addressing carbon emissions and transitioning to cleaner and more sustainable energy sources. The growths of CO₂ emissions and population by years in the world are presented in Fig. 1.

In order to control and operate the systems/processes/services in a sustainable manner, it is required to create a business model. Otherwise, these systems are controlled and operated by governments or government-supported programs, which really makes the processes unsustainable. If the processes/systems/programs/services do not create any assets which create valuable products or outputs, the private sector does not become part of them. Therefore, many promising technologies have not been getting enough attention from the commercial and industrial sectors. In conclusion, there is no doubt about the need for carbon-capturing systems due to environmental issues faced by the world and net-zero targets. In order to create a sustainable ecosystem for the carbon-capturing systems, it is required to develop a business model for it. Fig. 2 shows an economic ecosystem for carbon-capturing technologies from sources to utilization. In this ecosystem, the carbon can be captured from any source, such as exhaust streams, atmospheric air, oceans, etc., without interrupting the operations of existing systems that create carbon emissions. Then, the carbon captured can be used for practical purposes such as synthetic fuels and gas, concrete, ammonium bicarbonate, etc.

Several studies have been conducted on carbon-neutrality methods (Kumar Shukla et al., 2020; Wilberforce et al., 2019). The neutrality of carbon is the method of achieving a balance between CO₂ emissions and atmospheric carbon offsets through the development of economically

viable technologies with added value as well as promising methods that help with carbon sequestration and utilization (Nayak et al., 2022). In this regard, the use of geoengineering, switching from fossil fuels to renewable energy sources, as well as the capture and conversion of current atmospheric CO₂ into carbon-neutral bioenergy and other cutting-edge products, attracted the greatest attention (Fawzy et al., 2020). Through extensive environmental modification, such as promoting forestry, fertilizing marine ecosystems, carbon capture and storage (removal of CO₂), and managing solar radiation, geoengineering practices aim to reduce CO₂ emissions (Lockley et al., 2019). The approach that has the most promise for minimizing the impacts of CO₂ emissions is carbon capture, storage, or conversion. For instance, the most common methods for CO₂ capture are solvent absorption, adsorption, membrane technology, and chemical looping, although recently cutting-edge nanomaterials such as nanoparticles, metal-organic frameworks, carbon dots, MXenes, and MBenes have been used (Shewchuk et al., 2021). Moreover, among the several approaches performed for the achievement of carbon neutrality, is the use of microalgae, macroalgae, and microbes for carbon capture and conversion to a variety of sustainable commodities, lowering the atmospheric CO₂ footprint on a global level (Goveas et al., 2022). On the other hand, most of the studies focused on a single carbon-capturing process rather than comparing all capturing processes in detail (Daneshvar et al., 2022; Yu et al., 2022). Moreover, there is no study conducted on the comprehensive evaluation of carbon-capturing methods considering their maturity levels, CO₂ capture capacity and yield, environmental impacts, and cost. The carbon-capturing techniques are still at their beginning and need further research to verify that CO₂ can be safely captured, transported, injected, and stored without contaminating the environmental resources. Most of the studies directly focused on the carbon capturing methods or/and their utilization and storage without considering their possible environmental and economic impacts.

Therefore, in this study, the complete spectrum of direct and indirect carbon-capturing methods is discussed in detail. In addition, we outline the advantages and drawbacks of the carbon capturing technologies along with their technological advancements and mode of action. In addition, there is no detailed research on the environmental assessment of CO₂ capture methods using different methods, according to our humble opinion. On the other hand, the global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and ozone depletion potential (ODP) are essential environmental impact parameters to evaluate the performance of the CO₂-capturing processes. Therefore, there is significant needs to be a knowledge gap in estimating these impacts of CO₂-capturing processes for different methods, especially by means of direct environmental impact data. Overall, evaluating CO₂-capturing methods using different processes in terms of their technological availability, CO₂ capture capacity, economic sustainability, and environmental impacts is critical to provide sustainable and cleaner pathways for CO₂ capture. This study presents insight into the industrial applicability of direct and indirect CO₂-capturing processes using various methods by evaluating environmental and technological sustainability. The specific objectives of this study are overall listed as follows: (i) to discuss the advantages, possible drawbacks, and future directions of specified direct and indirect CO₂-capturing processes, (ii) to assess the economic and environmental impacts of processes as well as their capturing capacity, (iii) to compare the environmental impacts and economic sustainability, and CO₂-capturing capacity of processes, and (iv) to determine the level of environmental sustainability of the processes with a normalized ranking method. Consequently, this review paper provides insight into the real-scale applicability of processes for effective and sustainable CO₂ capturing by assessing their environmental impacts, efficiency, and economic affordability.

2. Carbon capturing methods

The technique of absorbing CO₂ produced during the production of

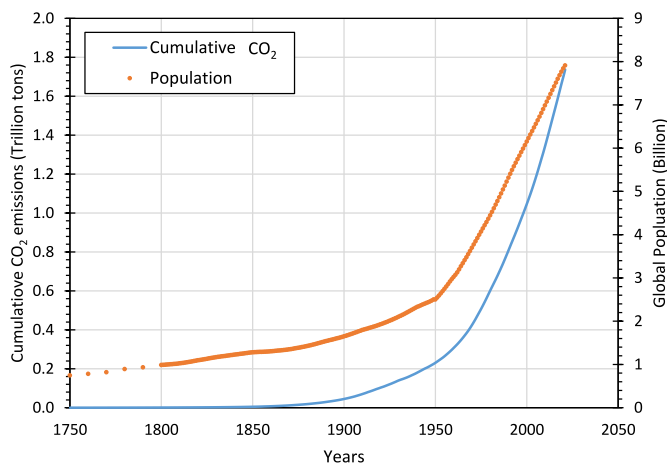


Fig. 1. Variations of CO₂ emissions and population over the years in the world (data from Ritchie et al. (2023)).

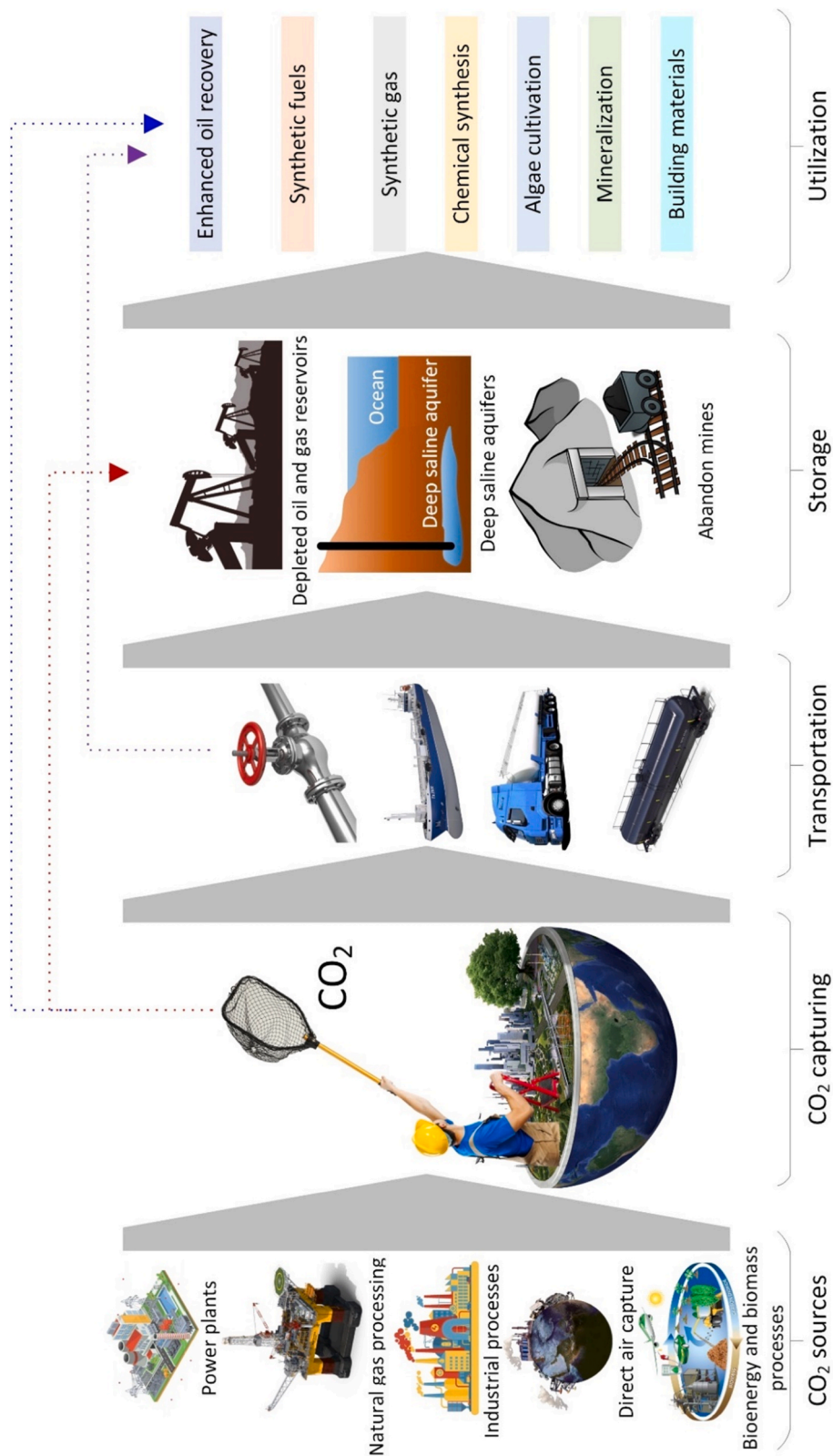


Fig. 2. A comprehensive illustration of carbon capturing, transportation, storage and utilization ecosystem: from source to utilization.

electricity and other industrial activities and storing it to ensure it is not released into the environment is known as carbon capture and sequestration (CCS). The use of CCS processes has the potential to substantially decrease CO₂ emissions from energy systems. CO₂ may be captured at the source using several types of methods. Then, captured CO₂ may be

utilized occasionally to produce manufactured products, in industrial operations, and in other processes instead of being trapped underground. The CO₂ capturing methods are divided into two main categories: direct carbon captures such as pre-combustion, post-combustion, oxy-combustion, and air capture systems, and indirect carbon captures

such as afforestation-reforestation, enhanced weathering-natural absorption, bioenergy options with carbon capture, and soil and farming practices (Fig. 3).

In this section, the direct and indirect carbon-capturing approaches are considered and discussed in more detail to evaluate their performance considering CO₂ capturing efficiency and economic aspects. Their working principles, advantages, disadvantages, essential remarks, and technology readiness levels are also discussed. Moreover, in the knowledge of the results obtained from the literature, the points that need to be developed and the gaps that need to be studied in more detail are emphasized, and light is shed on future studies.

2.1. Direct capturing approaches

A method called direct carbon capture fundamentally removes CO₂ directly from the atmosphere or exhaust gases. A potential technological tool for addressing climate change is the direct capture of CO₂ from the atmosphere. This approach is regarded as an essential part of negative emissions technologies (NETs), which aim to produce net-zero atmospheric carbon emissions. Direct air capture, pre-combustion, post-combustion, and oxy-combustion are the three most popular direct carbon capture techniques, while there are more approaches. The advantages of direct carbon capture are enormous. In addition to helping industries reduce their emissions, it may also help with the problem of carbon sequestration. This is crucial because there will still be some extra CO₂ in the atmosphere even if the world is thriving in reducing emissions to zero. Corporations may take this CO₂ out of the environment and store it safely by employing direct carbon capture technology. On the other hand, its biggest drawback is its high cost of direct carbon capture, particularly in the direct air capture process. Direct carbon capture (DCC) has also come under criticism for its inadequate rate of CO₂ capture with high energy costs. Namely, since CO₂ levels in the atmosphere are so low (0.04%), DCC from a manufacturing output should theoretically need several times more energy. Therefore, separating CO₂ from the capture mixture consumes most of this energy. Although direct capture technologies have advanced over the past decade, they are still in numbers and require feasible technology developments achieved before being used commercially. In this section, direct carbon capturing methods, including pre-combustion, post-combustion, oxy-combustion, and direct air capture systems, are summarized, and their progress until now discussed in terms of CO₂ capture efficiency, energy consumption, and operational costs.

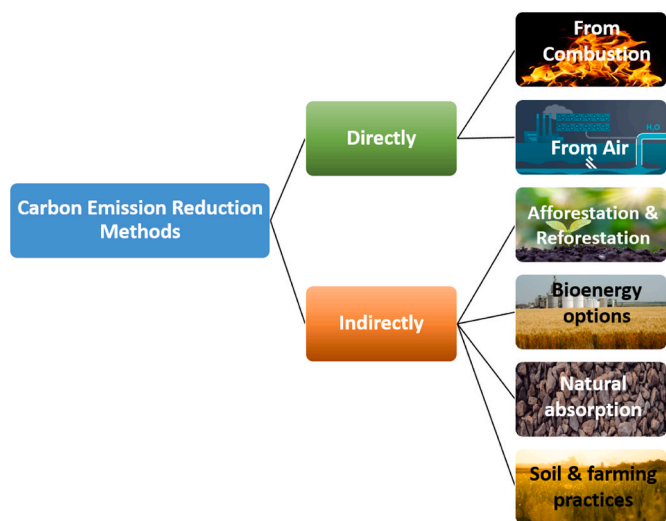


Fig. 3. Schematic illustration of direct and indirect carbon reduction methods, including carbon capturing.

2.1.1. Pre-combustion

Pre-combustion carbon capture is a technique to capture carbon dioxide from traditional fossil fuels or biomasses prior to the completion of the combustion process. Fig. 4 demonstrates the fundamental aspects of pre-combustion carbon capture techniques. Pre-combustion carbon capture technologies aim to separate CO₂ from the fuel source before it is burned, enabling the capture and potential storage of CO₂ emissions. These technologies are often integrated into power plants or industrial facilities that rely on fossil fuels, allowing for a significant reduction in greenhouse gas emissions.

There are two main types of pre-combustion carbon capture technologies.

- Pre-combustion capture with gasification
- Pre-combustion capture with reforming

While pre-combustion capture with gasification involves converting solid fossil fuels, such as coal or biomass, into a gas mixture consisting primarily of hydrogen (H₂) and carbon monoxide (CO) through a process called gasification, pre-combustion capture with reforming is primarily used for natural gas, which is composed mainly of methane (CH₄). Each method is defined below.

2.1.1.1. Pre-combustion capture with gasification. A pre-combustion carbon capture system begins with the gasification of fossil or biomass fuels to produce syngas, which mostly contain hydrogen, carbon monoxide, and carbon dioxide. Since syngas is usually used to power turbine generators and generate electricity, pre-combustion carbon capture technology usually removes carbon dioxide before the gas is combusted. This is accomplished by shifting syngas into water-gas-shift (WGS) reactions, which will create extra hydrogen and create extra CO₂. Increasing the density of carbon dioxide after the WGS reaction will improve the efficiency of carbon capturing.

In gasification reactions, the amount of air or oxygen available inside the gasifier is carefully controlled in order to perform partial combustion, which means only a portion of the fuel burns completely. A partial oxidation process generates the heat required to chemically decompose the fuel and produce synthesis gas (syngas), which consists primarily of H₂ and CO. After being processed in a WGS, the syngas is converted to CO₂ and H₂, resulting in a mole concentration of 40% and 55% of CO₂ and H₂. An illustration of pre-combustion CO₂ capture within a gasification plant can be seen in Fig. 5.

Compared to post-combustion technology, which removes dilute CO₂ from gas streams and is at low pressure, the shifted synthesis gas stream is rich in CO₂ and at higher pressure, which allows for easier removal before the hydrogen is combusted. Due to the more concentrated CO₂, pre-combustion capture typically is more efficient but the capital costs of the base gasification process are often more expensive

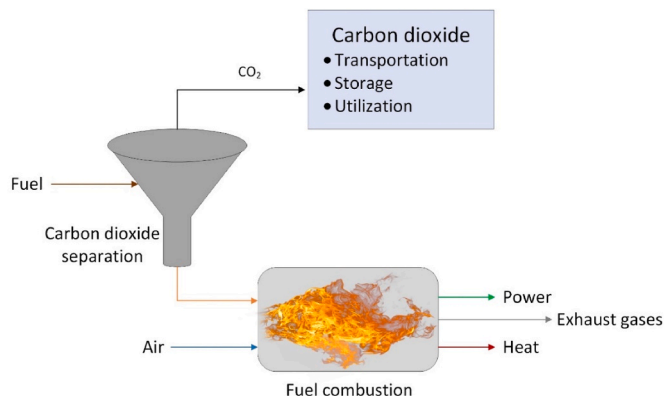


Fig. 4. A basic illustration of pre-combustion carbon capturing techniques.

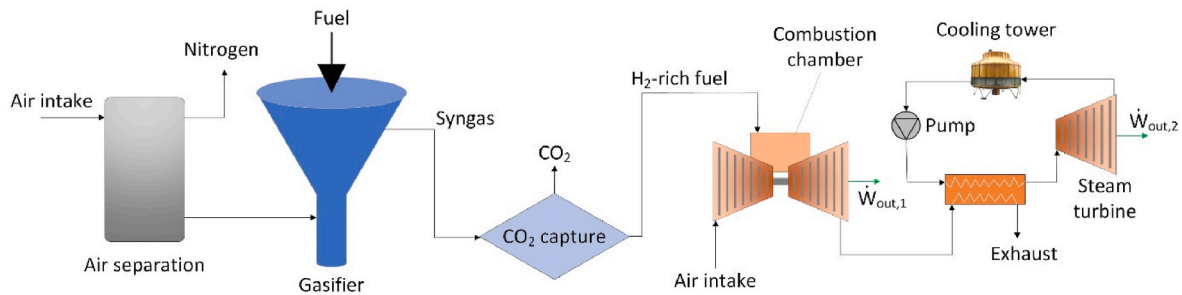
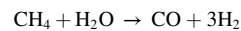


Fig. 5. A schematic illustration of pre-combustion CO₂ capture for gasification application.

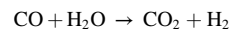
than traditional pulverized coal power plants. Pre-combustion carbon capture methods that are now commercially available typically employ physical or chemical adsorption techniques and will cost around \$60 per ton to absorb CO₂ produced by an integrated gasification combined cycle (IGCC) power plant (Padurean et al., 2012). The main goal of pre-combustion research in the case of natural gas as the primary fuel is to lower energy losses and investment costs related to the production of hydrogen fuel gas by integration, i.e. combining the reforming and/or WGS reactions with the CO₂ removal in one process step, shifting the reaction equilibrium further in the direction of the hydrogen-rich product gas (Jansen et al., 2015). In general, there are four components of pre-combustion capture that need to be studied: solvent-based carbon capture, sorbent-based carbon capture, membrane-based carbon capture, and innovative concepts. Pre-combustion CO₂ capture in natural gas combined cycles has been the focus of several techno-economic evaluation projects that have assessed energy restrictions and capturing costs in both more traditional setups and setups with new technologies incorporating multiple process stages. On the other hand, no natural gas-fueled pre-combustion power plant or pilot demo is currently in use. For instance, an extremely high-efficiency loss of 16% is determined for NGCC cycles with pre-combustion CO₂ collection in a recent report (IEA-GHGT, 2012) on CO₂ capture in gas fueled combined cycle power plants. The manufacture of syngas (6%), WGS (3%), H₂/CO₂ separation (5%), and CO₂ compression and drying (2%) are the sections that experience the greatest efficiency losses. Overall, pre-combustion capture provides benefits such as the ability to manufacture CO₂ at high pressure and the production of a carbon-free fuel (hydrogen under pressure), which reduces the power needed for the liquefaction or compression processes required for transporting and storing the CO₂ (Metz et al., 2005). Note that pre-combustion capture may also speed up the introduction of H₂ as an energy carrier in a system with minimal carbon emissions. This requires a further purification of the H₂ for low-temperature fuel cell applications in transportation, for which proven technologies are available. The flexibility in the power plant output, or the ability to switch between producing hydrogen and producing power (co-production of hydrogen and power) depending on the demand for electricity, is another benefit of the pre-combustion capture technique. Given the growing quantity of unstable wind and solar power entering the grid, power intermittency is becoming more crucial nowadays. This imposes more and more flexibility requirements on the fossil fuel-fired power plants, particularly the power plants equipped with CO₂ collection. Moreover, despite post-combustion method established status as the most popular CCS approach, pre-combustion capture is less capital expensive than post-combustion capture due to its typically greater pressure and higher CO₂ fugacity that favors smaller absorption columns. On the other hand, there has been limited application in the previous ten years to create pre-combustion CO₂ collecting routes. This is mostly due to the fact that post-combustion capture utilizing better and novel chemical solvents is the focus of power-generating, research and development, and demonstration.

2.1.1.2. Pre-combustion capture with reforming. Pre-combustion capture with reforming is a specific pre-combustion carbon capture technique primarily used for natural gas (Fig. 6). Natural gas (mainly CH₄) reacts with high-temperature steam in the presence of a catalyst, typically a nickel-based catalyst. This process, known as steam methane reforming, produces a gas mixture consisting of H₂ and CO. The following equation can represent the reaction:

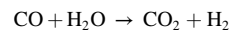


In the shift conversion process, the CO produced in the reforming step is reacted with steam to convert it into additional hydrogen and carbon dioxide. This process is called the water-gas shift reaction and typically takes place in two stages: high-temperature shift reaction and low-temperature shift reaction.

High-temperature shift (HTS) reaction: The first stage involves reacting CO with steam at high temperatures (around 350–450 °C) in the presence of a catalyst, often based on iron or copper. The reaction equation for the HTS process is written as follows:



Low-temperature shift (LTS) reaction: The second stage occurs at lower temperatures (around 200–250 °C) using a different catalyst, often based on copper, zinc, or chromium. The LTS reaction further converts the remaining CO into CO₂ and hydrogen:



After the shift conversion process, the resulting gas mixture contains primarily H₂ and CO₂, along with small amounts of other gases like nitrogen (N₂) and residual CH₄. Various separation technologies can be employed to capture CO₂ from the gas mixture, such as pressure swing adsorption (PSA), membrane separation, or solvent-based absorption processes. These technologies selectively capture CO₂, leaving behind H₂ gas.

2.1.1.2. Post-combustion

Post-combustion capture (PCC) is a carbon capture technology used to capture CO₂ emissions from the exhaust gases of power plants or industrial processes. It is called “post-combustion” because it captures CO₂ after the combustion of fossil fuels has occurred. PCC involves separating CO₂ from flue gases produced by burning fossil fuels - coal, natural gas, or oil. Fig. 7 demonstrates a typical post-combustion carbon capturing technique for a coal-fueled power plant. The combustion of coal in air produces heat, which is converted to electricity by steam-driven turbines and generators in coal-based power plants. In addition to N₂, CO₂, H₂O, O₂ and SO_x, NO_x, and heavy metals, the combustion process produces a flue gas mixture that contains a variety of compounds. Flue-gas desulfurization, selective catalytic reduction, and electrostatic precipitation are some of the technologies that can remove these gases. Fig. 7 further shows how the PCC process selectively separates CO₂ from the remaining gas mixture. It is possible to compress and store CO₂ underground, use it in other processes such as enhanced oil recovery, or use it in some other way that does not result in its emission

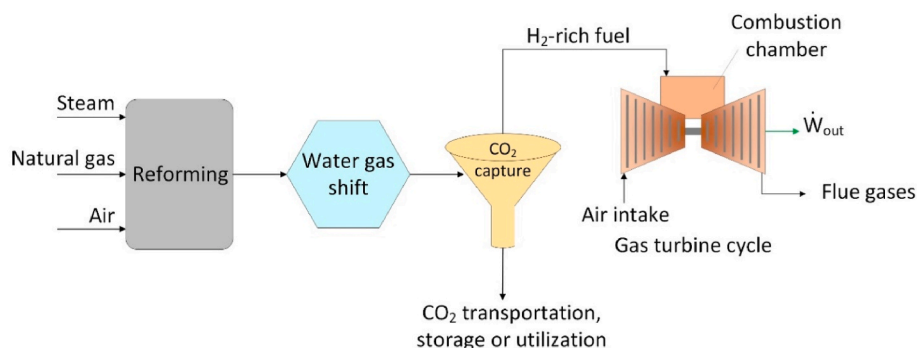


Fig. 6. A schematic illustration of pre-combustion carbon capturing with reforming (adapted from Cebucean and Ionel (2022)).

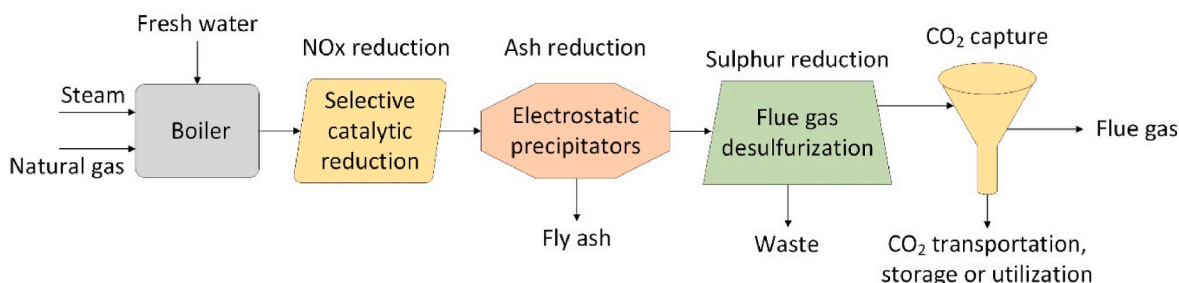


Fig. 7. A schematic illustration of the post-combustion carbon capturing process (adapted from GCCSI (2012)).

into the atmosphere.

The PCC process typically involves the following steps: flue gas separation, CO₂ capture, and CO₂ storage. The exhaust gases, or flue gases, are first separated from the power plant or industrial process emissions. Flue gases contain a mixture of CO₂, N₂, and other trace gases. The flue gases are directed to a CO₂ capture unit, where the CO₂ is separated from the other gases. Various technologies can be used for CO₂ capture, including chemical absorption, physical adsorption, and membrane separation. These technologies selectively remove CO₂ from the flue gases. The captured CO₂ is then compressed to increase its pressure, making it easier to transport and store. The compressed CO₂ is transported to a storage location, often underground, where it can be stored permanently. The common storage options may include deep saline formations, depleted oil and gas reservoirs, and unmixable coal seams.

The post-combustion capture has several advantages. It can be retrofitted to existing power plants and industrial facilities, allowing them to reduce their CO₂ emissions without major modifications. It also enables the capture of CO₂ emissions from multiple sources, as the flue gases can be combined from various plants before the capture process. However, PCC has some drawbacks as well. It requires significant energy for the capture and compression processes, which can reduce the overall efficiency of the power plant or industrial facility. It also adds to the overall cost of electricity generation or industrial production. Additionally, the storage of captured CO₂ requires careful monitoring and verification to ensure long-term safety and prevent leakage. The PCC is one of the technologies used to mitigate CO₂ emissions and combat climate change. It is often used in conjunction with other carbon capture, utilization, and storage (CCUS) technologies to reduce greenhouse gas emissions from various industrial sectors. Table 1 compares the flue gases for the power plant, which has a capacity of ~550 MWe, operated by coal and natural gas. While coal combustion emits 13.5 mol.% of CO₂, natural gas emits 4.04 mol.%. The flue gas compositions are separated after combustion, and then CO₂ is captured in order to reduce or eliminate the CO₂ emissions.

The commonly employed specific techniques for PCC are chemical

Table 1

Comparison of flue gases for coal- and natural gas-fueled power plants (data compiled from (Adu et al., 2020; James Robert E. et al., 2019)).

Parameter	Fuels	
	Coal	Natural gas
Net power output (MWe)	550	555
Power plant efficiency (%)	39.3	50.2
Flue gas properties from power plant		
Temperature (°C)	58	106
Pressure (kPa)	100	100
Mass flowrate (kg/s)	821.3	897.4
Flue gas compositions		
N ₂ (mol.%)	67.93	74.32
O ₂ (mol.%)	2.38	12.09
CO ₂ (mol.%)	13.5	4.04
H ₂ O (mol.%)	15.37	8.67
SO ₂ ppm	0	0
NO _x ppm	N/A	0
H ₂ S ppm	N/A	0
Ar (mol.%)	0.81	0.89

absorption, physical adsorption, Ca looping, membrane, and cryogenic separation (as illustrated in Fig. 8). The chemical absorption is a widely used technique for post-combustion capture. It involves using a liquid solvent or absorbent to selectively capture CO₂ from the flue gases (Spigarelli and Kawatra, 2013). Moreover, it is a mature method, and early applications in the natural gas industry and to produce food and beverage grade CO₂ are reported in the open literature (Yang et al., 2008). The most commonly used solvent is an aqueous solution of amines, such as monoethanolamine (MEA). The flue gases are brought into contact with the solvent, and the CO₂ reacts with the amine to form a soluble compound. The solvent is then regenerated by heating it, releasing the captured CO₂ for compression and storage. Overall, despite significant disadvantages such as high energy consumption and corrosion, the MEA is usually selected for practical industrial applications to remove CO₂ (Kittel et al., 2009). According to literature research, the energy cost is quite high, with the MEA reduction in efficiency predicted

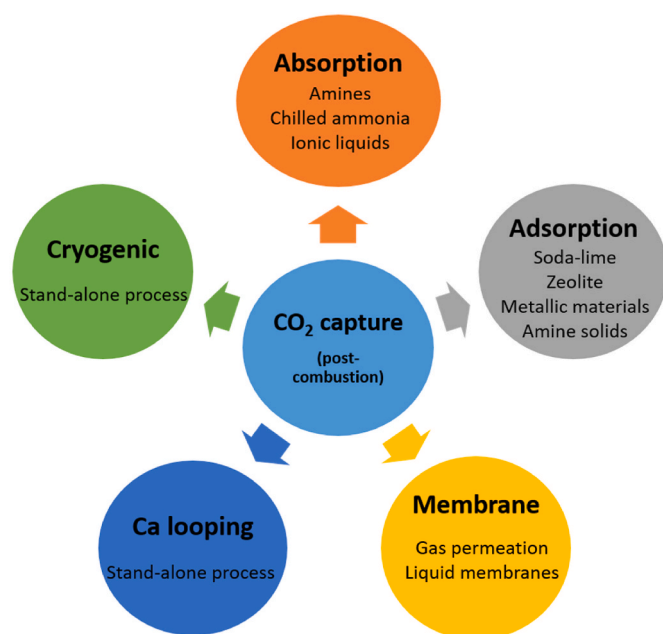


Fig. 8. An illustration of post-combustion carbon capture technologies.

to range between 25 and 28% for new construction and between 36 and 42% for upgrading an existing plant (Stöver et al., 2011).

The physical adsorption relies on the adsorptive properties of solid materials, such as activated carbon or zeolites, to capture CO₂ from flue gases. The flue gases are passed through a bed of adsorbent material, where CO₂ molecules selectively adhere to the surface of the solid. The adsorbent material is then regenerated by reducing the pressure or increasing the temperature, allowing the CO₂ to be released for compression and storage. Post-combustion capture methods via adsorption may be divided into temperature swing, pressure swing, vacuum swing, and hybrid processes based on the principles of regeneration (Chao et al., 2021). Temperature swing adsorption (TSA) method is associated with adsorbing volatile organic components from the air and in TSA, CO₂ adsorption and desorption occur by various cycles adjusting the operational temperature. TSA uses a number of interconnected vessels that use fluidized, stationary, or mobile beds. Adsorption often proceeds at lower temperatures, where desorption requires heating the adsorbent bed and is thus run in a cyclical manner. Multiple benefits of TSA include: (i) low-impact impurities in the flue gas as they removed at a temperature of about 160 °C, (ii) TSA systems are operated at low pressure (about 4 bar), and are therefore easily maintained, (iii) TSA is frequently inexpensive to operate, but has an expensive initial investment, and (iv) TSA is simple to incorporate into existing power plants, where low-grade waste energy is accessible for adsorbent regeneration. Therefore, it is a straightforward and low-risk solution for installation (Kuramochi et al., 2012). On the other hand, desorption process needs a higher temperature (120–160 °C), performing that the adsorption columns are sequentially operated at 60 °C, and then heated by hot air or steam to 120 °C to release CO₂, and finally to 160 °C to remove possibly present impurities, while the CO₂ adsorption is occurred at a low temperature (40–60 °C) (Tiili et al., 2009). The TSA heating and cooling cycles require a lot of energy, thus studies have been conducted to reduce this energy disadvantage by improving the capture process, integrating energy, and creating adsorbents that can be used at lower temperatures. On the other hand, power plants have lower operating costs since there is a lot of low-grade heat available. Regeneration heat is frequently also provided on site for industrial operations like cement and lime factories. In pressure swing adsorption (PSA), CO₂ is released at low pressure after being absorbed at high pressure onto the surfaces of solid sorbents. Moreover, the recovery and purity of CO₂

collected can be increased by combining PSA with TSA. For instance, using a special zeolite, the PSA and TSA combination may achieve CO₂ purity of 99% and CO₂ recovery of 90% (Ishibashi et al., 1996). Among the adsorption methods, the vacuum swing adsorption (VSA) process has been industrially used for CO₂ separation owing to its advantages like potentially long lifetime of the adsorbent, ease of process, and of low energy consumption (Ho et al., 2008). In contrast to PSA, the adsorption at atmospheric pressure is followed by desorption under vacuum. High separation efficiencies and yields are obtained in the VSA case due to the high desorption efficiency under vacuum, which allows the use of a single absorption/desorption vessel. For example, in a VSA using activated carbon as an adsorbent, CO₂ flue gas concentration of 17% can be concentrated to 99% with an effective recovery of 68.4% (Kikkinides et al., 1993). Overall, costs and energy penalties need to be taken into account when using the post-combustion CCS procedures that have already been explained. TSA is generally appropriate for both solvent-based absorption and adsorption using solids. The TSA does not have extremely tight regulations for contaminants in flue gas. At a higher temperature, the adsorbed/absorbed contaminants may be removed from adsorbents or solvents. The energy cost of TSA is substantial, nevertheless, as regeneration frequently occurs at temperatures around 160 °C while adsorption/absorption occurs around 40–60 °C. Energy is used constantly for heating and cooling the solvents and adsorbents. Therefore, it is critical to develop novel solvents and adsorbents with high capacities and low regeneration temperatures. On the other hand, PSA and VSA methods are promising for the adsorption methods and can be performed at room temperature, preventing the cost of repeat heating and cooling. Vacuum and pressurization, however, use a lot of energy in these processes.

The utilization of membranes in CO₂ reduction is a quite novel technology. In membrane separation, gas molecules are specifically separated from their mixture. However, membrane contactors promote the interaction of two phases, such as a liquid and a gas. Membranes may separate chemicals by a variety of mechanisms, including adsorption, diffusion, molecular sieving, solution, and ionic transport (Mondal et al., 2012). The membrane may be of several types, including organic, inorganic, and mixed matrix membranes, depending on the materials used. Regarding durability, operating and material costs, and CO₂ recovery effectiveness, each membrane has pros and cons. Fundamentally, membrane separation involves using a semi-permeable membrane to selectively separate CO₂ from the flue gases. The membrane allows the smaller CO₂ molecules to pass through while blocking the larger nitrogen and other gases. This method operates based on the differences in the molecular size and permeability of the gases. Membrane separation offers the advantage of being a simpler and potentially more energy-efficient technique but may require high-pressure operation to achieve significant CO₂ capture. Overall, the main issue, where multi-stage membrane systems may provide a solution, is the low partial CO₂ pressure in post-combustion flue gas. Efficient membrane separation additionally requires a much higher initial pressure, with 20% or higher CO₂ concentrations, making it doubtful. Cryogenic separation utilizes low-temperature conditions to capture CO₂. The flue gases are cooled to very low temperatures, typically below –78 °C, causing the CO₂ to condense into a liquid or solid state while other gases remain in the gaseous phase. The condensed CO₂ can then be collected and stored. Cryogenic separation is energy-intensive due to the need for cooling, but it can achieve high-purity CO₂ capture. These techniques can be applied individually or in combination to achieve higher capture efficiency. Additionally, ongoing research and development efforts are exploring new materials, processes, and hybrid approaches to improve efficiency and reduce the cost of post-combustion carbon capture. Moreover, chemical looping is a completely novel, cutting-edge method of burning fuel with the inherent potential to separate CO₂ extremely effectively (Ghannadi and Dincer, 2023). In chemical looping technology, the key concept is to introduce a solid oxygen carrier into the combustion process to provide the oxygen needed for fuel conversion. As a result, the

combustion process does not require air, which prevents the dilution of the resultant gases with nitrogen. Consequently, a clean CO₂ stream that can be used for carbon sequestration is obtained.

2.1.3. Oxy-combustion

Combustion capture with oxygen (approximately 98%) ensures that the products of combustion (flue gas) contain CO₂ and water with only trace amounts of other gases. Consequently, CO₂ recovery is easier through condensation from a purge stream rich in CO₂ and water and very low in nitrogen than from flue gases produced by conventional combustion, in which CO₂ is typically combusted in air containing 79.9% nitrogen (Simbeck and Roekpooritat, 2009). Oxygen separation is the main issue with this method. Most of these separations are completed cryogenically, which consumes a great amount of energy. Chemical looping combustion, a promising new technology, is currently being developed. The oxygen in the air is removed through the oxidation of a metallic compound, which can be reduced during combustion and thus release oxygen. It is possible to capture 100% of CO₂ with this process.

The oxy-combustion carbon capture is a carbon capture technique that involves burning fossil fuels in an oxygen-rich environment instead of air (Fig. 9). Instead of using air, which is primarily composed of nitrogen, the combustion process is fueled with a mixture of oxygen and recycled flue gases (Al-Hamed and Dincer, 2022). The flue gases are obtained from the carbon capture unit itself, which contains a high concentration of CO₂. The fuel, such as coal or natural gas, is burned in the presence of oxygen and recycled flue gases. This results in a high-temperature flue gas predominantly composed of CO₂ and water vapor (H₂O), without the presence of nitrogen.

The flue gas from the oxy-combustion process contains a higher concentration of CO₂ compared to traditional combustion processes. It requires less treatment to separate CO₂ from the flue gases, as nitrogen is not present to complicate the capture process. The flue gases are typically cooled to remove water vapor, and the remaining CO₂ can be easily captured. Various techniques, such as chemical absorption using solvents or physical adsorption using solid sorbents, can be employed to capture the CO₂ from the flue gases. These techniques selectively separate and capture the CO₂ for further processing.

Once the CO₂ is captured, it is compressed to increase its density and transported to a suitable storage site for permanent storage. Compression is necessary to meet the required pressure for safe and efficient transportation and storage. The storage options include underground geological formations, such as depleted oil and gas reservoirs or deep saline aquifers. Oxy-combustion carbon capture has some advantages. By burning fuels in an oxygen-rich environment, the flue gas is predominantly CO₂, simplifying the capture process. Additionally, the absence of nitrogen in the flue gases reduces the volume of gases to be processed, resulting in potentially smaller and more efficient carbon capture units. However, oxy-combustion also has challenges, such as the need for oxygen separation, which requires energy and additional infrastructure. The oxygen separation process can be achieved through

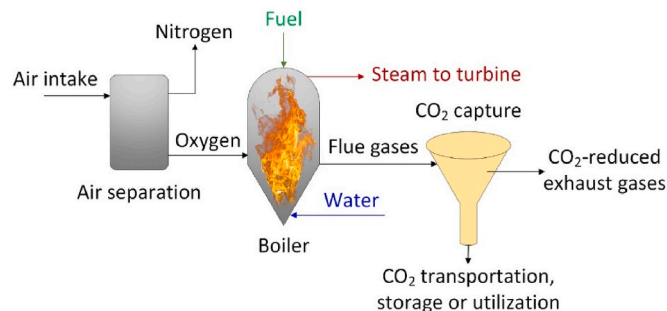


Fig. 9. A schematic illustration of the oxy-combustion carbon capturing.

various methods, including cryogenic distillation, pressure swing adsorption, or membrane separation. These processes contribute to the overall cost and energy requirements of oxy-combustion carbon capture. Each technique has its advantages and challenges. Table 2 essentially compares pre-combustion, post-combustion, and oxy-combustion methods over various parameters. Pre-combustion capture is integrated into the fuel conversion process, while post-combustion and oxy-combustion capture focus on capturing CO₂ after combustion. The choice between the techniques depends on factors such as the specific application, existing infrastructure, CO₂ concentration, energy requirements, and cost considerations.

2.1.4. Direct air capture

Implementing the direct air capture (DAC) method is essential for efficiently managing CO₂ removal from movable emission sources (Cao and Caldeira, 2010). DAC method has gained more attention in recent years as an alternative option to the carbon capture-utilization-storage approach since it can directly absorb CO₂ from the atmosphere, regardless of the source location (Zhang et al., 2022). Moreover, start-up projects support DAC with substantial funds and development due to the significant cost savings potential and the overall high efficiency of CO₂ extraction (Fasihi et al., 2019; Keith et al., 2018). DAC is a promising method for the utilization of CO₂ as a fuel in the transportation sector, especially in aviation, marine, and chemical manufacturing, where sustainable approaches are scarcely available (Fuss et al., 2018). The DAC methods are considered highly costly, with costs in the range of 200–1000 \$/ton of CO₂ (10 times more expensive than traditional capture from flue gas). On the other hand, recent economic evaluations indicate that with recent advances (particularly engineering), the DAC technology is close to profitability, capturing costs that can be decreased to less than \$100 \$/ton of CO₂ (Sinha and Realff, 2019). Even though the significant advantages presented compared to the most commonly investigated bioenergy carbon capture and storage, like the required land area, water consumption, technology training, the ability to scale, and life-cycle factors, the DAC method is still not proven as a significant CO₂ removal option (Grubler et al., 2018). Nevertheless, the DAC technology complies with sustainability guidelines for energy systems. Various DAC methods have been proposed for capturing CO₂, such as, high-temperature aqueous solvents and chemical solid sorbents with low-temperature adsorption processes (temperature swing adsorption, moisture swing adsorption) for regeneration purposes (Sinha et al., 2017). Overall, this section considered the main DAC methods to understand their performance regarding economic and sustainability points. A brief description of the considered methods, their advantages and disadvantages, and current progress status with other significant remarks are also considered in this section.

2.1.4.1. High-temperature aqueous solutions. Liquid DAC method is based on the CO₂ capture using a water-based basic solution (such as KOH and NaOH) using a series of modules conducting at high temperatures (in the range of 300–900 °C). DAC method using aqueous solutions first emerged as an effective method to decrease the level of CO₂ in the atmosphere in 1999 (Lackner et al., 1999). Basically, the suggested approach uses a 1 M NaOH solution regarding CO₂ absorption, and the reaction is strongly exothermic and thermodynamically advantageous, which exceeds the unfavorable entropy shift caused by removing CO₂ from the air and storing it in the solution (Zeman, 2007). Fig. 10 shows the entire DAC cycle, which consists of two recycling loops using different liquid solutions. In the first cycle, CO₂ from the contaminated air is captured using a liquid solution with ionic contents of almost 0.5 M CO₃²⁻, 1.0 M OH⁻, and 2.0 M Na²⁺ or K⁺. In the second cycle, Ca²⁺ is provided by dissolving Ca(OH)₂, while CO₃²⁻ forms precipitates by interaction with Ca²⁺ to produce CaCO₃. Finally, CaO is formed when the CaCO₃ is calcined to emit CO₂, which is then “slaked” or hydrated to form Ca(OH)₂. In the liquid DAC method, the reverse reaction that

Table 2
Comparison of pre-combustion, post-combustion and oxy-combustion carbon capturing methods.

Criterion	Pre-combustion	Post-combustion	Oxy-combustion
Process integration	Pre-combustion capture is integrated into the fuel conversion process before combustion occurs. It involves gasifying the fuel (coal, natural gas, etc.) to produce a syngas composed of H ₂ and CO, which is then converted to hydrogen and CO ₂ . The CO ₂ can be separated before combustion (Olabi et al., 2022a).	Post-combustion capture captures CO ₂ from the flue gases after the combustion of fossil fuels has occurred. It is retrofitted to existing power plants or industrial facilities (Akeeb et al., 2022).	Oxy-combustion modifies the combustion process by burning fossil fuels in an oxygen-rich environment, resulting in a flue gas predominantly composed of CO ₂ and water vapor (Ong and Chen, 2021).
CO ₂ Concentration in Flue Gas	In pre-combustion capture, the CO ₂ concentration in the gasification process is relatively high (typically above 50%) since the CO ₂ is separated from the syngas before combustion (Arora et al., 2023).	The flue gas in post-combustion capture has a relatively low CO ₂ concentration (typically around 10–15%) due to the presence of nitrogen and other gases (Figueroa et al., 2008).	Oxy-combustion produces a flue gas with a high CO ₂ concentration (up to 90%) and water vapor due to the absence of nitrogen (Miller, 2017).
Capture Techniques	Pre-combustion capture involves capturing CO ₂ from the syngas, which is typically done using physical or chemical absorption techniques (Alalwan and Alminshid, 2021).	Post-combustion capture techniques include chemical absorption using solvents (e.g., amines), physical adsorption using solid sorbents, or membrane separation (Allangawi et al., 2023).	Oxy-combustion simplifies the capture process since the flue gas is predominantly CO ₂ . Flue gas treatment and capture steps are typically simpler and require less energy compared to pre-combustion and post-combustion techniques (Ahn and Kim, 2020).
Energy requirement	Pre-combustion capture requires energy for the gasification process and the subsequent separation of CO ₂ from the syngas. It can be more energy-intensive compared to post-combustion capture (Oh et al., 2022).	Post-combustion capture requires additional energy for the capture process, such as solvent regeneration or sorbent regeneration. This can impact the overall energy efficiency of the power plant or industrial process (Einbu et al., 2022). Post-combustion capture can be retrofitted to existing power plants or industrial facilities, making it applicable to a wide range of existing infrastructure (Nessi et al., 2021).	Oxy-combustion has higher energy requirements upfront due to the separation of oxygen from air. However, it offers the potential for higher overall energy efficiency, as the combustion process is optimized for CO ₂ capture (Vega et al., 2019). Oxy-combustion requires significant modifications to the combustion system and infrastructure. It is more suitable for new-build power plants or facilities, as retrofitting existing infrastructure can be costly and challenging (López et al., 2021).
Suitability and Retrofitting:	Pre-combustion capture is suitable for applications where fuel gasification is already employed, such as integrated gasification combined cycle (IGCC) power plants. It may require substantial modifications or new infrastructure (Olabi et al., 2022b).		

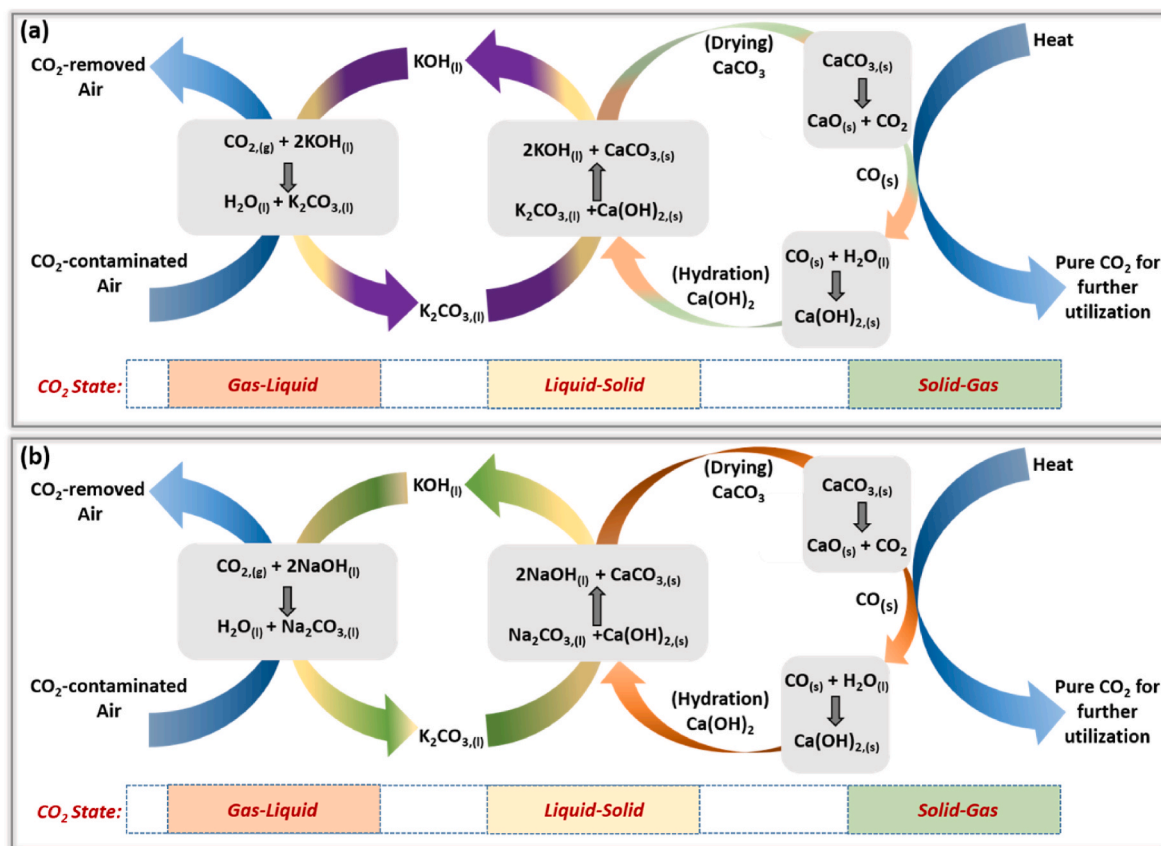


Fig. 10. Schematic illustrations of DAC cycle using (a) KOH and (b) NaOH (adapted from Zeman and Lackner (2004)).

results in the CO_2 release and regeneration of NaOH or KOH is remarkably unfavorable and requires extremely high temperatures ($T > 612 \text{ K}$) due to the tremendous thermodynamic forces of liquid solutions that drive it to absorb CO_2 . These circumstances would make it impossible and inefficient to thoroughly evaporate the water from the solvent. However, this problem can be solved by removing carbonate ions from the solution by reacting with a CaOH_2 colloid to precipitate CaCO_3 (calcite) and regenerating the NaOH or KOH solutions. The causticization process removes 94% of the carbonate ions from the solution while being thermodynamically advantageous and partially exothermic.

After being filtered from the solution and dried, the CaCO_3 is thermally converted into CO (lime) and CO_2 , and this calcination reaction is strongly endothermic and requires temperatures of about $900 \text{ }^\circ\text{C}$. Consequently, the hydration of the lime, also known as slaking, which is an exothermic reaction that regenerates CaOH_2 , completes the CO_2 separation cycle. It is important to note that recycling both of NaOH or KOH and CaOH_2 substances is essential in DAC method since neither these substances are found in nature as minerals. Moreover, the efficiency of CO_2 absorption, which specifies the size of the air-liquid contactor system and surface area required to process a particular quantity of air in a given amount of time, is equally critical to the thermodynamics of reactions, which are crucial because they establish the cyclical the capacity, the energy demands, and the conditions required for the absorption of CO_2 and release (Ahmad et al., 2023; Custelcean, 2022).

In the latest applications of the DAC method using liquid-based solutions widely based on the utilization of NaOH and KOH solutions (Keith et al., 2018; Zeman, 2007). However, as previously mentioned, results revealed that the aqueous alkali solutions are regenerated fortunately at high temperatures. Therefore, one of the major participants in the DAC method (Carbon Engineering) continually improves their system, one of which is the switch from aqueous NaOH to aqueous KOH as the sorbent utilized to boost CO_2 capturing performance of their systems since 2015 (Smith et al., 2019). In this regard, Fig. 11a

presented the schematic illustration of current operational configuration of the Carbon Engineering facility, in which CO_2 in the air is selectively absorbed by a liquid solution of KOH to generate carbonates, which are then transferred to a calciner to energetically liberate the CO_2 . The data collected from pilot scale DAC system is utilized to develop a continuous DAC process that could operate at a commercial level of around 1 Mt CO_2 captured annually (Fig. 11b-c). They reported that a total CO_2 stream of around $1.5 \text{ Mt CO}_2/\text{year}$ is produced by capturing and a further $0.5 \text{ Mt CO}_2/\text{year}$ from the on-site burning of natural gas needed to power the calciner equipment and other thermal and electrical activities. For 1-t-CO_2 capturing, the total energy demand is either 8.8 GJ of natural gas or 5.25 GJ of gas and 366 kW-hr of electricity. Moreover, the cost of the DAC system is predicted by the techno-economic evaluations to be between $\$94$ and $232/\text{t-CO}_2$ (Keith et al., 2018).

The CO_2 capturing performance of NaOH and KOH solution-based DAC systems are reported in Table 3 considering their CO_2 capturing efficiency. Several reactor types have been investigated for CO_2 capturing, including packed-bed, spray-based contractors, discs type contractors, airlift, and porous ceramic bubble sparger systems. The highest CO_2 capturing efficiencies are in the range of 57–97%. However, these results revealed that there is critical need for investigation of DAC of CO_2 using alkali liquid solutions. Most of the literature studies focused on the theoretical evaluation of CO_2 capturing instead of experimental studies. Therefore, experimental applicability of CO_2 capture with the DAC method in different reactor types and different operating parameters should be evaluated and further applications should be carried out on a pilot scale and on a real scale. Otherwise, theoretical studies will not be enough to enable the DAC method to be implemented as a viable technology in commercial scale. Moreover, studies should be concentrated on the development of materials such as effective and inexpensive catalysts in order to increase the performance of commonly used liquid solutions.

In addition, aqueous amines are the largest industry of point-source industrial CO_2 collection from natural gas and flue gas, although they

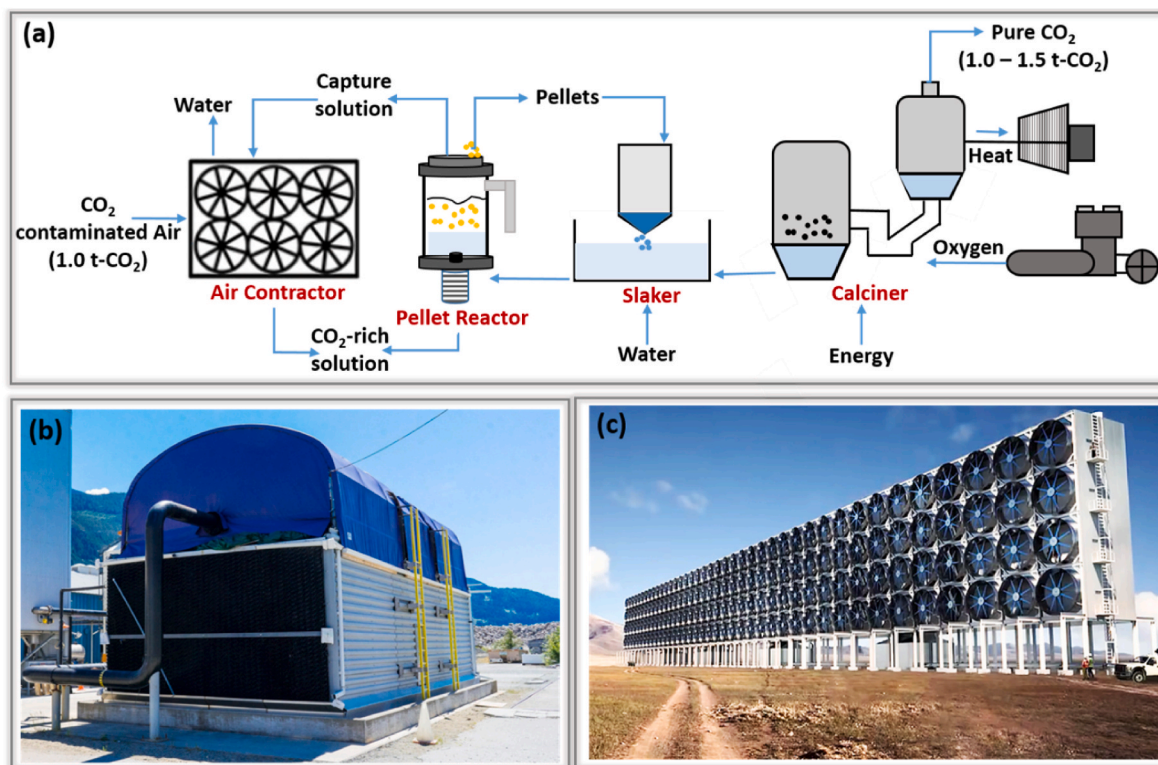


Fig. 11. Some specific representations: (a) a schematic diagram of the DAC system using high temperature liquid sorbent, (b) a photo of the pilot plant DAC system, and (c) a photo of the commercial-scale plant designed to continuous DAC process by Carbon Engineering Inc. (Carbon Engineering Facility, 2023).

Table 3

Summary of some leading literature studies on DAC of CO₂ using NaOH/KOH-based solution.

Direct air capture system	Operational conditions	CO ₂ removal efficiency	Ref.
Spray-based contactor	CO ₂ concentration: 0.04%; NaOH concentration: 0.33–5 M	3.7 mmol CO ₂ /L	Stolaroff et al. (2008)
Packed tower	CO ₂ concentration: 220–240 ppm; NaOH concentration: 3 M; KOH concentration: 3 M	68% for NaOH 95% for KOH	Mahmoudkhani et al. (2009)
String of discs contactor	CO ₂ concentration: 0.18–0.3%; NaOH concentration: 0.01–2 M; KOH concentration: 0.0089–1.76 M	–	Gondal et al. (2015)
Spray dryer	CO ₂ concentration: 4%; NaOH concentration: 3 wt %; Temperature: 100 °C	63%	Tavan and Hosseini (2017)
Three-packed column reactor	CO ₂ concentration: 14%; NaOH concentration: 15 wt %	95%	Shim et al. (2016)
Packed column reactor	CO ₂ concentration: 10–15%; NaOH concentration: 0.5–1 M	97%	Salmón et al. (2018)
Internal-loop airlift reactor	CO ₂ concentration: 20–80%; NaOH concentration: 0.1 M; Temperature: 25 °C	42%	Pichler et al. (2021)
Tubular reactor	CO ₂ concentration: 30%; NaOH concentration: 0.28 wt %	96.5%	Azizi et al. (2022)
Batch-typed Pyrex cylindrical reactor	CO ₂ concentration: 31.5%; NaOH concentration: 1–5 wt %; Temperature: 25 °C	57%	Yoo et al. (2013)
Porous ceramic bubble sparger reactor	CO ₂ concentration: 45%; NaOH concentration: 0.1–0.2 M; Temperature: 25 °C	1.7 mol CO ₂ /L	Gaur et al. (2009)
Fed-batch reactor	CO ₂ concentration: 0.0153–1.2 %; NaOH concentration: 6 wt %; Temperature: 20 °C	–	Ghaffari et al. (2023)
Batch trapper reactor	CO ₂ concentration: 4 %; NaOH concentration: 3 wt %; Temperature: 100 °C	63%	Singh et al. (2018)

have not been extensively utilized for DAC up to this point. The most extensively studied aqueous amines for CO₂ capture at point sources is aqueous MEA, methyldiethanolamine (MDEA), and diethanolamine (DEA) which also serves as a benchmark for other alkanolamines (El Hadri et al., 2017). Amine solutions are attractive since they respond quickly, partially absorb CO₂, and are cost-effective. However, oxidative decomposition and the high regeneration heat of amine solutions are their main drawbacks (Miao et al., 2022). Potential amine decay causes solvents reduction, equipment corrosion, and the production of volatile degradation chemicals that may be hazardous to both human health and the natural environment (Leung et al., 2014). Alkanolamines have also been indicated to have a lower rate of CO₂ absorption than alkaline liquid sorbents, when exposed to oxygen, to have a high energy demand for regeneration because of the absorption of water, and to be mostly unfavorable to the environment (Veltman et al., 2010). The high volatility of most amine solvents, which is unsuitable with the open design of DAC contractors that require blowing huge quantities of air over the solvent, leading to high evaporation rates, may be the cause of their limited application. For instance, at a CO₂ concentration of 400 ppm, MEA is observed to be inadequate for DAC (Socolow et al., 2011). On the other hand, the most effective sorbents for DAC procedures are observed to be aqueous unhindered primary amines, which are also as effective as aqueous alkali hydroxide liquid solutions. They also provide an

opportunity for energy savings with a reasonably high efficiency owing to their low temperature requirements for regeneration. The comparison of the NaOH liquid solution with the amine-based solvents considering their CO₂ capturing efficiency is presented in Fig. 12. Results revealed that most of the amine-based aqueous sorbents provided similar CO₂ capturing performance compared to NaOH solution in DAC method. The average CO₂ capturing efficiency of amine-based solvents are in the range of 22.2–88.4%, while it is obtained as 88.1% using NaOH solution. The high efficiency of the aqueous solutions of 2-(butylamino)-ethanol (BUEA), 2-(2-aminoethoxy)-ethanol (DGA), MEA, 2-(ethylamino)-ethanol (EMEA), 2-(methylamino)-ethanol (MMEA), 1-amino-2-propanol (1A2P), 2-amino-1-butanol (2A1B), and in particular is not significantly various from that of the liquid NaOH solution, and those values remained practically unaltered throughout the entire experiment. On the other hand, the less effective absorbents included the sterically hindered amines 2-amino-2-methyl-1-propanol (AMP), 2-amino-2-methyl-1-3-propanediol (AMPD), 2-(tertbutylamino)-ethanol (TBMEA), and 2-amino-2-(hydroxymethyl)-1,3-propanediol (TRIZMA), as well as the secondary and tertiary amines diethanolamine (DEA) and bis(2-hydroxypropyl)-amine (DIPA), N-methyl-diethanolamine (MDEA), and 2-(dimethylamino)ethanol (DMMEA), respectively.

In summary, the substantial regeneration of energy makes the use of solid sorbents in DAC method more appealing than the use of liquid-based sorbents since regeneration with solid sorbents can be performed at lower temperatures (400 °C). As a consequence, solid sorbent-based DAC is more economically appealing since it can meet its regeneration energy needs using waste heat from industrial operations, and it when integrated, would eventually result in reduced expenses for operation. Moreover, capturing CO₂ from the atmosphere is more expensive than capturing it from an individual source since it requires more energy. This is explained with that atmospheric CO₂ is significantly more diluted than, for instance, CO₂ found in flue gases from power plants or cement factories. Therefore, DAC requires more energy and is more expensive than other CO₂ capture techniques and applications. However, this review paper revealed that studies on CO₂ capture by DAC method using liquid solutions are concentrated in the literature. Further experimental work on improving the efficiency of processes and materials used will allow the DAC method to be used as an environmentally friendly and cost-effective process in the future.

2.1.4.2. Chemical solid sorbents. The majority of the technologies in this category consist of one module with solid sorbent, in which adsorption and desorption (regeneration) occur sequentially. In the first phase of

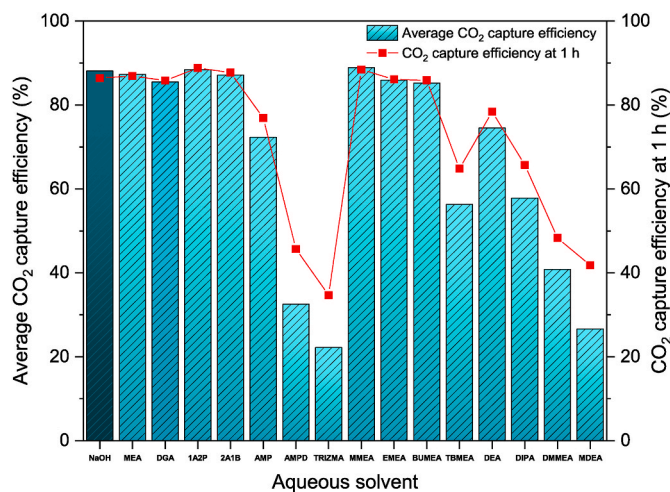


Fig. 12. Comparison of average and 1 h CO₂ capture efficiency of unhindered amines with NaOH solution under the same operational conditions (adapted from Barzagli et al. (2020)).

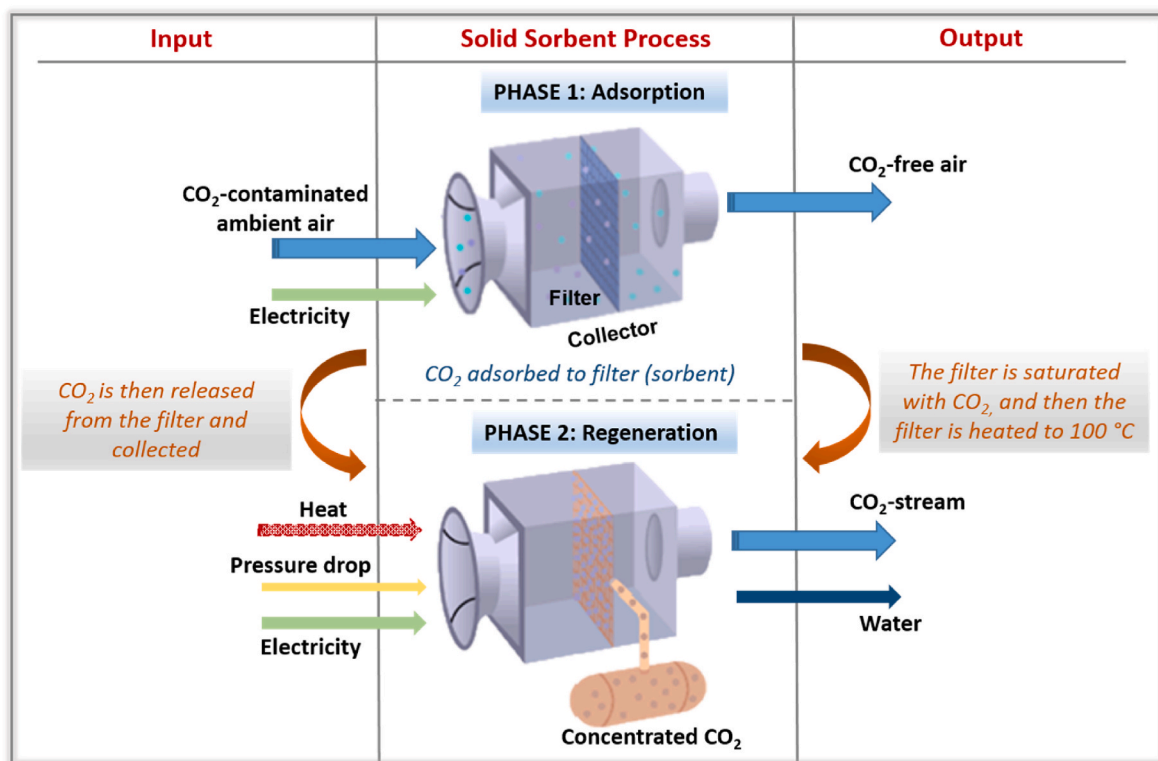


Fig. 13. Low-temperature solid sorbent utilization for CO₂ capture and regeneration process in the DAC system.

the chemical sorbent adsorption, system allows natural or fan-assisted flow of CO₂-contaminated ambient air as presented in Fig. 13. CO₂ chemically bonds to the filter at ambient temperature, and CO₂-depleted air leaves the system, and when the sorbent material is completely saturated with CO₂, this first phase is finalized. In the second phase, the input valve is closed, the fans are turned off, and if needed, vacuuming or adding steam to the system can be used to vacuum out the remaining air with a pressure drop. The system is then heated to a specific temperature (100 °C), depending on the type of the sorbent material, to perform regeneration. Finally, the released CO₂ from the system is collected and sent outside for cleaning, compression, or other utilizations.

Fundamentally, solid-based CO₂ sorption divided into two categories as chemisorption and physisorption, and these categories also subdivided into inorganic and organic types. The solid Ca(OH)₂, CaO, NaOH, Na₂CO₃, and NaHCO₃ salts have been performed for inorganic chemisorption of CO₂ in contaminated air (Sodiq et al., 2022). On the other hand, the relatively low CO₂ adsorption performance and requirement of high temperatures (>927 °C) for regeneration are critical drawbacks of NaOH, Na₂CO₃, and NaHCO₃ (Nikulshina et al., 2008). Although higher rates of adsorption are attained for CaO and Ca(OH)₂, but it only occurs at high temperatures (>400 °C), which is impractical for DAC systems (Nikulshina et al., 2009). Therefore, several sorbent materials have been developed or modified for effective CO₂ capture. Recently, the DAC of CO₂ using different lime-based solid sorbents are investigated and their performances are compared (Samari et al., 2020). The CO₂ capturing process are performed in fixed-bed reactor using 100% raw limestone and 10% calcium aluminate-90% raw limestone mixture. In comparison to the performance obtained when the intake air is humidified alone, the greatest performance is achieved when the sorbents are pre-humidified and the inlet air reached 55% relative humidity, while the worst adsorption performance is observed under dry system without humidity in inlet air and sorbents. When the effectiveness of the sorbent units is compared following nine cycles, the mixed limestone degraded more slowly (from 80 to 71%) than the natural

limestone (from 93 to 76%), which is thought to be due to the higher porosity. Nevertheless, despite the stated improvements in performance, it is crucial to remember that the regeneration temperature is still 850 °C, which is still quite high in terms of economic consequence. Furthermore, the hybrid ultramicroporous materials (HUMs), which have great selectivity against other airborne components, such N₂ and O₂, and can strongly encapsulate CO₂, have been recommended for DAC applications (Kumar et al., 2017). These crystalline frameworks are constructed from [M(pyrazine)₂]²⁺_n square grids interconnected by pillar-like counter anions. The small pore diameters and powerful electrostatics from the inorganic anionic pillars combine to provide a specific fit and improved selectivity for small polarizable substances like CO₂. Zaworotko et al. (2015) performed the DAC of CO₂ using different porous sorbent materials including TEPA-SBA-15 (amine-loaded mesoporous silica), Zeolite 13X (inorganic), HKUST-1 and Mg-MOF-74/Mg-dobdc (metal-organic frameworks, MOFs), and SIFSIX-3-Ni (nickel loaded HUMs) (Kumar et al., 2015). Moreover, the MOFs and hydrogen-bonded frameworks (HBFs) have been utilized for DAC of CO₂ (Inagaki et al., 2017). Another solid metal hydroxides and oxides which have been investigated for DAC of CO₂ include AgOH, MgO, Mg(OH)₂, LiOH, and Zn(OH)₂ (Campbell, 2019). In addition, attaching amine groups to porous solid frameworks has been the preferred method up until now since it mainly minimizes their loss with evaporation (Darunte et al., 2016). Some of the studies conducted on CO₂ capture using solid-based sorbent materials in the DCA method are summarized in Table 4.

In addition to the primary approaches that have been detailed, different approaches have been proposed in the literature. For instance, the CO₂ adsorption and regeneration performance of ion exchange resins has been proven in the literature to be highly excellent although sorption of CO₂ is achieved when the resins are dry, and desorption occurs when they are wet (a mode known as moisture swing) (Lackner and Wright, 2016). The main barrier to their usage in DAC is the requirement to constantly dry the resins, which is unfavorable for the environment in humid climates. In a separate study, a hypothetical model of

Table 4
Summary of some leading literature studies on DAC of CO₂ using solid-based sorbents.

Process	CO ₂ concentration (ppm)	CO ₂ removal efficiency	CO ₂ capture capacity	Reusability	Ref.
Liquid Amine–Solid Carbamic Acid	400	>%99	201 mmol/h	100 h	Kikkawa et al. (2022)
Faujasite Zeolite	400	95%	0.4 mmol/g	4 cycle	Wilson and Tezel (2020)
AEAPDMS-NFC	506	97%	1.39 mmol/g	12 h	Gebald et al. (2011)
Amine-grafted porous polymer networks	400	–	1.04 mol/kg	–	Lu et al. (2013)
Functionalized MIL-101(Cr)-TREN loaded	400	–	2.63 mmol/g	3 cycle	Darunte et al. (2016)
Amine-bearing pore-expanded MCM-41 Silica	400	<5%	0.98 mmol/g	6 cycle	Belmabkhout et al. (2010)
Hyperbranched aminosilica	400	–	1.72 mmol/g	4 cycle	Choi et al. (2011)
Amine-grafted silica gels	415	–	2.3 mmol/g	17 cycle	Anyanwu et al. (2019)
Aminopolymer-loaded hierarchical silica	400	–	2.6 mmol/g	5 cycle	Kwon et al. (2019)
TIFSIX-3-Ni	400	17.1%	17.9 mg/g	–	Kumar et al. (2017)
NbOFFIVE-1-Ni	–	16.55%	18.5 mg/g	–	–
Zeolite 13×	400	1%	1.5 mg/g	–	Madden et al. (2017)
ZIF-8	–	23%	2.3 mg/g	–	–
SIFSIX-3-Ni	400	<8	8 mg/g	–	Kumar et al. (2015)
HKUST-1	–	1%	2.1 mg/g	–	–
Mg-MOF-74	–	<4%	6.3 mg/g	–	–
UiO-66-NH ₂	–	2%	11.2 mg/g	–	–
TEPA-SBA-15	–	93%	158 mg/g	–	–
MOF Mg/DOBDC	400	–	1.35 mmol/g	4 cycle	Choi et al. (2012)
mmen-Mg ₂ (dobpdc)	390	96%	2 mmol/g	–	McDonald et al. (2012)
Mg ₂ (dobdc)	400	78%	3.86 mmol/g	5 cycle	Liao et al. (2016)
Zn(ZnO ₂ CCH ₃) ₄ (bibta) ₃	400	–	2.2. Mmol/g	5 cycle	Bien et al. (2018)
MXDA	400	–	5.6 mmol/g	–	Inagaki et al. (2017)

*TIFSIX-3-Ni: [Ni(pyrazine)₂(TIF₆)_n]; Mg/DOBDC: Magnesium dioxybenzenedicarboxylate; MOF: Metal organic framework; mmen: N,N'-dimethylethylenediamine; dobpd⁴⁻: 4,4'-dioxido-3,3'-biphenyldicarboxylate; bibta: 1, bibta²⁻ = 5,5'-bibenzotriazolate; MXDA: m-xylylenediamine; AEAPDMS: N-(2-aminoethyl)-3-aminopropylmethyldimethoxysilane; NFC: nanofibrillated cellulose; TREN: tris (2-amino ethyl).

solar-powered molecular filters that are based on nano-factories and can absorb CO₂ from the air has been studied (Freitas Jr, 2015). This equipment provides a pure CO₂ stream at a pressure of 100 bar and only needs 333 kW h/t-CO₂, with a final production cost of roughly 14 €/t-CO₂. The DAC of CO₂ is also performed using crystallization with a guanidine sorbent (Seipp et al., 2017). This technology eliminates the high-grade heat requirement of traditional liquid solution-based DAC systems by allowing regeneration to occur at temperatures in the range of 80–120 °C.

Furthermore, the MXenes and MBenes nanomaterials have been utilized for CO₂ capturing (Nayak et al., 2022). The MXene selectively transforms CO₂ into useful chemicals when it is combined with other transition-metal compounds, modifying agents, and photocatalysts (Tang et al., 2022). The newest member of the two-dimensional layered material category is the class of MXene, which includes two-dimensional transition-metal carbide, carbonitride, and nitride. These materials have unique features, including great stability, a significant amount of specific surface area, and remarkable thermal and electrical conductivity (Baskaran and Jung, 2022). It is also possible to precisely control its chemical characteristics by adding terminal functional groups to the metal atoms on the external surface of MXene (N. N. Li et al., 2021). For instance, it has been established that Mo₂C MXene has a remarkable electrocatalytic performance for reducing CO₂ (Lim et al., 2020). Moreover, it has been experimentally demonstrated that MXene surfaces such as Ti₃C₂, Ti₂C, and Nb₂C can be terminated with halogen species and then with chalcogen species (O, S, Se, and Te) through surface exchange processes (Kamysbayev et al., 2020). MXene-based single-atom catalysts are thus attractive options for enabling efficient electrochemical CO₂ reduction reaction catalysts. A recent investigation revealed that using g-C₃N₄/Ti₃C₂T_x MXene composite contributed to better photocatalytic production of CH₄ in comparison to using bare g-C₃N₄. The substantial surface area of the composite facilitated several CO₂ adsorption sites, which improved CH₄ production (X. Li et al., 2021). Likewise to the aforementioned, g-C₃N₄/BiOIO₃/Ti₃C₂ photocatalyst has been demonstrated to be 6.6 times more active than pure g-C₃N₄ in producing CO from CO₂ (Hong et al., 2022). Overall, the CO₂ adsorption capacity of the conventional adsorbents can be improved by adding MXene supports that provide resistance to wear and thermal conductivity. Recently, numerous two-dimensional transition metal

borides, called MBenes from the MAB phase (where M is a transition metal and A is a group IIIA or IVA element), have been also produced experimentally and utilized for CO₂ capturing (Ma et al., 2022). It is possible to produce a novel family of two-dimensional transition metal borides that is like the well-known MXene family by simply eliminating the A element from the MAB phase. For instance, the layered Ti₂B₂ structure by dealloying the Ti₂InB₂ MAB phase is produced under a vacuum environment. Results proved that the produced Ti₂B₂ presented excellent stability over the MXenes and sustained its layered feature at high temperatures (Wang et al., 2019). MBenes like Cr₂B₂ and Mo₂B₂ are also effectively synthesized from their corresponding MAB phases. All MBenes can be stabilized without surface passivation groups, unlike MXenes, resulting in an ideal framework to investigate the catalytic behavior of materials containing boron (Alameda et al., 2019). First-principles calculations are used to account for their electrical and chemical reactivity characteristics, and potential uses of MBenes as a high-efficiency catalyst for the CO₂ reduction reaction and the hydrogen evolution process have been presented. It has been reported that several MBene materials have been used in CO₂ electrocatalytic reduction, either experimentally or conceptually. For instance, the MB₂ MBene monolayers are utilized for the effective production of CO₂ to CH₄ in practical applications (Guo et al., 2017). Further research into the electrochemical properties of Cr₂B₂ and Mo₂B₂ has been performed in order to facilitate the development of a unique CO₂ reduction catalyst.

Moreover, a great deal of interest has been demonstrated in pressure swing adsorption-based CO₂ capture because of its easy procedure, low energy need, and low price (Agarwal et al., 2010). However, low CO₂ recovery performance is causes this method difficult to implement. Vacuum and temperature swing adsorption methods are often preferred for post-combustion CO₂ capture, but pressure swing adsorption method is more attractive for the pre-combustion operation (Marx et al., 2016). Furthermore, the prolonged cooling phase duration and significant energy need for adsorbent regeneration prevent the temperature swing adsorption process for CO₂ capture from being widely used. These scaling-up difficulties may be handled by novel methods that provide heat-management choices, such as hollow-fiber adsorbents with a medium that are carried in the bore side with efficient heat management (Rezaei et al., 2013).

2.2. Indirect capturing approaches

In this section, the reforestation and agricultural practice, enhance weathering, and bioenergy with carbon capture methods as an indirect CO₂ capture processes are summarized. Moreover, their advantages over direct capturing methods, critical drawbacks, and important remarks are considered to present their current applicability potential in real-scale.

2.2.1. Reforestation, solid and farming practice

Large-scale tree planting is an essential component of reforestation applications. Moreover, fast-growing plantations have a significant impact on decreasing global warming and have significant indirect carbon capture capacity. In order to prevent the world average temperature from rising by more than 2 °C throughout the 21st century and reduce emissions, governments are cooperating by negotiating attributes, such as the Kyoto Protocol and the Paris Agreement (Kim et al., 2020). About 4100 billion hectares of the surface of the earth are covered by forest ecosystems, which provide enormous opportunities for carbon absorption (Altamirano-Fernández et al., 2023). About 45% of this total area is composed of exotic plantations, while the remaining 55% is constituted of natural forests. Expanding forest areas and prolonging the age of rotation, particularly in exotic plantations of trees, have been suggested as significant approaches to maximize carbon capture and minimize the adverse impacts of global climate change since forest ecosystems can accumulate the most significant amounts of carbon (Kaipainen et al., 2004; Lewis et al., 2019). Moreover, significant amounts of CO₂ can be eliminated from the atmosphere and stored as carbon in organic compounds of ecosystems through the management of soil and vegetation for agricultural carbon sequestration. However, unless there are financial rewards or penalties connected to CO₂ control, such practical adaptations cannot take action. Moreover, agricultural carbon sequestration must not only contribute to carbon storage in plants and soil but also to a decrease in the net emission of CO₂ or other GHGs in order to be effective.

Note that there is a significant amount of literature that evaluates carbon capture based on the reforestation approach. The amount of carbon content and carbon capture in forest, especially in protected fields, are evaluated (Fragoso-López et al., 2017). Results demonstrate that this forest has an average carbon content of 105.72 Mg-C/ha, with a carbon adsorption rate of 1.03 Mg-C/ha/yr. These results also indicate that improving carbon capture depends on volume growth. Consequently, sustainable forest management must be established in place in order to maximize output in a forest and promote the long-term use of soil fertility. In a separate study, the underground carbon uptake in a tropical forest in Southern Europe has been estimated to be between 443 and 634 Tn-C/ha in the three species studied (*P. radiate*, *Eucalyptus nitens*, and *Eucalyptus globulus Labill*), with rotation periods varying from 10 to 35 years (Pérez-Cruzado et al., 2012). The carbon minimization potential of the same plant species investigated in Chile is 212, 180, and 117 Tn-C/ha for *P. radiate*, *Eucalyptus nitens*, and *Eucalyptus globulus Labill*, respectively (Olmedo et al., 2020). In Panama, the carbon capture potential of *Tectona grandis* E.L (Teca) species is evaluated and reported as 2.9 Tn-C/ha for 1 year and 40.7 Tn-C/ha for 24 years (Derwisch et al., 2009). However, because the trees have to remain in the field for extended periods of time to improve CO₂ capture, the rotation age is extended (Sohngen and Mendelsohn, 2003). Moreover, under some circumstances, extending the rotation age in order to maximize carbon absorption is challenging since it increases the possibility of forest fires. In this context, increased emissions of CO₂ from more forest fires will contribute to more intense climate circumstances and a decrease in relative humidity throughout many parts of the planet (Brown et al., 2004). In addition, various mathematical models have been proposed in order to accurately reflect the dynamics of CO₂ capture in reforestation tasks (Verma and Misra, 2018; Verma and Verma, 2021). Results proved that the level of CO₂ in the atmosphere reduces as the rate of reforestation expands. Overall, establishing the best management practices that

maximize carbon absorption is essential because forests may help mitigate climate change. While methods like extensive replanting are effective at absorbing significant amounts of carbon, managing forest plantations can also decrease CO₂ emissions by optimizing thinning, fire protection, and harvesting methods (Kerdan et al., 2019).

2.2.2. Natural absorption

The most significant method that nature controls the amount of CO₂ in the atmosphere is through weathering (natural absorption), which has been overlooked until lately. This lack of attention is possibly a result of individuals being unaware of its capacity to sequester CO₂ or not recognizing a valuable strategy to accelerate weathering. Increasing the rate of chemical weathering, a chemical/biochemical process that occurs naturally place in soils and bedrock is the basis of this technique. Namely, the natural weathering of land surface minerals over thousands to millions of years affects the climate of the world since the alkalinity formed by the weathering of calcium and magnesium-bearing rocks passes through the oceans and absorbs atmospheric CO₂ (Bufe et al., 2021). This is the consequence of the equilibrium between the total dissolved inorganic carbon content in the ocean and the atmospheric CO₂ concentration. Owing to this equilibrium, 1 Gt of atmospheric CO₂ is naturally absorbed each year and deposited in ocean waters, primarily as inactive bicarbonate and to a smaller amount as carbonate ions. In ocean waters, carbon can be safely kept for as long as thousands of years until it precipitates and generally takes the form of carbonate minerals (Renforth, 2019). Approximately 38,000 Gt of carbon are currently stored in oceans as dissolved inorganic carbon, which is 40 times greater than the quantity of carbon in the atmosphere. On the other hand, passive mitigation of rising anthropogenic CO₂ emissions is a long-term option due to the comparatively slow rates of the weathering processes that control atmospheric CO₂ absorption (Taylor et al., 2016). Therefore, the current focus of research is on increasing the rates of mineral weathering reactions, primarily by mining, crushing, and dispersing silicate rocks either (i) on land (usually in humid tropical regions in which weathering processes are more rapid), a method called terrestrial improved weathering, as well as basically boosted weathering, or (ii) in coastal areas, in which the weathering can be triggered by natural wave and tidal forces (Campbell et al., 2022). Both have demonstrated potential as CO₂ removal techniques, with additional benefits of nitrogen enrichment and the reduction of both soil and ocean acidification (Maesano et al., 2022). However, in particular, a portion of the produced alkalinity in enhanced weathering could be transported to the oceans via rivers and streams. The substantial amounts of alkalinity discharged with enhanced weathering might have negative impacts as freshwater ecosystems are sensitive to pH level fluctuations and may already be impacted by salt and alkalinity due to human activities and rapid weathering (Pinheiro et al., 2021). This prohibition is less strict in coastal enhanced weathering since seawater has a significantly higher average pH (8.1), marine carbonate chemistry is less responsive to alkalinity input globally, and oceans are influenced by acidification (Doney et al., 2020). Because of this, the higher alkalinity in coastal enhanced weathering may quickly be diluted, which could be helpful in preventing the production of secondary compounds like clays through reversed weathering. These factors have contributed researchers to focus on coastal enhanced weathering as well, especially when utilizing olivine, which combines broad availability with quick-dissolving (Meysman and Montserrat, 2017). Overall, enhanced weathering of minerals on land needs huge amount of substances indicating adverse effects from mining and transport but could permanently store a sizable amount of CO₂.

2.2.3. Bioenergy with carbon capture

The EU has set goals for 2030 that include reducing greenhouse gas emissions (GHG) by a minimum of 40% from 1990 levels, increasing the share of renewable energy sources in the final consumption of energy by over 32%, and improving efficiency in energy use by further than 32.5%

(Pignolet, 2015). Bioenergy is considered to be an essential part of these objectives. On the other hand, although carbon neutral, bioenergy is linked to both direct and indirect CO₂ emissions depending on its application, utilization, and conversion method (Bolt and Dincer 2023). By allowing a European zero-emission energy system in a cross-sectoral manner, bioenergy with carbon capture and storage or bioenergy with carbon capture and utilization may progress beyond decarbonizing carbon-intensive industries. The de-carbonization of the power and heat sector has been tackled by the use of biomass in current and future applications, and the adoption of CO₂-utilization methods into these plants allows it possible to use and generate value from waste streams. In particular, the use of H₂ in the total conversion process is connected to the carbon utilization concept, which involves the production of biofuels and chemicals. Renewable-based H₂ production may be attained by using the H₂ obtained from biomass resources or provided by renewable energy to power water electrolysis systems (Koytsoumpa et al., 2018). Several comprehensive review papers have been reported on bioenergy with carbon utilization and capture (Briones-Hidrovo et al., 2022; Geissler and Maravelias, 2022; Hanssen et al., 2022; Koytsoumpa et al., 2021; Michaga et al., 2022; Testa et al., 2023). These studies have comprehensively reported the relationship between bioenergy and CO₂ reduction.

3. Commercial carbon capturing facilities

Globally, there are now 40 commercial capture facilities, with an annual capture capacity of over 45 Mt CO₂. Fig. 14a shows the capacity of current CO₂-capturing facilities and future projections by 2030. Fig. 14a also compares the difference between the carbon capturing capacity and the amount to be needed to reach net zero target. There are currently around 40 commercial facilities that capture, utilize, and store carbon in industrial processes, fuel transformation, and power generation. The deployment of carbon capturing has lagged behind expectations in the past, but momentum has grown substantially in recent years, with more than 500 projects in various stages of development. By 2030, around 50 new capture facilities are expected to be operating, capturing around 125 Mt CO₂. The Net Zero Emissions by 2050 Scenario requires around 1.2 Gt CO₂ per year, but even at this level, CCUS deployment would remain substantially below (by around one-third) (IEA, 2021).

It has been growing since around the beginning of 2018 that carbon capturing projects have gained momentum, as depicts in Fig. 14b. Since the start of 2018, momentum has been growing behind carbon capturing

projects. By 2030, over 50 new capture facilities are expected to be operational, capturing around 125 Mt CO₂. Around 20 commercial capture projects under development have taken a final investment decision as of June 2023. Moreover, the commercial-scale CO₂-capturing facilities are summarized with their capturing capacities in Table 5. Results revealed that the liquid-based sorbents with the post-combustion process are widely utilized for carbon capturing. On the other hand, only one company performed CO₂-capturing using the DAC process. Moreover, carbon capturing is widely utilized in natural gas processing facilities, and its followed by coal-fired power plants, cement facilities, and fertilizer production plants. The CO₂-capturing capacities may practically change in the range of 0.007–7 Mt-CO₂/year.

4. Storage and transportation

In addition to developing effective CO₂-capturing techniques, storing captured CO₂ is another critical issue for reaching the zero target. CO₂ storage methods that minimize environmental impact and prevent release CO₂ back into the environment are essential. A variety of techniques can be used to store captured carbon dioxide. CO₂ is commonly stored in the ways demonstrated in Fig. 15. Geological storage involves injecting captured CO₂ deep underground into geological formations. In depleted oil and gas reservoirs, empty oil and gas reservoirs can be repurposed to store CO₂. The CO₂ is injected into the reservoirs and trapped by a combination of structural, residual, and solubility trapping mechanisms. Also, deep underground saline aquifers can be used to store CO₂. The CO₂ is injected into the porous rock formations and trapped by physical and chemical mechanisms. Additionally, in enhanced oil recovery, CO₂ can be injected into oil reservoirs to enhance oil recovery. This process is technically considered beneficial as it both stores CO₂ and increases oil production.

In addition to the geological storage reservoirs, CO₂ can be stored in the deep ocean. This method is still under research and is not widely implemented due to potential environmental impacts and concerns. Another technique to store CO₂ is the conversion of CO₂ into stable carbonate minerals through a process called mineralization or carbonation. This involves reacting CO₂ with certain types of rocks or minerals, such as basalt, to form solid carbonates. This method has the potential for long-term storage but is still in the experimental stage. It is worth noting that the storage of captured CO₂ requires careful monitoring and verification to ensure its long-term safety and prevent any leakage that could contribute to climate change. Additionally, the transportation of CO₂ from capture sites to storage sites also requires consideration,

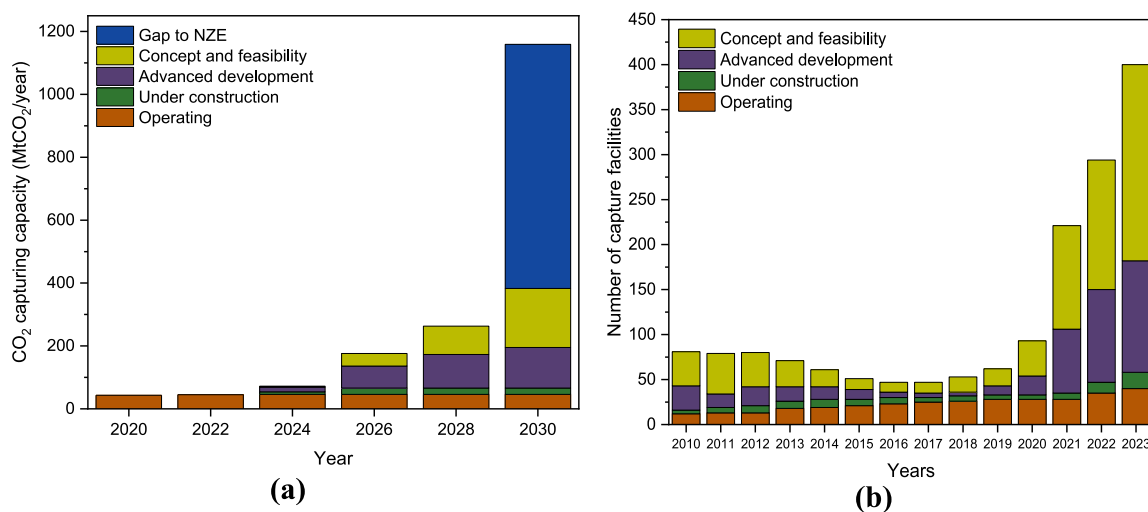


Fig. 14. Capacity of current and planned large-scale CO₂ capture projects for (a) 2020–2030 and (b) evolution of the CO₂ capture projects globally (data compiled from IEA, 2021).

Table 5
Some commercial-scale carbon capturing facilities with their capacities.

Company and country	Capturing method	Utilize technology	Main CO ₂ source	CO ₂ capture capacity (Mt/year)	Year	Ref.
Terrell natural gas plant, USA	Storage	Transform CO ₂ discharge from exhaust streams into oil field enhanced oil recovery (EOR) storage site	Natural gas processing	0.5	1972	Madejski et al. (2022)
IMC Global Inc. Soda Ash Plant, Canada	Amine	Solvent scrubbing	Coal-fired boilers	0.29	1978	Folger (2010)
Enid Fertilizer, USA	Storage	Injection to enhanced oil recovery storage	Fertilizer production	0.7	1982	Madejski et al. (2022)
Shute Creek gas processing facility, USA			Natural gas processing	7	1986	
AES Shady Point Power Plant, USA	Amine	Solvent scrubbing	Coal-fired power plant	0.06	1991	Folger (2010)
Bellingham Cogeneration Facility, USA			Natural gas processing	0.11		
Soda Ash Botswana Sua Pan Plant, Botswana			Coal-fired power plant	0.11		
Sumitomo Chemicals Plant, Japan	Amine	Absorption processes use a sorbent containing ammine	Gas and coal boilers	0.05	1994	
Statoil Sleipner West Gas Field, Norway			Natural gas processing	1.0	1996	
Petronas Gas Processing Plant, Malaysia			Natural gas processing	0.07	1999	
Warrior Run Power Plant, USA			Coal-fired power plant	0.05	2000	
Great Plains Synfuels, USA	Storage	Injection to enhanced oil recovery storage	Natural gas processing	3.0	2000	Madejski et al. (2022)
BP Gas Processing Plant, Algeria	Amine	Absorption processes use a sorbent containing ammine	Natural gas processing	1.0	2004	Folger (2010)
Mitsubishi Chemical Kuroaki Plant, Japan			Natural gas processing	0.12	2005	
Sinopec, Shengli power plant, China	Post-combustion	Transported 80 km via pipeline for use in EOR at 3 km depth in the Shangdong Province	–	0.04	2007	Salvi and Jindal (2019)
Snohvit Field LNG, Norway	Capturing with amine and storage	Absorption processes use a sorbent containing ammine and storage in deep saline formation	Natural gas processing	0.7	2008	Madejski et al. (2022)
Huaneng Co-Generation Power Plant, China	Amine	Absorption processes use a sorbent containing ammine	Coal-fired power plant	0.003	2008	Folger (2010)
Wallula, USA	Storage	Injected gaseous CO ₂ into solid carbonates	Geothermal power generation	0.001	2009	Kelemen et al. (2019)
Kemper County IGCC, USA	Pre-combustion and storage	Pre-combustion IGCC plant using TRIG™ technology and EOR	Power plant	3.0	2010	Salvi and Jindal (2019)
Century plant, USA	Storage	Injection to enhanced oil recovery storage site	Natural gas processing	8.4	2010	Madejski et al. (2022)
Decatur, USA	Capturing with amine and storage	CO ₂ capture using Alstom's amine process and sequestration in Mount Simon Sandstone	Chemical production	0.3	2011	Kelemen et al. (2019)
Capitol SkyMine, Skyonic Corp, USA	Storage	Transform CO ₂ discharge from exhaust streams into solids and mineralization of CO ₂ as sodium bicarbonate	Cement facility	0.08	2013	Salvi and Jindal (2019)
Cement Corp, China	Calcium looping	Pumping to underground to enhance the production of natural gas	Cement facility	0.009	2013	
Air Products steam methane Reformer, USA	Storage	Injection to enhanced oil recovery storage site	Hydrogen production	1.0	2013	Madejski et al. (2022)
Lost Cabin Gas Plant, USA			Natural gas processing	0.9	2013	
Coffeyville Gasification, USA			Fertilizer production	1.0	2013	
Petrobras Santos Basin pre-salt oilfield, Brazil			Natural gas processing	3.0	2013	
CarbFix, Iceland	DAC and storage	CO ₂ capturing on the surface of a highly selective filter materials and storage in basaltic formations	Power generation	0.007	2014	Kelemen et al. (2019)
Boundary Dam CCS, Canada	Storage	Injection to enhanced oil recovery storage site	Coal power generation	1.0	2014	Madejski et al. (2022)
Kemper County IGCC Project, USA			Natural gas processing	3.5		
Quest, Canada	Capturing with amine and storage	Absorption processes use a sorbent containing ammine and injected into the porous rock formation	Power generation	1.2	2015	Kelemen et al. (2019)
Saudi Arabia	Storage	Injection to enhanced oil recovery storage site	Natural gas processing	0.8	2015	Madejski et al. (2022)

(continued on next page)

Table 5 (continued)

Company and country	Capturing method	Utilize technology	Main CO ₂ source	CO ₂ capture capacity (Mt/year)	Year	Ref.
Dongguan Taiyangzhou Power Corporation, Xinxing Group, and Nanjing Harbin Turbine Co, China	Pre-combustion and storage	Pre-combustion capture (KBR and Southern Company Technology and injection to enhanced oil recovery storage site	–	1.0	2015	Salvi and Jindal (2019)
Petra Nova W.A. Parish, USA	Post-combustion	Post combustion: KM-CDR amine scrubbing CO ₂ developed by MHI and KEPCO	Coal power generation	1.4	2016	
Abu Dhabi CCS, United Arab Emirates	Pre-combustion and storage	Pre-combustion capture and injection to enhanced oil recovery storage site	Iron and steel production	0.8	2016	Madejski et al. (2022)
Illinois industrial, USA	Amine	Capture using Alstom’s amine process	Ethanol production	1.0	2017	
Abu Dhabi Future Energy Company and Taweelah Asia Power Company, China	Post-combustion	Absorption using highly effective sorbents	–	2.0	2018	Salvi and Jindal (2019)
Jilin oilfield, China	Storage	Injection to enhanced oil recovery storage site	Natural gas processing	0.6	2018	Madejski et al. (2022)
Texas Clean Energy Project, USA	Pre-combustion	Siemens IGCC technology and Linde Rectisol acid-gas capture technology	–	2.0	2019	Salvi and Jindal (2019)
Gorgon Carbon Dioxide Injection, Australia	Storage	CO ₂ is taken from offshore gas reservoirs and injected into a giant sandstone formation	Natural gas processing	4.0	2019	Madejski et al. (2022)
Alberta Carbon Trunk Line with North West Feedwater Partnerships, Canada			Natural gas processing	1.6	2020	
Sargas Power, UK	Pre-combustion and storage	IGCC: Pre-combustion and sequestration in offshore deep saline formations	Power generation	4.5	2020	Salvi and Jindal (2019)
Captain Clean Energy Limited, UK	Pre-combustion	Siemens Pre-combustion process	–	3.8	2022	Salvi and Jindal (2019)

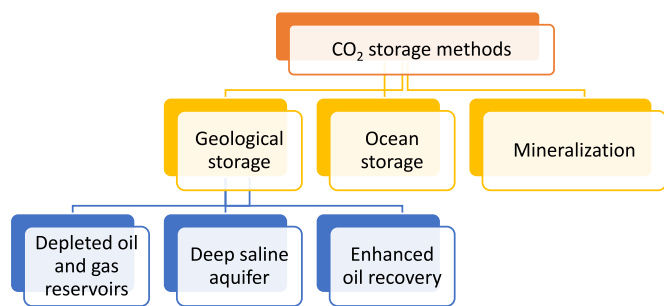


Fig. 15. A classification of storage techniques used in the CO₂ capturing.

typically involving pipelines or ships for long distances.

Generally, CO₂ is not stored and utilized in the location it is captured. Therefore, it is required to create a network for transport and distribute CO₂ for further processing after capturing. That’s why transporting carbon dioxide after it has been captured is an important step in the carbon capture, utilization, and storage process. There are several methods for transporting CO₂, and the choice depends on the distance, volume, and infrastructure available. Here are some common methods for transporting CO₂.

- Pipelines
- Ships and tankers
- Trucks and rails

Here, the pipelines are the most common and efficient means of transporting large volumes of CO₂ over long distances. Dedicated pipelines for CO₂ are similar to natural gas pipelines, but with specific design considerations to handle the properties of CO₂. The CO₂ is compressed into a dense phase and transported in liquid or supercritical form. Pipelines are often used for transporting CO₂ from industrial sources to storage sites or utilization facilities.

For transporting CO₂ across oceans or large bodies of water, ships and tankers can be used. CO₂ is typically stored and transported in liquid

form at high pressures. These vessels are specifically designed to handle and contain CO₂ safely during transportation. Ships and tankers are commonly used for long-distance transportation of CO₂ between continents or to remote storage sites. CO₂ can also be transported by trucks or railcars for shorter distances or when pipeline infrastructure is not available. This method is commonly used for transporting CO₂ from smaller industrial sources to nearby storage or utilization sites. CO₂ is compressed into a dense phase and stored in specialized containers or tanks designed for transportation. It’s important to note that the transportation of CO₂ requires careful consideration of safety measures to prevent leaks or accidents. Proper monitoring and control systems should be in place to ensure the secure transportation of CO₂. Additionally, it’s worth mentioning that the transportation of CO₂ is often part of a larger carbon capturing utilization and storage infrastructure as shown in Fig. 2, which includes capturing, transporting, and storing or utilizing the CO₂. The specific requirements and considerations for transportation will vary depending on the overall carbon capturing utilization and storage project and local regulations.

5. Capturing to utilization systems

Global awareness of CO₂ utilization employing CO₂ captured from power plants or other facilities is emerging. It provides economic benefits in addition to reducing atmospheric CO₂ emissions. The two main types of CO₂ utilization are direct CO₂ use and CO₂ conversion to valuable chemicals. To date, CO₂ has been utilized in several industries, including agro-chemistry, food, foaming, fire-extinguishers, propellant, soft drink, welding, or as a solvent in different processes such as drying-cleaning, packaging, separation, and water treatment. The alternative option to direct the use of CO₂ is to convert it into something that is more valuable overall. This option is called indirect utilization, like electrochemical transformation, and is generally not proposed the directly capture CO₂ from the atmosphere. The indirect use of CO₂ proposes to establish a kind of human-made carbon cycle in which CO₂ could be transformed into valuable molecules that will ultimately be converted back into CO₂. Namely, this CO₂ could be captured once again and converted back into valuable compounds without releasing extra CO₂ into the atmosphere. On the other hand, it is crucial to understand that

the typical CO₂ utilization options ultimately become inadequate for achieving net-zero emissions when dealing with utilization as an entire concept. The portion of oil recovery, valuable carbonation methods, and storage in construction components could possibly be increased to a few billion Gt-CO₂/year. Nevertheless, in order to manage 45 Gt-CO₂/year, it is important to establish new CO₂ utilization strategies and begin to eliminate the loop on human CO₂ consumption. In this section, the CO₂ utilization systems are briefly summarized and discussed to provide their potential applications on real scale.

The primary barrier facing renewable energy sources now is not the production of energy in the first place, it's the storage needed to keep it available until it is required. Producing fuel from the captured CO₂ and storing the energy until it is required is a fascinating approach that addresses this problem (Verdegaal et al., 2015). As contrast to using pure CO₂ from underground, this has the extra benefit of producing a carbon-neutral fuel because the CO₂ that will be produced during burning comes from the atmosphere or fuel that has previously been consumed. With the right treatment, this may be utilized to generate an anthropic carbon cycle, in which fuels are produced exclusively from atmospheric CO₂, completely eliminating the emission of extra CO₂ emissions into the atmosphere. For instance, conversion of CO₂ into methanol, methane, and polyoxymethylene dimethyl ethers have been considered (Jeong-Potter et al., 2022). The reduction is another method used for converting CO₂ into valuable chemicals. This can be accomplished through thermochemical methods, providing adequate power while a reducing agent exists, or simply through an electrochemical method that uses electricity directly. The critical drawback of the thermochemical processes is that they demand relatively high temperatures and pressures, and they are also more challenging to manage using catalysts since the catalysts require to be stable under essential conditions. On the other hand, in order to attain significant selectivity, effectiveness, and productivity, electrochemical processes need catalysts. The electrochemical method is appealing due to its minimized temperature and pressure requirements, particularly when utilized to selectively produce complex compounds.

Moreover, researchers have studied the impact of increasing CO₂ concentration in agricultural greenhouses on the yields of vegetative plants (Oreggioni et al., 2019; Saha et al., 2015). For instance, Clime-works constructed a DAC plant in Switzerland to supply captured CO₂ to the surrounding greenhouse for cultivation of vegetables (Gutknecht et al., 2018). In their study, the waste incineration facility supplied low-grade heat for regeneration of captured CO₂. Researches have also revealed that the necessary CO₂ concentration for cultivation of algae and plants varies between 1%-3% and 0.1–0.2%, respectively, regardless of the fact that conventional agricultural greenhouse fertilization uses concentrated CO₂ collected from flue gas (Hou et al., 2017). Bao et al. (2018) suggested a concept of urban greenhouse farming and this project has been carried out in an attempt to improve food production, protect farmland, decrease CO₂ concentration in the atmosphere through the application of the DAC technique, and utilize captured CO₂ in agricultural greenhouses (Bao et al., 2018). In addition, several organisms in nature, including plants, bacteria, and microalgae, have the capability of processing CO₂ by photosynthetic mechanisms. Utilizing biological carbon is an indirect approach to storing carbon that depends on the conversion of CO₂ into organic carbon during photosynthesis by organisms using sunlight for energy, and these organism can be used for the production of biofuels (Li et al., 2023). It is an environmentally friendly for CO₂ conversion presenting the production of biofuels and valuable end-products (Cheah et al., 2016). In summary, the DAC CO₂ can be further utilized for the cultivation of plants, bacteria, and microalgae.

6. Comparative assessment of carbon-capturing methods

In this section, the maturity levels, CO₂ adsorption capacity and yields of the commercialized CO₂ capturing processes, energy

requirements, and cost of the different CO₂ capturing methods are summarized and discussed. Moreover, the environmental impact assessment of methods are performed considering their global warming potential (GWP), acidification potential (AP), and ozone depletion (OD) values based on the literature studies on the life cycle assessment.

6.1. Maturity levels

In this section, technology readiness levels (TRL) of liquid solvent, solid sorbent, membrane, solid-looping, and inherent CO₂ capture methods from a gas stream with their utilization fields are evaluated. The term “TRL” refers to the level of technological maturity within an increasing commercial application. Fundamentally, higher TRL values are primarily concerned with commercial feasibility than lower levels, which are often more focused on the potential that technology might be feasible. In Table 6, the TRLs of different methods considering their sub-sections are summarized for the 2020 year according to a report published by the International Energy Agency (IEA) (IEA, 2012). In 2014, IEA commissioned a study on the assessment of emerging CO₂ capture technologies and their potential to reduce costs to assess the technical status, and potential for cost reduction, of a series of emerging CO₂ capture technologies. Furthermore, the updated report on the CO₂ capture benchmark technology provides an update on the current status of these technologies by measuring their progress in terms of TRL and performing the techno-economic assessment of selected CO₂ capture technologies for fossil-fired power plants (IEA, 2019a). Moreover, the maturity level of the processes is illustrated using a heat map to understand their current technical level and which area needs more focus to achieve commercialization (Fig. 16). Compared to the TRL of CO₂ capturing methods, the liquid-based solvents are presented relatively highest TRL compared to other methods. Namely, the most used method for gas separation is liquid-based solvent absorption, which uses either chemical or physical solvents. Among the liquid-based solvents, the highest TRL of 9 is obtained for the Benfield process, conventional amine solvents, and commercial physical solvents, these are followed by sterically hindered amines with TRL of 8 (Fig. 16a). The Selexol™ and Rectisol® systems (Mohammed et al., 2014), which are based on methanol and glycol, respectively, are the two most commonly utilized physical solvent-based solutions. On the other hand, the lowest TRL of 2 is observed for both ionic liquids and encapsulated solvent-based capturing methods since these methods only performed on lab-scale. In addition, the chilled ammonia and water-lean solvent processes revealed as the pilot scale or/and large-to-commercial scale applications with their moderate TRL (6). For solid-based sorbent capturing processes, pressure-vacuum swing adsorption CO₂ capturing process is commercialized with TRL of 9 and currently utilized in Air Products Port Arthur SMR CCS (Fig. 16b). However, most of the solid-based adsorbent capturing methods, such as, enzyme-catalyzed adsorption (TRL: 6), solid sorbent-improved water gas shift (TRL: 5), and temperature swing adsorption (TRL: 6), are present as pilot-scale, large-scale, or/and demonstration phases. In addition, the recently performed carbon capturing process of electrochemically forced adsorption showed the lowest TRL of 1 due to its performance being just investigated on a lab scale. Another capture method is membrane-based processes, and among these processes, gas separation membranes (TRL:9) have been actively utilized in commercial-scale pre-salt oil fields (Fig. 16c). The lowest TRL levels of 2 and 4 are obtained for the polymeric membrane-solvent hybrid and room temperature-ionic liquid membrane methods.

In the solid-looping process, chemical and calcium looping methods include using metal oxides as reusable solid sorbents to transfer CO₂ from one system to another. For instance, the Carbon Engineering company have been performed feasibility studies for industrial scale using calcium looping and hence, these processes have a TRL of 7. Similarly, the CO₂ capturing pilot tests (TRL: 6) using chemical looping method has been performed by Alstom company. Recently, the inherent

Table 6

Technology readiness level (TRL) assessment, technology owners (marketers), and utilization fields of numerous CO₂ capture methods (compiled from IEA, 2012, 2019a).

Capture method	TRL 2020	Utilization field	Marketer		
Liquid solvent	Amino acid-based solvent	6	Lab-scale test	Siemens	
	Benfield process	9	Fertilizer plants	Honeywell UOP	
	Chilled ammonia	6	Pilot tests	GE	
	Conventional amine solvents	9	Fertilizer, soda ash, natural gas processing	Aker Solutions, Fluor, Dow, KerrMcGee, Shell, etc	
	Encapsulated solvents	2–3	Lab-scale tests	R&D	
	Phase change solvents	4–6	DMX™ Demonstration	IFPEN/Axens	
	Physical solvent	9	Natural gas processing and coal gasification plants	Air Liquide, Linde, and UOP	
	Sterically hindered amine	8	Demonstration to commercial plants	CSIRO, Toshiba, MHI, etc	
	Ionic liquids	4	Lab-scale tests	R&D	
	Water-lean solvent	5	Pilot-scale test and commercial scale	CHN Energy, Ion Clean Energy, and RTI	
	Solid adsorbents	Electrochemically forced adsorption	1	Lab-scale tests	R&D
		Enzyme-catalyzed adsorption	6	Pilot demonstrations	CO ₂ solutions
		Pressure-vacuum swing adsorption	9	Air Products Port Arthur SMR CCS	Air Liquide, Air Products, UOP
		Solid sorbent-improved water gas shift	5	Pilot-scale tests	ECN
Temperature swing adsorption		6	Large pilot tests	Svante	
Membrane	Electrochemical membrane-MFCs hybrid	7	Large pilot tests	FuelCell Energy	
	Gas separation membrane	9	Pre-salt oil field	Air Liquide and UOP	
	Polymeric membranes	7	Front-end engineering design for large pilot tests	MTR	
	Polymeric membrane- cryogenic separation hybrid	6	Pilot-scale tests	Air Liquide, Linde Engineering, and MTR	
Solid-looping	Polymeric membrane-solvent hybrid	4	Conceptual researches	MTR-University of Texas	
	Room temperature-ionic liquid membrane	2	Lab-scale tests	R&D	
	Calcium looping	7	Feasibility studies for industrial scale	Carbon Engineering	
Inherent capture	Chemical-looping combustion	4–5	Pilot tests	Alstom	
	Allam-fetvedt cycle	7	Demonstration of commercial plants	8 Rivers Capital	
	Calix-advanced calcine	6	Large pilot tests	Calix	

carbon capturing methods like Allam-Fetvedt cycle and calix-advanced calcine method have gained significant attention and technological improvement with TRLs of 7 and 6, respectively. These technologies provide inherent CO₂ capture possible, with no extra labor or energy needed to separate CO₂. As they include CO₂ capture into their core process architecture, they show a lot of potential for a step change decrease in capture costs, but they cannot be adapted directly to current facilities.

6.2. Energy consumption and cost

The energy consumption of carbon capturing techniques can vary widely depending on the specific technology employed, the scale of the project, and the conditions under which it operates. Generally, carbon capturing techniques require energy for the capture process itself, as well as for compression, transportation, and storage of the captured CO₂. Fig. 17 provides an overview of the energy consumption for some common carbon capturing techniques. Direct air capture requires the highest energy input as it captures CO₂ directly from the atmospheric air which has lower CO₂ concentration. Since the concentration of CO₂ in the air is relatively low (about 400 ppm), the process requires a considerable amount of energy to capture and concentrate the CO₂. The energy consumption can range from about 1.5 to 3.0 MJ/kg CO₂ or even higher.

The energy requirement of CO₂ capturing during pre-combustion, post-combustion and oxy combustion are much lower than direct air capturing. Post-combustion capture involves separating CO₂ from flue gases emitted by power plants or industrial facilities after the combustion process. The process typically requires the use of solvents or solid materials to absorb the CO₂, which can be energy-intensive. The energy consumption of post-combustion capture is estimated to be 0.317 kW h/kg CO₂ for pulverized coal plants using amines and 0.414 kW h/kg CO₂ for natural gas combined cycle plants (David and Herzog, 2000). Energy consumption of post-combustion capture using monoethanolamine is

calculated to be 0.1 MJ/kg CO₂ for coal plants and 0.15 MJ/kg CO₂ for natural gas plants (Rubin et al., 2015). Rubin et al. (2015) have also reviewed that energy consumption of post-combustion capture using various solvents and reports a range of 0.1–0.3 MJ/kg CO₂. Pre-combustion capture involves converting fossil fuels into a hydrogen-rich gas and CO₂ before combustion. The CO₂ is then separated from the gas stream. While the pre-combustion process itself requires some energy, the overall energy consumption is generally lower compared to post-combustion capture. (Zheng et al., 2023) have analyzed the energy consumption of pre-combustion capture using physical absorption at 0.15 MJ/kg CO₂ for coal plants. (Chiesa et al., 2005) evaluated the energy consumption of pre-combustion capture using pressure swing adsorption at 0.18 MJ/kg CO₂ for coal plants. (Bolland and Undrum, 2003) have proposed a novel method for pre-combustion capture using chemical looping combustion at 0.1 MJ/kg CO₂ for natural gas plants. Oxy-fuel combustion involves burning fuel in pure oxygen, resulting in a flue gas primarily composed of CO₂ and water vapor, which simplifies CO₂ separation. However, the process of separating oxygen from air can be energy-intensive, impacting overall energy consumption. (Buhre et al., 2005) have reviewed the oxy-fuel combustion technology and estimated the energy consumption of oxy-combustion carbon capture at 0.3 MJ/kg CO₂ for coal plants. (Duan et al., 2012) have compared the energy consumption of post-combustion and oxy-combustion carbon capture for coal plants and reported that oxy-combustion has a lower energy penalty than post-combustion (0.24 MJ/kg CO₂ vs. 0.4 MJ/kg CO₂). Lastly, (Chen and Yang, 2021) have analyzed the energy consumption of pulverized coal-fired oxy-combustion power generation systems using different oxygen purity levels (95%, 99%, and 99.5%) and different flue gas recycle ratios (60%, 70%, and 80%). The results show that the energy consumption of oxy-combustion carbon capture decreases with increasing oxygen purity and decreasing flue gas recycle ratio.

Although it is really essential to implement carbon capturing techniques to reach the net-zero target in local and global scales, the cost of

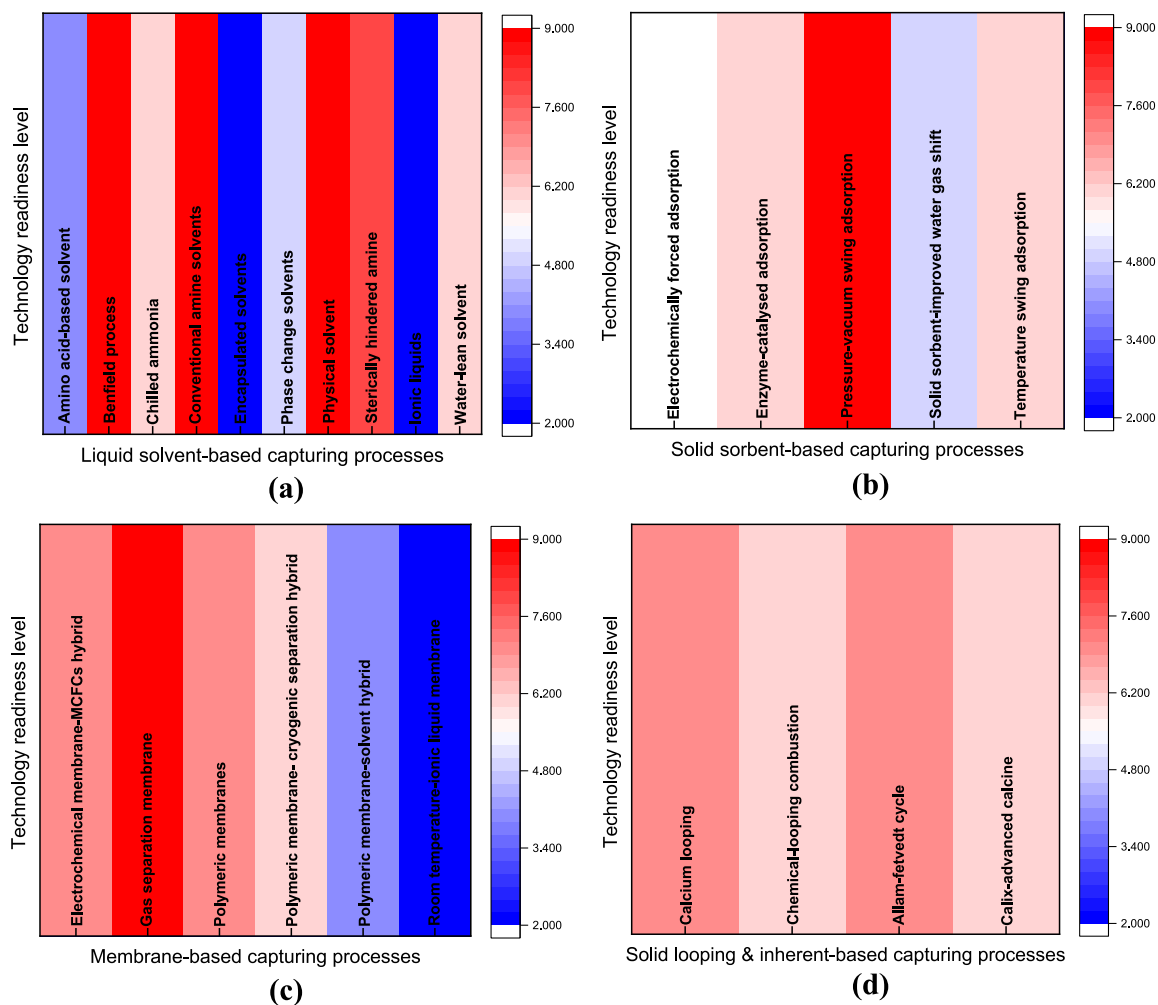


Fig. 16. Technology readiness levels (TRLs) of different carbon capturing method: (a) Liquid solvent, (b) solid sorbent, (c) Membrane, and (d) solid looping and inherent carbon capture.

CO₂ capturing is one of the main obstacles to its widespread use. It really varies from sector to sector and application to application. Fig. 18 demonstrates the carbon capturing cost for different applications. It is clear Fig. 18 that direct air capturing requires higher cost comparing to the other carbon capturing sources due to the lower CO₂ content of air. The cost of direct air capturing methods varies from \$134.3 and \$341.7 per ton depending on the technique to be used. Other carbon capturing methods require much lower cost comparing to the direct air capture. Iron/steel industry and power generation sectors have similar trend. While the cost range is between \$50 and \$100 for power generation, it ranges from \$40.2 and \$100.2 per ton, respectively. The carbon capturing in the cement production can be achieved with the cost of \$60.4 to \$120.4 per ton. The carbon capturing during the steam methane reforming for hydrogen production can cost between \$50.2 and \$80.4 per ton. Carbon capturing in other industries, which are natural gas processing, coal to chemicals and synthetic gases/fuel, ammonia production, and bioethanol production can cost between about \$15 to \$35 per ton.

Consequently, it is important to note that the cost of carbon capture varies greatly according to CO₂ source, ranging from \$15–25 per ton CO₂ for processes that produce “pure” or highly concentrated CO₂ streams (for example, ethanol production or natural gas processing) to \$40–120 per ton CO₂ for processes with “dilute” gases, such as cement production and power generation. Although it is currently the most expensive method for removing carbon dioxide, it could nonetheless play a unique role in the future. The wide range of costs is further

attributed to the fact that some CO₂ capture technologies are commercially available now, while others are still under development.

6.3. Environmental impacts

In this section, CO₂-capturing processes performed using pre-combustion, post-combustion, and oxy-combustion methods considering their environmental impacts are evaluated and discussed in more detail. Overall, evaluated parameters are normalized with the feature scaling normalization method to compare each CO₂-capturing method to provide their sustainability levels. The environmental impact assessment of selected parameters is based on the life cycle assessment (LCA) received from various studies, and all these corresponding references are listed in Table 7 and illustrated in Fig. 19. In the post-combustion method, amines and solvents are used for CO₂ capture, while the physical absorption and pressure swing adsorption processes are performed in the pre-combustion method. On the other hand, there is no specific method indicated for oxy-fuel combustion method in the reviewed studies.

The CO₂-capturing processes are compared regarding AP, GWP, ODP, and EP. The AP (kg SO₂ eq.) and GWP (kg CO₂ eq.) measure the amount of polluting acid deposited into water resources, soil, and organisms and CO₂ released into the atmosphere, respectively. ODP (kg R11 eq.) and EP (kg PO₄³⁻ eq.) present the amount of ozone destroyed by emission and eutrophication related to phosphate contamination in environment, respectively. The investigated environmental impact

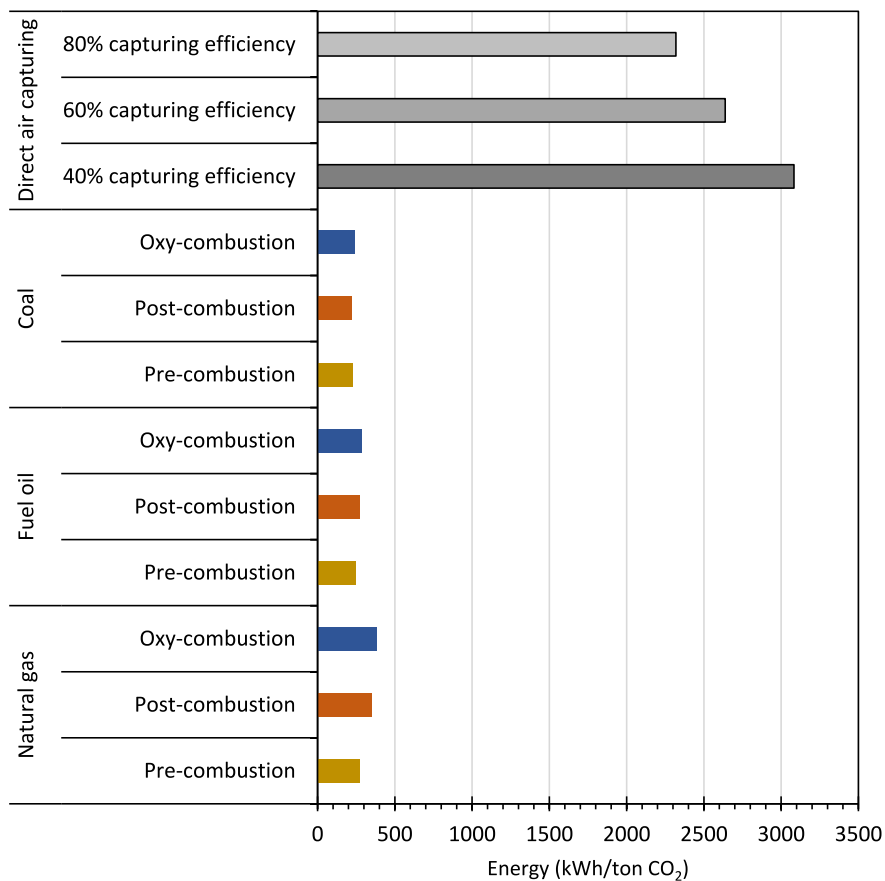


Fig. 17. Energy consumption comparison for pre-combustion, post-combustion, oxy combustion and direct air capturing techniques (data compiled from Kikkawa et al. (2022); Vasudevan et al. (2016)).

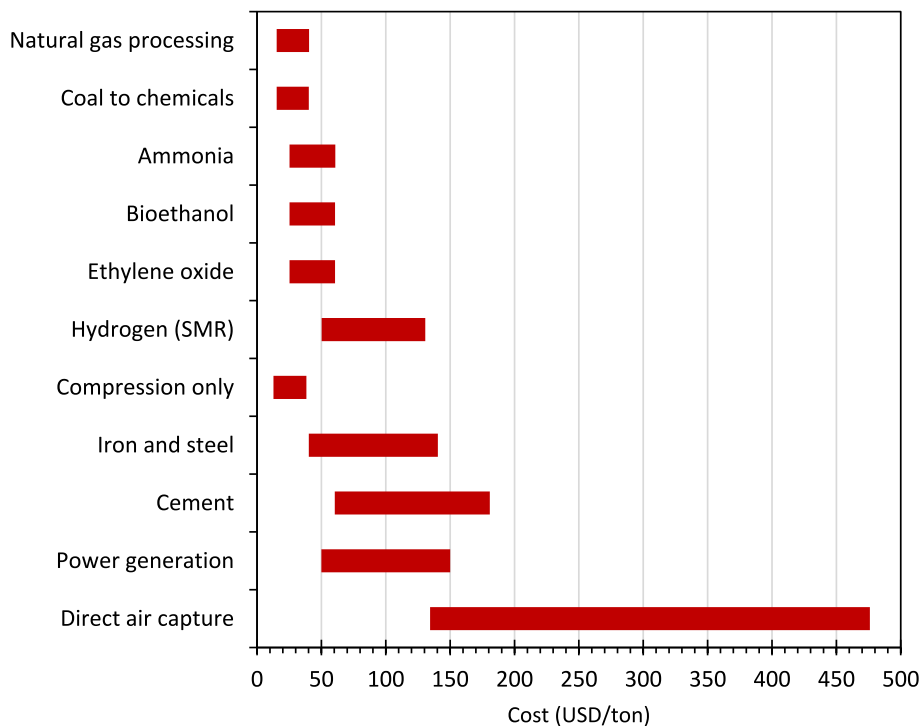


Fig. 18. A levelized cost comparison of CO₂ capture by sector and direct air capture along with other processes and methods (data compiled from IEA (2019b)).

Table 7
The average concentrations of some environmental impact parameters.

Capture method	Environmental impact parameter				Ref.
	GWP (kg-CO ₂ eq./MWh)	AP (kg-SO ₂ eq./MWh)	ODP (kg-R11 eq./MWh)	EP (kg-PO ₄ ³⁻ eq./MWh)	
Post-combustion	219.5	1.23	0.11	0.25	(Cuéllar-Franca and Azapagic, 2015; Hertwich et al., 2008; Hosseini et al., 2023; Korre et al., 2010; Petrescu et al., 2017; Troy et al., 2016; Yang et al., 2019; Zang et al., 2020)
Pre-combustion	236.3	0.79	0.0003	0.18	
Oxy-combustion	166.6	0.74	0.06	0.35	(Cuéllar-Franca and Azapagic, 2015; Korre et al., 2019; Nie et al., 2011; Troy et al., 2016)

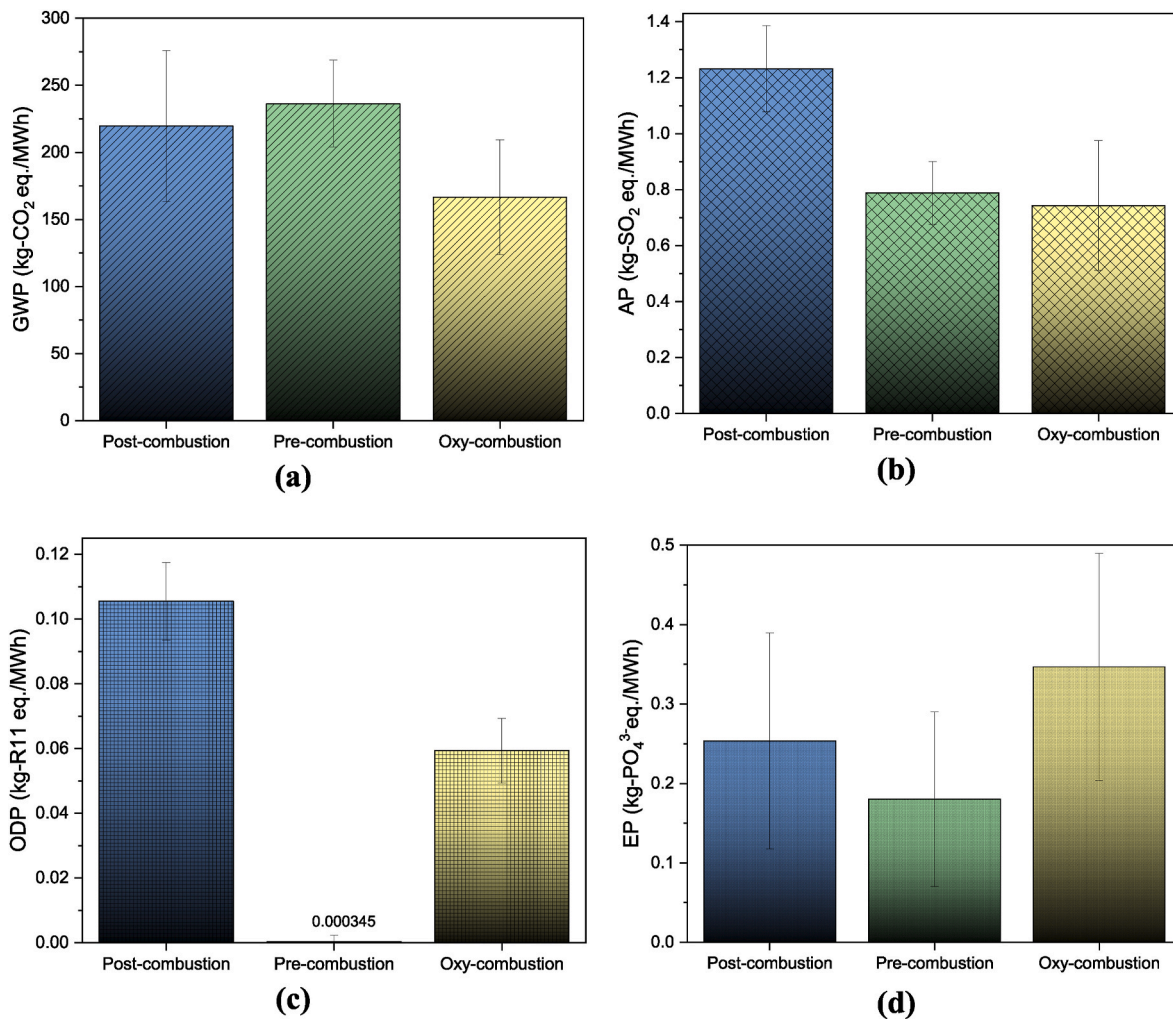


Fig. 19. The average values of some environmental impact parameters for different carbon capturing methods: (a) GWP, (b) AP, (c) ODP, and (d) EP.

categories are selected according to the Operational Guide to the ISO Standards to define the LCA approaches (Guinée, 2002). Moreover, the investigated environmental impact variables are obtained from the LCA studies performed elsewhere. The average values of the selected environmental impact parameters are considered for assessment. These results also revealed that there is limited research in the literature extensively investigating the environmental impacts of CO₂-capturing processes, and there is a serious gap in this regard.

Moreover, the selected environmental impact parameters are normalized with the feature scaling normalization method to compare each CO₂-capturing processes using different methods using the following equation:

$$Rank_{method,i} = ((Rank_{method,i} - Rank_{min}) / (Rank_{max} - Rank_{min})) \times 10 \quad (1)$$

Here, the ranking ranges from 0 to 10, with 0 presenting poor performance and 10 representing the ideal case (zero-environmental impacts). Lower values of selected environmental impact parameters are given higher rankings. In evaluated parameters, “0” is assigned to the highest environmental contaminations, while “10” defines the lowest contamination. The results of their environmental impact comparisons of CO₂-capturing methods are presented in Fig. 20.

Regarding the GWP (10/10) value, the oxy-fuel process presented the close-to-ideal conditions with lowest environmental contaminations related to air emissions. On the other hand, the GWP values are 0/10 for

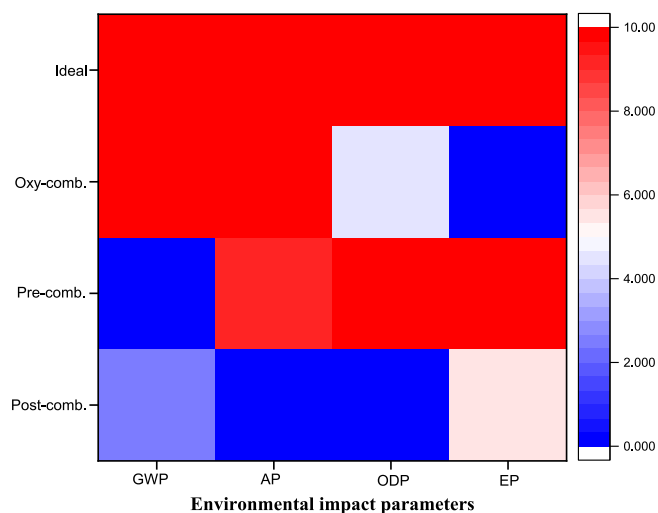


Fig. 20. A normalized ranking comparison of some environmental impact parameters.

pre-combustion and 2.4/10 for post-combustion processes, which have a significant potential to cause serious environmental impacts due to CO₂ emissions. Moreover, the normalized ranking results proved that the oxy-combustion method presented ideal result (10/10) for AP, which is one of the most important parameters in environmental sustainability assessment. Similarly, the pre-combustion method achieves relatively similar performance in the ideal case considering AP (9.07/10). Lowest AP value of 0/10 is obtained for the post-combustion method most probably due to the utilization of sulfur containing agents during the process. In addition, the pre-combustion method presented the close-to-ideal case conditions considering ODP (10/10) and EP (10/10) values and these results indicated that pre-combustion method provided lowest environmental pollution related to phosphate and other air

contaminants. On the other hand, the ODP and EP values of the post and oxy-combustion processes indicated the highest environmental contamination potential of these methods.

7. Future directions

The future role of CO₂-capturing methods depends upon how effectively sustainable carbon capture production technologies will reach commercial maturity with environmentally friendly approaches and advance developments. The path to sustainable CO₂ capture implies that there is a need to link bioenergy and renewable sources to the end-users in the market via sustainable CO₂-capturing systems (Fig. 21). Moreover, the detailed future recommendations are reported as follows.

- Global warming and climate change have been very critical for humanity, so continuing research, innovation and technology development are badly needed for improving energy efficiency, resource utilization and cost-effectiveness of carbon capturing technologies. The deployment of these technologies at scale can be accelerated by policy support, financial incentives, and international cooperation. In order to transition towards a more sustainable and climate-resilient future, we need to integrate carbon capture and storage into a comprehensive climate strategy alongside renewable energy deployment, energy efficiency improvements, and sustainable practices. It is required to create a business model combining those.
- The successful deployment of carbon-capturing technologies will require a multi-faceted approach involving collaboration between governments, industries, researchers, and the general public. Using these technologies to mitigate climate change and transition to cleaner energy sources simultaneously will help us achieve our ambitious goals of safeguarding our planet for future generations while mitigating climate change. In conjunction with other climate mitigation measures, carbon capture can be an essential tool in the fight against global warming, fostering a sustainable world for present and future generations.

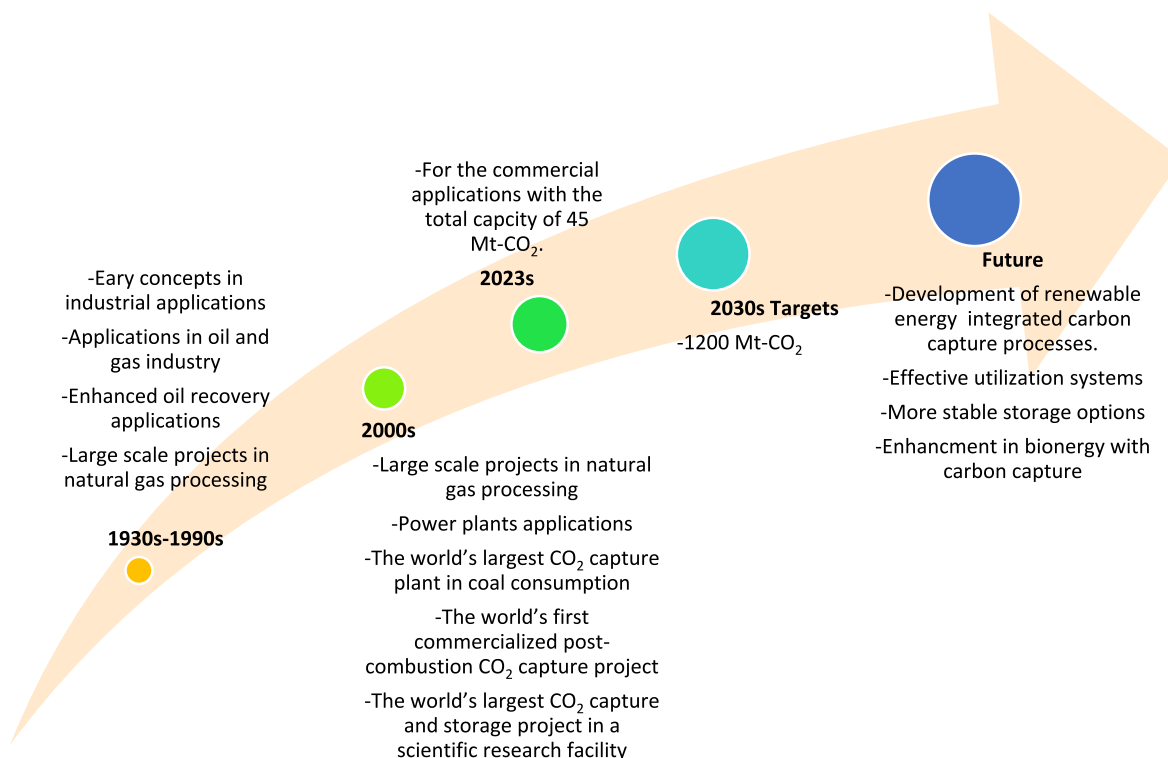


Fig. 21. Some pathways identified to reach sustainable and cost-effective CO₂-capturing approaches.

- Indirect air capturing methods are limited research and therefore there is a critical need for their improvement in large-scale industries to improve the performance of different processes. Namely, it is possible to use this geologically stored and geothermally heated CO₂ to generate base-load electricity with a twofold increase in electricity production over utilizing groundwater to extract geothermal heat.
- This study further demonstrated that other variables of power plant design, economics, and operation, and not only the price of the CO₂ capture unit, have a significant impact on the cost of CO₂ capture. Long-term R&D should consequently concentrate on future increases in power plant efficiency, which will typically also tend to decrease the unit cost of CO₂ capture.
- A further investigation that includes all aspects and integrates hybrid technologies comprised of ionic liquids, amines, additives, and membranes is essential to improve CO₂ capture capacity of current processes.
- Cost associated with all parts of the CCS should be decreased with advance research and demonstration. For application of direct and indirect carbon capturing methods at commercial-scale, essential research is needed in various areas, particularly in capture processes, improved performance of liquid solvents, enhanced membrane units, and development of effective chemical looping cycles.

8. Conclusions

Carbon capturing technologies hold immense promise in the global efforts to combat climate change and reduce greenhouse gas emissions. These innovative solutions aim to capture carbon dioxide from various sources, including power plants, industrial facilities, and even directly from the ambient air. While the development of carbon capture and storage technologies has made significant strides, it remains an evolving field with ongoing research and development. The success of carbon capture largely hinges on striking a balance between effective capture rates, energy efficiency, environmental sustainability, and economic viability. Therefore, this paper aimed to present a realistic evaluation of the prospects for enhanced, more affordable CO₂ capture systems for use in power plants and other industrial sites in order to reduce emissions of greenhouse gases associated to climate change. Toward that end, this review paper considered the direct approaches to CO₂ capture, namely, post-combustion method for CO₂ capture using liquid solvents; pre-combustion method, particularly from the coal-fired power plants with chemical solvents; oxy-combustion method, in which pure oxygen is utilized for combustion to form a flue gas with high CO₂ content flexible to capture without a further chemical agents or processes; and direct air capture from the atmosphere using liquid solvents, solid adsorbents, and membranes. In addition, the potential of indirect carbon capturing processes, such as reforestation, enhanced weathering, bio-energy with carbon capture, and agricultural practices are briefly evaluated.

- Post-combustion, pre-combustion, and oxy-fuel combustion captures are among the conventional techniques used to capture CO₂ emissions from concentrated sources. These methods have demonstrated varying degrees of success, with pre-combustion capture showing relatively higher energy efficiency compared to post-combustion and oxy-fuel methods. On the other hand, direct air capture offers the potential to capture CO₂ from the atmosphere but currently faces challenges related to its relatively higher energy consumption.
- The energy consumption for post-combustion carbon capturing with amines can range from about 0.1 to 0.3 MJ per kilogram of CO₂ captured (MJ/kg CO₂). It is 0.1–0.25 MJ/kg CO₂ for pre-combustion with physical absorption, pressure swing adsorption, and chemical looping, and 0.05–0.2 MJ/kg CO₂ for oxy-combustion. Direct air capturing requires the highest energy consumption (1.5–3.0 MJ/kg CO₂ or even higher).

- Carbon capturing costs depends on the processes and sectors to be applied. Parallel to energy consumption, direct air capturing has the highest cost, varies from \$134.3 and \$341.7 per ton CO₂. The CO₂ capturing cost per ton ranges between \$50 and \$100 for power generation applications. The carbon capturing in the cement production can be achieved with the cost of \$60.4 to \$120.4 per ton.
- Among the carbon capturing methods, the post-combustion and pre-combustion methods are widely utilized and commercial-scale in natural gas processing facilities for gas stream purification, while the oxy-combustion method is not still commercial and is yet under improvement stage.
- The CO₂ capturing potential of enhanced weathering indirect capture process is found as inadequate due to its requirement of long operational times. On the other hand, results revealed that the modification of rocks or solids with chemical process can be decreased the required time for effective and fast CO₂ capture.
- The amines have significant CO₂ solubility and relatively low-cost. The potential for their application exists nevertheless, and a decrease in cost is anticipated with further research and their commercialization due to the development of a significant number of new ionic liquids.
- The environmental impact results showed that the highest GWP (219.53 kg-CO₂ eq./MWh), AP (1.2319 kg-SO₂ eq./MWh), and ODP (0.1055 kg-R11 eq./MWh) are observed for post-combustion process with amines and solvents related to relatively high energy and chemical requirement of these processes.
- The oxy-combustion method presented the lowest environmental contamination considering its low GWP of 166.56 kg-CO₂ eq./MWh and AP of 0.7431 kg-SO₂ eq./MWh since this process does not need chemical agents.
- Regarding the GWP (10/10) value, the oxy-fuel process presented close-to-ideal conditions with the lowest environmental contaminations related to air emissions based on the normalized ranking results. However, the GWP values are 0/10 for pre-combustion (physical absorption and pressure swing adsorption processes) and 2.4/10 for post-combustion processes, which have a significant potential to cause serious environmental impacts due to CO₂ emissions.
- Among the liquid-based solvents, the highest TRL of 9 is obtained for the benfield process, conventional amine solvents, and commercial physical solvents, these are followed by sterically hindered amines with TRL of 8.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Abbreviations

1A2P	1-amino-2-propanol
2A1B	2-amino-1-butanol
AEAPDMS	N-(2-aminoethyl)-3-aminopropylmethyltrimethoxysilane
AMP	2-amino-2-methyl-1-propanol
AMPD	2-amino-2-methyl-1-3-propandiol
AP	Acidification potential
bibta	1, bibta2- = 5,5'-bibenzotriazolate
BUMEA	2-(butylamino)-ethanol
CCS	Carbon capture and sequestration
CCUS	Carbon capture, utilization, and storage
CH ₄	Methane
CO	Carbon monoxide

CO ₂	Carbon dioxide
DAC	Direct air capture
DCC	Direct carbon capture
DEA	Diethanolamine
DEA	Tertiary amines diethanolamine
DGA	2-(2-aminoethoxy)-ethanol
DIPA	bis(2-hydroxypropyl)-amine
DMMEA	2-(dimethylamino)ethanol
dobpdc4	4,4'-dioxido-3,3'-biphenyldicarboxylate
EMEA	2-(ethylamino)-ethanol
EP	Eutrophication potential
GWP	Global warming potential
H ₂	Hydrogen
HTS	High-temperature shift
LCA	Life cycle assessment
LTS	Low-temperature shift
MDEA	Methyldiethanolamine
MDEA	N-methyl-diethanolamine
MEA	Monoethanolamine
Mg/DOBDC	Magnesium dioxybenzenedicarboxylate
MMEA	2-(methylamino)-ethanol
mmen	N,N'-dimethylethylenediamine
MOF	Metal organic framework
MXDA	m-xylylenediamine
MXene	Transition metal carbides, nitrides, and carbonitrides
N ₂	Nitrogen
NETs	Negative emissions technologies
NFC	Nanofibrillated cellulose
ODP	Ozone depletion potential
PCC	Post-combustion capture
PSA	Pressure swing adsorption
SMR	Steam methane reforming
TBMEA	2-(tertbutylamino)-ethanol
TIFSIX-3-Ni	[Ni(pyrazine) ₂ (TiF ₆) _n]
TREN	Tris (2-amino ethyl)
TRIZMA	2-amino-2-(hydroxymethyl)-1,3-propanediol
TRL	Technology readiness levels
WGS	Water-gas-shift

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