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REVIEW ARTICLE

Recent advances, challenges, and perspectives on carbon capture

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HIGHLIGHTS

- Recent advances in promising CCUS technologies are assessed.
- Research status and trends in CCUS are visually analyzed.
- Carbon capture remains a hotspot of CCUS research.
- State-of-the-art capture technologies is summarized.
- Perspective research of carbon capture is proposed

GRAPHIC ABSTRACT

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ABSTRACT

Carbon capture, utilization and storage (CCUS) technologies play an essential role in achieving Net Zero Emissions targets. Considering the lack of timely reviews on the recent advancements in promising CCUS technologies, it is crucial to provide a prompt review of the CCUS advances to understand the current research gaps pertained to its industrial application. To that end, this review first summarized the developmental history of CCUS technologies and the current large-scale demonstrations. Then, based on a visually bibliometric analysis, the carbon capture remains a hotspot in the CCUS development. Noting that the materials applied in the carbon capture process determines its performance. As a result, the state-of-the-art carbon capture materials and emerging capture technologies were comprehensively summarized and discussed. Gaps between state-of-art carbon capture process and its ideal counterpart are analyzed, and insights into the research needs such as material design, process optimization, environmental impact, and technical and economic assessments are provided.

1 Introduction

Fossil fuels account for 80% of the energy needs of the world (IEA, 2021). In 2021, the global carbon dioxide

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(CO_2) emissions amounted to 3.63 billion tons, nearly 89% of which is contributed by the fossil fuels utilization (Le Quéré et al., 2021; IEA, 2022). Excessive CO_2 emissions intensify global warming since the industrial revolution, resulting in notable rise in the frequency and severity of climate-related disasters, including wildfires and intense tropical cyclones (Yu et al., 2022; Shan et al., 2023; Zheng et al., 2023). The World Meteorological Organization (WMO) proclaimed during COP28 that the year 2023 established a new record as the hottest year on record (WMO, 2023). Reducing CO_2 emissions to mitigate climate change becomes a global consensus (Tong et al., 2019).

The Intergovernmental Panel on Climate Change (IPCC) have recognized carbon capture, utilization and storage (CCUS) as a crucial technology to mitigate the global warming (IPCC, 2001, 2014, 2018, 2023). In the context of achieving Net Zero CO_2 Emissions, besides the intensive deployment of renewable energy, CCUS is still projected to contribute a cumulative reduction of 15% (IPCC, 2018). Nevertheless, the CCUS technology encounters challenges such as technological innovation, financial resources, and regulatory frameworks. Considering the lack of timely reviews on the recent advancements in promising CCUS technologies, it is crucial to provide an appropriate and prompt summary of these advanced technologies and gain a thorough understanding.

This review focuses on the recent advancements, obstacles, and forthcoming prospects in CCUS technologies. Herein, this review summarizes the CCUS development history and its current large-scale demonstrations. A visually bibliometric analysis is employed to identify the current research hotspots pertained to the CCUS. As a result, the state-of-the-art carbon capture technologies and materials was systematic summarized and discussed. The review further assesses challenges associated with material design, process optimization, environmental impact, and technical and economic assessments to advance the CCUS development and fulfill its industrial application.

2 CCUS overview

2.1 CCUS development history

CCUS includes the process of isolating CO_2 from point emission sources or the atmosphere to achieve enduring reductions in emissions (Müller et al., 2020). CCUS can be categorized into four key stages based on the technical process: CO_2 capture, CO_2 transportation, CO_2 utilization, and CO_2 storage (Fig. 1). The history of CCUS development dates back to the 1970s, when CCUS developed, and it has been 52 years since the first large-scale carbon capture project began operation in 1972 at the Kelly Snyder oil field in West Texas, USA (Orujov et al., 2023). From the 1970s to the early 1990s, CCUS technology primarily found application in oil recovery and the purification of natural gas. The practice of injecting CO_2 into oil fields during the oil extraction process was employed to enhance oil recovery (EOR) (Ku et al., 2023). An example of such an endeavor is the Enid project in Oklahoma, initiated by the USA in 1982, where a fertilizer plant produced CO_2 to fill the oil field. This project had a CO_2 capture capacity of 700000 tons per annum (Milad et al., 2024). In 1996, CCUS technology was used in the Norway Sleipner gas field project to separate CO_2 from the produced natural gas and store it underground, storing nearly one million tons of

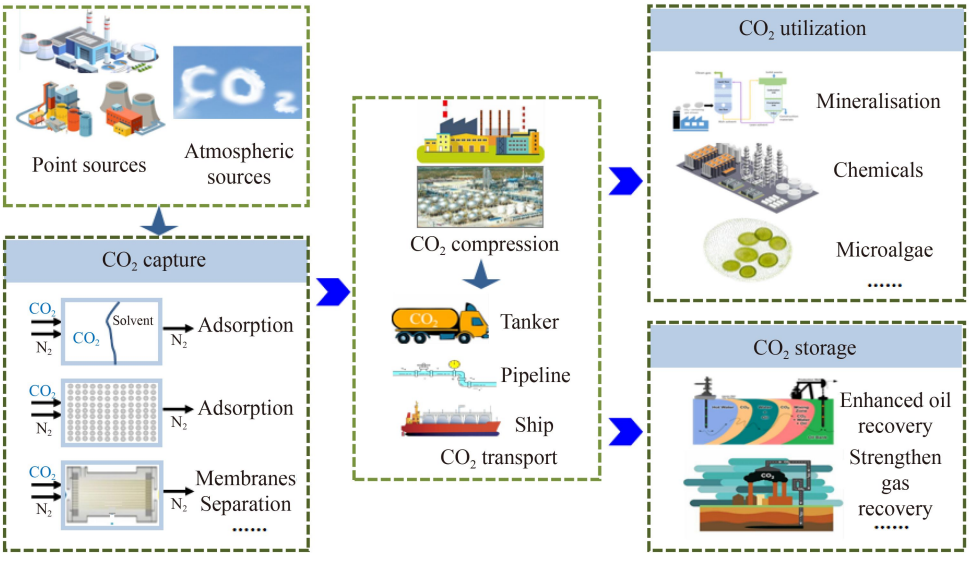

Fig. 1 Schematic diagram of the CCUS technique.

CO_2 per year.

Initially, CCUS technologies were primarily employed for the purification of natural gas and various other products. However, as concerns regarding climate change and greenhouse gas emissions have escalated, CCUS technologies have assumed an ever more pivotal role in mitigating carbon emissions (Shen et al., 2020). In the early 2000s, several large-scale projects, such as the carbon capture and storage (CCS) project of the Great Plains Coal Gasification Treatment Plant in the USA, began to apply CCUS to the coal gasification industry. Subsequently, several other CCUS demonstration projects have come to fruition, including the Weyburn-Midale project in Canada and the Conoco Phillips project in the USA. These initiatives are primarily focused on the capture and sequestration of CO_2 into underground reservoirs (Zhao et al., 2021). Moreover, CCUS technology is being applied in various industrial sectors. High-carbon emitting industries such as power and steel are actively exploring the capture, utilization, or storage of CO_2 to diminish their impact on climate change. In 2014, Canada's SaskPower's Boundary Dam Power project achieved the distinction of being the world's first successful CO_2 capture project for a power plant. This facility averaged 2674 t/d and reached a peak of 2852 t/d. Sweden's Hybyrit project endeavors to replace coke, commonly used in traditional ironmaking, with hydrogen generated from renewable electricity, thereby achieving emissions neutrality in the ironmaking process.

While some aspects of CCUS, such as CO_2 capture, have reached a relatively mature stage ready for commercial application, the technology portfolio and overall operation of the entire process are still in their early developmental stages. This is primarily due to the high costs associated with CCUS technology, which can impede its widespread application and affect its feasibility (Li et al., 2022b; Storrs et al., 2023). Among these costs, the operating cost is a significant component, including the input costs of CCUS technology throughout the entire operational process, including capture, transportation, utilization, and storage (Liu et al., 2022a). The cost of the capture phase primarily comprises equipment investments, operating energy consumption, and chemical expenses. This part of the cost accounts for approximately 60%–70% of the total cost of CCUS technology (Dubey and Arora, 2022), and varies widely depending on the source of CO_2. For industrial processes that produce highly concentrated CO_2 streams, such as ethanol production or natural gas processing, the cost can range from $ 15–25/t CO_2. However, for processes with more dilute gas streams, like cement production and power generation, the cost is ranging from $ 40–120/t CO_2 (Baylin-Stern and Berghout, 2021). Transportation costs mainly involve pipeline construction and logistical expenses, while storage costs include the leasing of reservoirs and storage operations. The cost of CCUS technology can vary depending on the specific scenario and region. The IEA's CCUS Technology Roadmap outlines the goal of making CCUS technology cost-competitive in the market by 2050 and advancing full-process integration projects into the commercial application stage (IEA, 2013). Therefore, the cost of CO_2 capture technology represents the most substantial cost component within the entire CCUS process (Liu et al., 2022a).

2.2 Current large-scale demonstration

In response to the global climate change challenge, many countries have been engaged in CO_2 capture projects for an extended period. The earliest reported large-scale CCUS project is the Terrell project, constructed in the USA in 1972, offering a CO_2 capture capacity of up to 1.3 Mt/a (Orujov et al., 2023). In comparison, China's initiation of CCUS projects occurred later, and most of the operational or under-construction CCUS demonstration projects primarily involve small-scale capture and displacement trials within the petroleum, coal chemical, and power sectors (Wang, 2024). According to a report from the Global CCS Institute in September 2022 (Fig. 2), there are 196 commercial CCUS infrastructure projects at varying stages of progress worldwide, with an average CO_2 capture capacity of 243.9 Mt/a. However, only 30 of these projects are currently in operation, 11 are under construction, 78 are in the late-stage development phase, 75 are in early-stage development, and 2 are in a state of shutdown (Global CCS Institute, 2022).

Since the beginning of the 21st century, as industrialization has accelerated and global warming has intensified, CO_2 capture projects have garnered increasing attention from countries. The USA, China, Canada, Norway, and other nations have expedited the industrialization of CO_2 capture projects (Gao et al., 2020). Table 1 compiles data on a total of 21 large-scale integrated CCUS projects in the world, with a capture

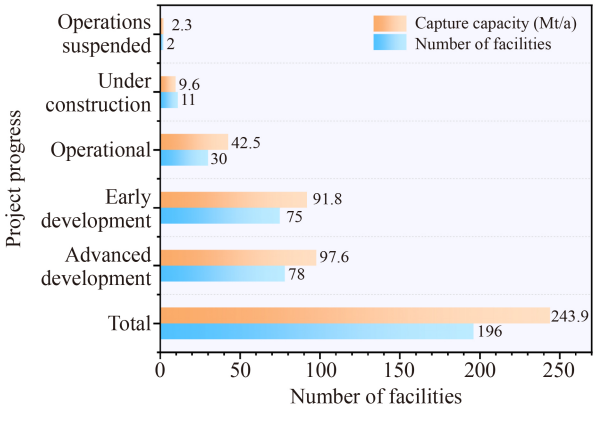

Fig. 2 CO_2 capture capacities of commercial-scale CCUS projects at various levels of advancement worldwide.

Table 1 The global large-scale CCUS projects (Global CCS Institute, 2020)

No.	Name of the project	Year of operation	Capture capacity/ (Mt/a)	Country	Source of CO_2
1	Taizhou Power Plant CCUS Project	2023	0.5	China	Flue gas
2	Qilu Petrochemical-Shengli Oilfield Million-ton CCUS Project	2022	1.0	China	Qilu Petrochemical Capture
3	Gorgon CO_2 Injection Project	2019	3.4–4.0	Australia	Natural gas plant
4	PetroChina Jilin Oilfield-Changling Natural Gas Plant Project	2018	0.6	China	Natural gas plant
5	Illinois Industrial CCS Project (IL-ICCS)	2017	1.0	USA	Ethanol plant
6	Petra Nova Carbon Capture	2016	1.4	USA	Coal power plant
7	Abu Dhabi CCA (Phase 1 Emirates Steel Industries)	2016	0.8	United Arab Emirates	Steel plant
8	Quest	2015	1.08	Canada	Hydrogen production
9	Uthmaniyah CO_2-EOR Demonstration	2015	0.8	Saudi Arabia	Natural gas plant
10	Boundary Dam CCS	2014	1.0	Canada	Coal power plant
11	Petrobras Santos Basin Pre-Salt Oil Field CCS	2013	3.0	Brazil	Natural gas plant
12	Coffeyville Gasification Plant	2013	1.0	USA	Chemical fertilizer plant
13	Air Products Steam Methane Reformer	2013	1.0	USA	Oil refinery
14	Lost Cabin Gas Plant	2013	0.9	USA	Natural gas plant
15	Century Plant	2010	8.4	USA	Natural gas plant
16	Snehvit CO_2 Storage	2008	0.7	Norway	Natural gas plant
17	Great Plains Synfuels Plant and Weybum-Midale	2000	3.0	USA	Natural gas plant
18	Sleipner CO_2 Storage	1996	1.0	Norway	Natural gas plant
19	Shute Creek Gas Processing Plant	1986	7.0	USA	Natural gas plant
20	Enid Fertiliser	2003	0.68	USA	Chemical fertilizer plant
21	Terrell Nature Gas Processing Plant (formerly Val Verde)	1972	1.3	USA	Natural gas plant

scale exceeding 500000 tons per annum. Domestic demonstration projects in China were initiated somewhat later (Yang et al., 2022), including the PetroChina Jilin Oilfield-Changling Natural Gas Plant, Sinopec Qilu Petrochemical EOR Project, and National Energy Group Jiangsu Taizhou 500000 tons per year CCUS Project. Among these, the "Qilu Petrochemical-Shengli Oilfield Million-ton CCUS Project", officially commissioned and operational since August 2022, stands as China's inaugural million-ton CCUS project. This project has the capacity to reduce CO_2 emissions by 1 million tons annually, equivalent to the environmental benefit of planting nearly 9 million trees, and will contribute valuable engineering experience and technical data for the large-scale construction of CCUS projects in China (Yao et al., 2023b).

3 Research hotspots analysis of CCUS

To study the research status, hotspots and trends in this field, this section applied a visually bibliometric analysis approach to gain a deeper understanding of the structure and dynamics of related CCUS research. In the realm of CCUS, scholars have generated valuable research outcomes. For look back and forward of the basic researches on CCUS, and to reflect its research trends, hotspots and core scientific discoveries, we followed a specific set of procedures in this review: The data set was extracted from the Web of Science (WoS) bibliographic database, including all publications categorized as "Article" or "Review Article". Publications were selected from the WoS subject categories "Carbon Capture, Utilization and Storage" or "CO_2 Capture, Utilization and Storage" OR "CCUS". The timeframe for inclusion ranged from 1970 to 2024. In this step, we screened 5974 papers and found that most of them were from the energy and chemical industries through the analysis of database screening results.

The actual number of publications within a field during a specific period can serve as an indicator of research intensity and provide insight into its overall trend (Jiang and Ashworth, 2021). Consequently, we charted the number of publications released each year based on WoS data (Fig. 3(a)). It is apparent that there has been a general upward trajectory in the number of publications in the field over the past 16 years. Between 1970 and 2011, research publications of CCUS exhibited relatively slow growth with the accounting for only 5% of the total publications. However, the annual publication output increased significantly from 2012 to 2023. Notably, in 2020, the introduction of the concepts of "carbon peaking" and "carbon neutrality" garnered widespread attention and discussion among researchers worldwide.

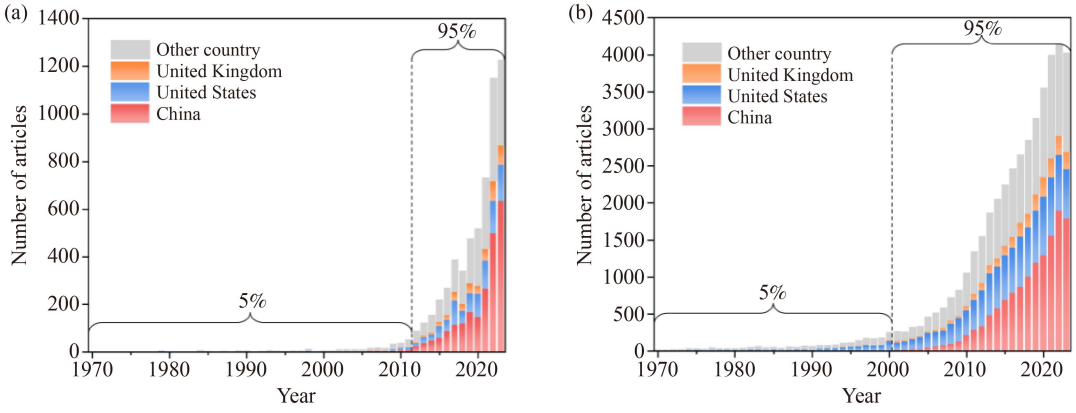

Fig. 3 Number of papers published annually and over time related to (a) CCUS and (b) carbon capture topics in the WoS database.

This reflects the current research significance and interest in CCUS technologies.

Data analysis via bibliometric software revealed that there were 115 different countries/regions with published articles in related fields. The results illustrates that China has been the subject of more extensive research in the field of CCUS, with 2235 publications accounting for 37.4% of the total. Following China, countries such as the USA (952 publications, 15.9%) and the UK (453 publications, 7.5%) have also made significant contributions, underscoring their growing importance in this field.

Given the contemporary emphasis on energy conservation and carbon reduction, CCUS has swiftly emerged as one of the most extensively discussed topics across various industries (Yan et al., 2021). Researchers are continually broadening the scope of their investigations, and the subjects of their research are evolving and becoming more profound. The subsequent analysis allows us to discern annual trends in CCUS research. The research trends and correlations of CCUS in the past 20 years are shown in Fig. 4(a). The research focus has always been on "CO_2 capture", "Storage", and "CO_2 utilization". The correlation between carbon capture and other keywords seems to be higher compare to others.

Additionally, by analyzing the data using Citespace software, we were able to identify the top 10 most cited keywords related to CCUS in the past 20 years, as presented in Table 2. The time periods during which these keywords appeared are denoted by the dark blue lines, with the red line segments indicating the outbreak duration, and the light blue portions signifying when the keyword was not mentioned. Over time, CCUS applications have shifted from power plants to industries such as cement, for which it is difficult to reduce emissions. Within the spectrum of CCUS technologies, carbon capture technology has consistently been a prominent research area. Research in this field has been continuously expanding since 2008 and has sustained the longest period of explosive growth. It is evident that the concept of CO_2 capture continued to surge in 2023, indicating that it remains a major hotspots of CCUS research.

To delve deeper into the latest research hotspots within the field of carbon capture, we conducted a search in the WoS database using the query "Carbon Capture (Topic) NOT CCUS (Topic) NOT Storage (Topic) NOT conversion (Topic) NOT Utilization (Topic) NOT Carbon Capture, Utilization and Storage (Topic)". The search was restricted to the timeframe from 1970 to 2023, resulting in a total of 43403 findings. Figure 3(b) illustrates that there has been a notable surge in the volume of literature pertaining to CO_2 capture in recent years. Between 1970 and 2000, the number of research publications on carbon capture accounted for only 5% of the total publications. However, from 2001 to 2023, the annual production of publications increased significantly.

By increasing the threshold for the frequency of keyword occurrence in VOSviewer software, we can narrow down the selection of keywords. In Fig. 4(b), a more detailed representation of recent research topics related to CO_2 capture is presented, with the top 100 high-frequency keywords chosen. It is evident that in the early stages, researchers primarily concentrated on factors such as concentration, pressure, and temperature variations during the capture process. Over time, the focus shifted toward model simulations and their impact on the capture rate, subsequently delving into interfacial migration during the reaction process and the constitutive relationship between structure and performance. Currently, researchers have begun to place emphasis on the effects of performance, stability, and cost on the industrial application of CO_2 capture technologies.

4 Carbon capture technologies and materials

Based on the visualization analysis results, we thought the carbon capture technology remains a major hotspots of

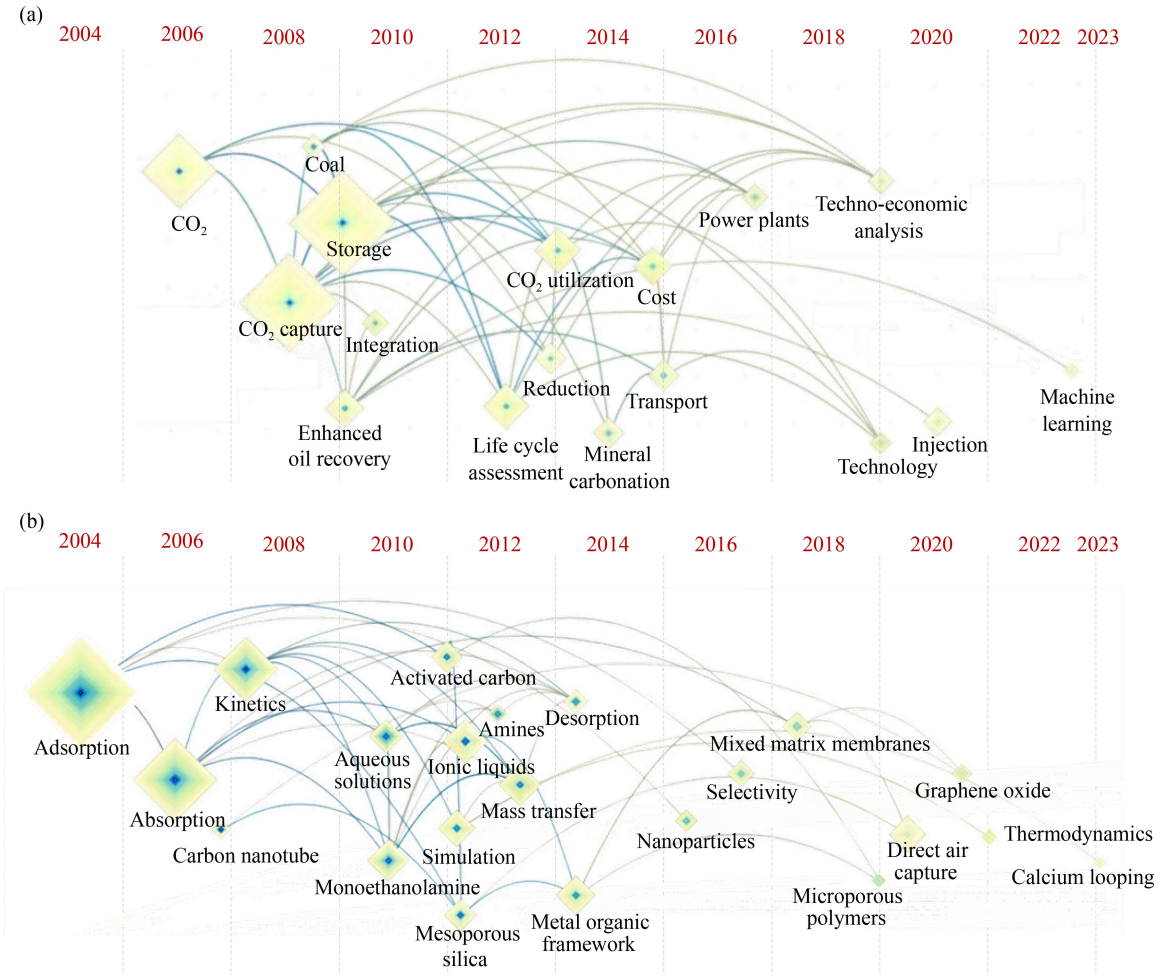

Fig. 4 Relationship between research hotspots over time in (a) CCUS and (b) carbon capture.

Table 2 The relationship between the 10 most frequent keywords over time in CCUS

Keywords	Start year	Begin of outbreak	End of outbreak	2004–2023
CO_2	2006	2014	2015	
Storage	2009	2011	2017	
CO_2 capture	2008	2016	2018	
Transport	2015	2015	2016	
Enhanced oil recovery	2014	2017	2019	
Coal	2009	2017	2018	
Power plants	2017	2017	2018	
CO_2 utilization	2013	2018	2021	
Integration	2010	2019	2020	
Cost	2015	2020	2021	

CCUS research. The development of absorption, adsorption, and membrane separation technologies is currently receiving the most attention in this field. Additionally, the appearance of emerging carbon capture technologies, such as chemical looping combustion (CLC), electrochemical capture, and direct air capture (DAC), has also aroused the interest of researchers. Therefore, this section provides an overview of these state-of-the-art carbon capture technologies and materials.

4.1 Absorption

Liquid absorption is presently one of the most commonly utilized CO_2 capture technologies. In this process, a gas mixture is brought into contact with a specific liquid, and the gas components are separated and purified based on their varying solubility in the liquid. According to the different absorption principles, CO_2 capture technology can be divided into physical and chemical absorption methods. Chemical absorption methods involve alkaline absorbents selectively reacting with CO_2 in mixed flue gas to produce unstable salts such as carbonate, bicarbonate, and carbamate. When external conditions, such as temperature and pressure, change, certain salts can facilitate the reversal of CO_2 desorption, enabling the removal of CO_2 and the regeneration of the absorber (Kortunov et al., 2015). In chemical absorption, amine-based solvents or ionic liquid (IL)-based solvents can be used to capture CO_2 (Fig. 5).

4.1.1 Amine-based solvents

The reaction principle of CO_2 capture by the organic amine method involves the reaction of the amino group in the organic amine with CO_2 by acid–base neutralization; thus, facilitating the separation and absorption of CO_2. Organic amines can be divided into primary amines (RNH), secondary amines (R_2NH), and tertiary amines (R_3N), where R represents an alkyl group. These amines exhibit varying levels of basicity. The following are the net reactions between different types of amines and CO_2 (Eqs. (1) and (2)):

Primary/secondary amines:

$$CO_2 + 2R_1R_2NH \leftrightarrow R_1R_2NH_2^+ + R_1R_2NCOO^- \quad (1)$$

Tertiary amines:

$$CO_2 + H_2O + R_1R_2R_3N \leftrightarrow R_1R_2R_3NH^+ + HCO_3^- \quad (2)$$

where R_1 and R_3 refer to the alkyl/alkanol groups, and R_2 refers to the hydrogen atom for the primary amine or the alkyl/alkanol substituent for the secondary amine and tertiary amine, respectively (Chakraborty et al., 1986).

Amine solvents have good CO_2 absorption properties, but they have problems such as high energy consumption for regeneration, all of which are related to the inherent properties of the amine solvents selected. Therefore, much research has been focused on developing alternatives to various amine absorbents. These alternatives include blended, biphasic and non-aqueous amine solvents, with the aim of optimizing the carbon capture performance of amines (Ghaedi et al., 2022). Table 3 provides a summary of the research progress in these three liquid amine-based absorbents.

4.1.1.1 Blended amine solvents

Recognizing the limitations of using a single amine for CO_2 capture, Chakraborty et al. introduced the concept of preparing hybrid amine solutions by mixing amine solutions with different properties (Chakraborty et al., 1986). Mixed amine solvents containing multiple components have demonstrated significant enhancements in overall performance. For instance, the monoethanolamine-activated Methyldiethanolamine (MEA-activated MDEA) absorber exhibits a mass transfer rate similar to that of an aqueous MEA solution and higher absorption rates than MDEA at lower partial CO_2 pressures. This results in a 6%–12% reduction in regeneration energy compared to conventional aqueous MEA solutions (Lawal et al., 2005).

The addition of activator Piperazine (PZ) to Methyldiethanolamine (MDEA) or amphetamine (AMP) absorbers not only enhances the absorption rate but also addresses the issue of PZ solid precipitation (Brúder et al., 2011). Hybrid amine solutions combining PZ and AMP have demonstrated rapid absorption rates and high

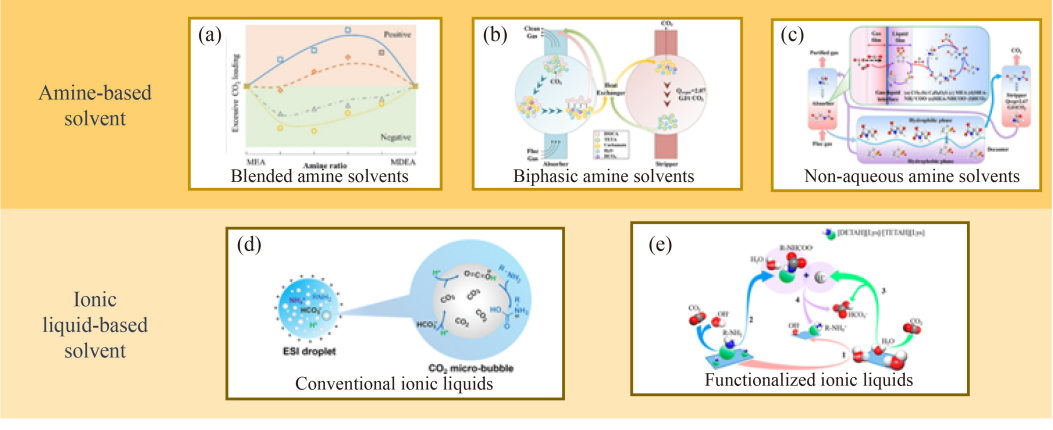

Fig. 5 Technology options for liquid-based CO_2 capture and strategies for improving CO_2 capture performance: (a) Blended amine solvents. Copyright 2023, Elsevier (Zhang et al., 2023b); (b) Biphasic amine solvents. Copyright 2018, American Chemical Society (Zhang et al., 2018); (c) Non-aqueous amine solvents. Copyright 2018, American Chemical Society (Wang et al., 2018); (d) Conventional IL solvents. Copyright 2021, American Chemical Society (Feng et al., 2021); (e) Functionalized IL solvents. Copyright 2018, American Chemical Society (Jing et al., 2018).

Table 3 CO_2 capture by chemical absorption

Absorbent type	Absorbing material	Temperature (K)	Absorption capacity	Energy consumption	Ref.
Amine-based solvents					
Blended amine absorbents	MEA/$TiO(OH)_2$/H_2O	298	0.54 mol/mol	Around 3.2 GJ/t	Lai et al. (2018)
	MEA/EG/H_2O	293–323	0.91 mol/mol	1823 GJ/t	Kang et al. (2017)
	DEEA/MAPA	313	0.87 mol/mol	−54.35 kJ/mol (Reaction heat of absorbents with CO_2)	Knuutila & Nannestad (2017)
Biphasic amine solvents	TETA-DMCA	313.15	0.95 mol/mol	2.07 GJ/t CO_2	Zhang et al. (2018)
	MEA/Sulfolane (phase-changed)	318	3.88 mol/L	2.67 MJ/kg	Wang et al. (2018)
	DEEA/TETA/Sulfolane (phase-changed)	303	4.92 mol/L	1.81 MJ/kg	Tao et al. (2018)
	DEEA/TETA/H_2O (phase-changed)	303	3.1 mol/L	2.3 MJ/kg	
	AEEA/PMDETA/DMSO (phase-changed)	333	1.78	1.76 MJ/kg CO_2	Zhou et al. (2020)
Non-aqueous amine solvents	MEA/DEGMEE	298	0.48	929 kJ/mol CO_2	Bougie & Fan (2018)
	MEA/PEG200	313	0.483	2547 kJ/g CO_2	Tian et al. (2021)
	TETA/PEG200	333	1.86	25 MJ/kg	Li et al. (2022a)
	TETA/BDO	303	1.75	92MJ/kg	Li et al. (2020)
	AMP/AEEA/NMP	298	1.65 mol/kg	2.09 MJ/kg	Lv et al. (2020)
Ionic liquid-based solvents					
Conventional IL solvents	[hmim][Tf2N]	298	0.7	−12.1 kJ/mol (partial molar enthalpies)	Muldoon et al. (2007)
Functionalized IL solvents	[Cho][His]	318.15	1 (mol CO_2/kg IL)	−45.85 kJ/mol (enthalpy of chemical absorption)	Noorani & Mehrdad (2022)
	[B_4MPyr][L-Val]	298K	0.47 (mol CO_2/kg IL)	−49.92 kJ/mol (enthalpy of chemical absorption)	Noorani et al. (2021)
	[BMIm][Val]	318.15K	0.59	−11.07 kJ/mol (enthalpy of chemical absorption)	Noorani & Mehrdad (2020)

absorptive capacities, with regeneration energy consumption approximately 80% of that of conventional MEA absorbers (Yang et al., 2010). Furthermore, hybrid absorbers comprising more than two different amines have garnered recent attention. Zhang et al. (2017) investigated the energy consumption for carbon capture in MEA/MDEA/PZ amine absorbers with varying composition ratios and found that energy losses could be reduced by 15.22%–49.22% depending on the mixing ratio.

Blended amine solvents can utilize typical amine uptake processes without further modification and are a good alternative to single amines. However, factors such as viscosity, volatility and cost should also be considered when investigating mixed amine solvents.

4.1.1.2 Biphasic solvents

There are two main types of biphasic absorbents based on the type of solvent used: aqueous (Zhou et al., 2023) and non-aqueous (Li et al., 2021) biphasic absorbents. In the case of biphasic solvents, the design of the reactive amine is crucial for achieving high absorption and desorption efficiencies. For instance, Wang et al. (2018) investigated an MEA-based biphasic adsorbent and found that the regeneration heat consumption of the MEA-sulfoxide-H_2O system was 2.67 GJ/t CO_2, which was 31% lower than that of the conventional MEA process.

To increase the absorption load of CO_2, it is recommended to design a polyamine biphasic absorber. For example, for a Triethylenetetramine /Diethylethanolamine/Sulfolane (TETA/DEEA/Sulfolane) absorber with a rich-phase volume ratio of 39% and a CO_2 loading of 4.92 mol/L in the rich phase, this method reduces the heat of regeneration by 54.6% compared to a 30 wt% MEA solution (Wang et al., 2020). However, a common problem with biphasic solvents is the high viscosity of the CO_2-rich phase, and the design of the active amine must take into account both the absorption limit of the single amine and the viscosity of the biphasic amine.

4.1.1.3 Non-aqueous solvents

Large energy losses for the regeneration of amine solutions are the main drawback of absorption-based CO_2 capture. For typical aqueous amine absorbents, approximately half of the total energy is wasted in heating and vaporizing water during the absorption process due to the high specific heat capacity and enthalpy of vaporization

of water. Recently, considerable research has focused on novel potential non-aqueous absorbents.

Alcohols, ethers, and glycols are common cosolvents in non-aqueous absorbents. Liu et al. (2018) investigated TETA and AMP mixed amine absorbents using ethanol as a cosolvent. It was found that this non-aqueous absorbent exhibited a high absorption capacity (3.71 mol/kg) and regeneration efficiency (95.4%). Barbarossa et al. (2013) developed a range of AMP-based solutions for chemical CO_2 capture. According to their findings, the AMP/Methylethanolamin (MMEA)/1-propanol mixture exhibited an equilibrium absorption efficiency of 95.9% at 333 K. Furthermore, all AMP-based blended absorbents demonstrated over 90% equilibrium absorption efficiency at a regeneration temperature of 363 K.

Viscosity is a key factor affecting the absorption of CO_2 by nonaqueous amine-based absorbents, which can lead to deterioration of mass transfer and liquid transportation. A new strategy for reducing solution viscosity is proposed. A series of ethylenediamine derivatives were constructed. Favorable low viscosity and good regeneration during CO_2 capture was achieved in the temperature range of 50–80 °C (Liu et al., 2019).

4.1.2 Ionic liquid-based solvents

The utilization of organic amine-based absorbents for CO_2 capture is prevalent due to its numerous advantages. However, it is essential to consider some of its drawbacks, including cost and solvent degradation. Therefore, there is a need to explore promising alternative materials that can address issues such as corrosion and pollution. In recent years, ILs have emerged as a promising and environmentally friendly absorption material with significant application potential. ILs possess several advantageous properties, including adjustable structure, low saturation vapor pressure, high chemical and thermal stability, and strong selectivity for CO_2 absorption (Aghaie et al., 2018). These compounds are salts composed of specific cations and anions, typically existing in a liquid state at room temperature (Hallett and Welton, 2011). ILs can be further categorized into conventional ILs and functional ILs.

4.1.2.1 Conventional IL solvents

Conventional IL solvents can be further classified into various categories based on the type of anion and cation they contain, such as ammonium, imidazole, pyridine, and sulfonate salts. A notable milestone in the use of ILs for CO_2 capture was achieved by Blanchard et al. (1999), who synthesized an ionic liquid, [Bmim][PF_6], with a solubility of 0.6 mol CO_2/mol in the temperature range of 40 to 60 °C and at pressures ranging from 0 to 9.5 MPa. This groundbreaking work demonstrated the feasibility of utilizing ILs as CO_2 absorbents. Consequently, ILs have gained recognition as green and environmentally friendly alternatives to organic solvents, offering lower exposure risks and the ability to fine-tune solvent properties (Fernández, 2023).

However, ILs still exhibit relatively lower absorption performance when compared to organic amine solutions due to differences in the absorption mechanisms. ILs are also known for their high viscosity and limited absorption capacity (Gardas and Coutinho, 2008). To enhance the solubility of CO_2 in ILs, it is essential to assess how the structure of ILs affects their CO_2 absorption performance. For example, Muldoon et ;al. (2007) introduced ILs containing fluoroalkyl chains, which led to improved CO_2 solubility .

4.1.2.2 Functionalized IL solvents

To address the limitations of conventional ILs, researchers have explored the modification of these liquids by introducing specific functional groups. This approach results in functionalized ILs, which possess tailored chemical properties that can significantly enhance their performance in terms of absorption, desorption, stability, and antioxidation capacity. Functionalized ILs represent a promising avenue for improving the utility of ILs in various applications, including CO_2 capture and separation. Compared with conventional ILs, they not only physically absorb but also chemically absorb CO_2. Amino functionalized ILs that exhibited an absorption capacity of approximately 0.5 mol CO_2/mol TSIL, comparable to MEA, the mechanism behind this absorption involves the deprotonation of carbamic acid intermediates by the amine functional groups in the IL (Bates et al., 2002).

Industrial applications of functional ILs are limited by their high cost and viscosity. This can be solved by modifying its composition, using proppants and encapsulants, etc. developed A biphasic solvent using a bi-functionalized ionic liquid ([DETAH][Tz]) diluted with a 1-propanol-water co-solvent. This biphasic solvent has good phase separation properties and low viscosity (2.57 MPa·s). In addition, the heat of regeneration of this solvent was 47.63% lower than that of MEA, which is commonly used in CO_2 capture processes (Zhan et al., 2020).

The blend of MDEA and [BEIM][BF_4] (imidazoline IL) as an absorbent exhibited significant CO_2 capacity, low viscosity, and good renewability. This approach of conventional blending amine solutions with functional ILs as activators was effective in maintaining the desired performance of both the amines and ILs (Xiao et al., 2019). Table 3 summarizes some of the research details of functionalized ILs.

4.2 Adsorption

CO_2 adsorption technology is extensively researched and

utilized to mitigate CO_2 emissions. Based on different application scenarios, CO_2 sorbents can be categorized into three types: low-temperature sorbents (less than 200 °C), medium-temperature sorbents (200 to 400 °C), and high-temperature sorbents (above 400 °C) (Fig. 6).

4.2.1 High-temperature sorbents

4.2.1.1 CaO-based sorbents

Due to its low cost, abundant availability of the calcium resource, high theoretic adsorption capacity and rapid adsorption rate during the chemical control stage, CaO has considerable potential for practical high temperature CO_2 absorbent application. However, sorbents based on calcium are prone to sintering during repeated adsorption cycles, leading to a significant decrease in adsorption performance. The residual uptake of 1.13 mmol/g after 500 calcination-carbonation cycles is a major challenge in the development of the CaO process (Krödel et al., 2020; Geng et al., 2021).

Three types of nano CaO sorbents were prepared by Liu et al. (2023) using MOF precursors through a two-step thermal transformation process. Among these, LAC MOF demonstrates the highest potential as a precursor. After four cycles of adsorption, this material exhibits a fast adsorption capacity of 11.8 mmol/g. Adsorption performance remains independent of pore structure, leading to superior adsorption performance.

The development of the CaO process requires the synthesis of Ca-based absorbent nanoparticles with stabilized backbones and porous structures. Future work must fully consider the economic, environmental, and mechanical properties of synthetic Ca-based absorbents.

4.2.1.2 Alkaline silicate-based sorbents

Various alkali silicate based sorbents have been investigated for high temperature CO_2 capture. Due to its high theoretically sorptive capacity, low regeneration temperature (resulting in low energy required) and excellent cyclic stability, lithium orthosilicate (Li_4SiO_4) has shown promise (Chen et al., 2016). The sorption performance of Li_4SiO_4 can be improved by incorporating other elements. Previous studies have reported that the sorption properties of Li_4SiO_4 are significantly enhanced by doping with K, Na, Al, Fe, or Ge (Zhang et al., 2021a).

A new one-step process for the preparation of macroporous pellets of K_2CO_3-doped Li_4SiO_4 for the capture of CO_2 at high temperatures and low CO_2 concentrations has been proposed by Stefanelli et al. (2022). The sorption tests were carried out at a temperature of 580 °C and 400 ppm CO_2. Pellets derived

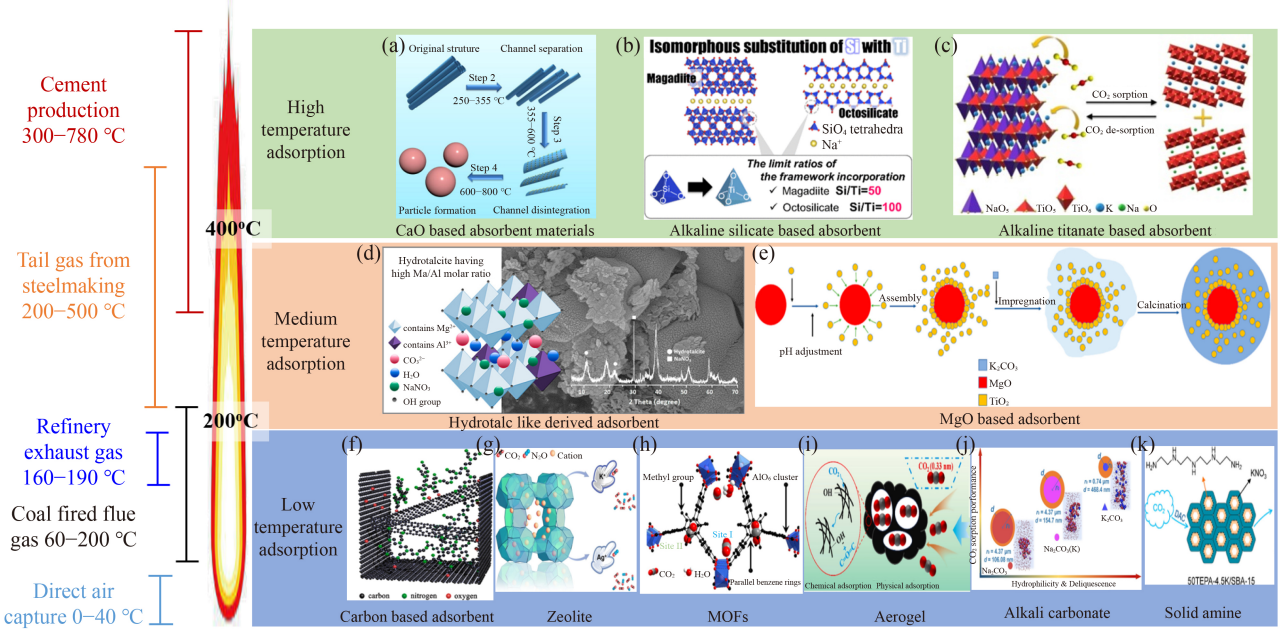

Fig. 6 Technology strategy for CO_2 capture by adsorption: (a) CaO based sorbents. Copyright 2023, Elsevier (Liu et al., 2023); (b) Alkaline silicate based sorbents. Copyright 2022, American Chemical Society (Morita et al., 2022); (c) Alkaline titanate based adsorbent. Copyright 2020, Elsevier (Zheng et al., 2020); (d) Hydrotalc like derived sorbents. Copyright 2016, American Chemical Society (Kim et al., 2016); (e) MgO based sorbents. Copyright 2023, American Chemical Society (Wu et al., 2023); (f) Alkali carbonate based sorbents. Copyright 2021, Elsevier (Wu et al., 2021); (g) Zeolite based sorbents. Copyright 2023, John Wiley and Sons (Wang et al., 2023b); (h) Metal-organic framework (MOF) based sorbents. Copyright 2023, American Chemical Society (Hu et al., 2023); (i) Aeroget. Copyright 2024, Elsevier (Wang et al., 2024); (j) Alkali carbonate based sorbents. Copyright 2021, Elsevier (Cai et al., 2021); (k) solid amine. Copyright 2023, American Chemical Society (Wang et al., 2023a).

from LiOH and further treated with K_2CO_3 showed the highest CO_2 uptake of 5.7 mmol/g. Adding 20 wt% cellulose fiber as a template (PLHK3-20 C) improved CO_2 absorption, and Li_4SiO_4 was converted to 89.7%.

Lithium-based sorbents were prepared through alkali melting treatment at 550 °C using various CDWM sources (ceramic household waste, sand, concrete, and blocks). The results show that Li_4SiO_4, produced from block waste, can capture 4.15 mmol/g at a temperature of 580 °C, with 20% CO_2. Furthermore, silicates derived from blocks exhibit chemical stability throughout 20 adsorption cycles, maintaining maximum CO_2 adsorption within the range of 178–183 mg CO_2/g (Hernández-Palomares et al., 2023) (Table 4).

4.2.1.3 Alkaline titanate-based sorbents

Alkali titanates have recently garnered significant attention as emerging high-temperature CO_2 sorbents. The focus of current research primarily centers around Li_2TiO_3, Li_4TiO_4, Na_2TiO_3, and $K_2Ti_2O_5$, among others. These sorbents exhibit sensitivity to CO_2 concentration, with a notable decrease in capture capacity at low CO_2 concentrations.

Among all types of Na-doped alkali titanates, potassium titanate ($KNaTiO_3$) has emerged as one of the most promising types for high-temperature CO_2 capture. This can be attributed to its remarkable cyclic stability and rapid CO_2 sorption rate (Zheng et al., 2020). A novel alkali titanate-based sorbent, $K_xNa_{2-x}TiO_3$, has been reported. The material exhibits exceptional thermal stability and can capture up to 19.0 wt% of CO_2 at 700 °C. Notably, it maintains a CO_2-capture capacity of 17.4 wt% even at low CO_2 concentrations of 20 vol%, respectively. To facilitate its industrial application, Fan et al. (2023) employed a cost-effective titanium ore for synthesizing $KNaTiO_3$. The optimized adsorbent maintains a rapid and recoverable adsorption capacity of 15.5 wt% after 100 cycles, showing excellent CO_2 capture kinetics. A high CO_2 capture rate of 92.5% (at levels below 20% CO_2) is reached in just 4 min.

4.2.2 Intermediate-temperature sorbents

4.2.2.1 MgO-based sorbents

MgO has recently garnered significant attention as a solid CO_2 adsorbent for reducing CO_2 in flue gas. This interest stems from its abundant sources, cost-effectiveness, and high theoretical CO_2 adsorption capacity. Adsorption usually takes place in the range of 200 to 300 °C, whereas regeneration is frequently carried out at temperatures higher than 400 °C. MgO has an impressive theoretical maximum absorption of CO_2 of 24.8 mmol/g, suggesting its potential for applications in efficient carbon capture (Zhu et al., 2023).

However, previous studies have revealed a considerable discrepancy between the actual adsorption capacity (0.24 mmol/g) and the theoretical predicted adsorption capacity of MgO (24.8 mmol/g) (Gregg and Ramsay, 1970; Harada et al., 2015). In addition, the application of MgO in practice faces a variety of obstacles, such as wear, loss of adsorption capacity during prolonged cycle cycles, and the potential for competitive sulfation-reactions, especially when dealing with high-sulfur feedstocks. To overcome these limitations, researchers have put forward two main strategies aimed at enhancing the performance of MgO-based sorbents:

1) Constructing porous MgO. This was made possible by employing a porous sorbent called AMS/CaMgO in conjunction with Ni_xCo_y alloy catalysts. The AMS/CaMgO sorbent demonstrated consistently stable CO_2 adsorption capacity of 12.8 mmol/g during the carbonation-decarbonation cycle (Sun et al., 2023).

2) Coating with alkaline metal salts. This paper deals with the preparation of MgO sorbents by a mixture of alkali metal nitrate and carbonate. At 325 °C, with 10% $[(Li_{0.44}K_{0.56})NO_3]_2[(Na_{0.5}K_{0.5})CO_3]$, the CO_2 capturea-mount of the composite adsorbent increased to 19.06 mmol/g (Ding et al., 2020).

Enhancing the granulation techniques and optimizing the performance of MgO sorbents in granular form are of utmost importance for their widespread practical application on a larger scale. These advancements are necessary due to the remarkable mechanical and chemical properties exhibited by MgO sorbents.

4.2.2.2 Hydrotalc like derived sorbents

Hydrotalcite has attracted considerable attention as a potential sorbent for CO_2 capture at high temperatures. It has good thermal stability and is easy to regenerate. However, its CO_2 sorption capacity at elevated temperatures is relatively limited for practical applications (Kim and Lee, 2019).

To address this limitation, Kim et al. (2023) introduced $NaNO_3$ into the hydrotalcite structure using a specific preparation method to create high Mg/Al molar ratio hydrotalcite, which was employed for CO_2 capture. The maximum CO_2 sorption uptake reached 14.9 mmol/g when the Mg/Al molar ratio was 30. While the introduction of alkali metals can enhance CO_2 capture capacity, the persistent challenges of relatively limited adsorption capacity and cycling stability remain

4.2.3 Low-temperature sorbents

4.2.3.1 Zeolite based sorbents

Regarding low-temperature adsorption, particularly focusing on zeolite-based sorbents, zeolites are aluminosilicate crystals with porous lattices that allow easy diffusion of CO_2 molecules. The reason for this is

Table 4 Different technologies for CO_2 adsorption

Adsorbent type	Adsorbing material	Adsorption condition	Absorption capacity (mmol/g)	Desorption condition	Enthalpy of absorption / adsorption (kJ/mol)	Ref.
Low-temperature solid CO_2 sorbents						
MOF sorbents	Diamine-appended Mg_2(dobpdc)	30%RH, 0.044%CO_2, 30 °C	5.7	140 °C, N_2		Holmes et al. (2023)
	Dobpdc	50%RH, 0.04%CO_2, 20 °C	1.7	150 °C, N_2		Bose et al. (2023)
	MOF-74(Ni)-24-140	15%CO_2, dry, 25 °C	3.82	60–70 °C, N_2	−30.0 to −52.0	Lei et al. (2022)
Amine-based sorbent	Ph-X-YY/SBA-15	0.04%CO_2/He, 30%RH, 35 °C	2.9	90 °C, He		Kumar et al. (2020)
	PEI-80a and PEI-80b	0.042%CO_2/N_2, 41%RH, 33 °C	2.36	100 °C, N_2		Wijesiri et al. (2019)
	PM01	0.04%CO_2/N_2, 65%RH, 25 °C	1.5	100 °C, N_2	−87.15	Al-Absi et al. (2022)
	TEPA@ZIF-8	15%CO_2/N_2, 30 °C, 100 mL/min	1.45	800 °C, N_2	−37.8	Shen et al. (2022)
Silica materials sorbents	HMS-4 h-75% TEPA	5%CO_2, dry, 90 °C	4.9	100 °C, N_2	−69.49	Yan et al. (2022)
	Al-MCM-41-0.3	5%CO_2/N_2, dry, 50 °C	1.35	Steam regeneration, 120 °C, N_2, 30 min		Jahandar Lashaki et al. (2022)
		5%CO_2/N_2, dry, 25 °C	1.48			
Carbonaceous adsorbent	HG-HCNTs-PEI-2	10%CO_2/Ar, dry, 40 mL/min, 25 °C	4.43	100 °C, Ar, 1 h, 30 mL/min	−65	Wu et al. (2021)
	2K0U800	1barCO_2, dry, 25 °C	4.02	100 °C under vacuum	−37.2	(Shi et al., 2022)
	aPAni/GO10	1barCO_2, dry, 25 °C	4.11		−31.2 to −27.0	(Szcześniak and Choma, 2020)
Intermediate-temperature solid CO_2 sorbents						
MgO based adsorbent materials	AMS/CaMgO	45%CO_2/N_2, 50 mL/min, 1 h, 350 °C,	12.8	450 °C, N_2, 50 mL/min	−100.7	Sun et al. (2023)
	10 mol % $NaNO_2$+MgO	100%CO_2, 62 mL/min, 325 °C, 55 min, 1atm	6.8	450 °C, N_2, 60 mL/min, 5 min		Gao et al. (2021)
Hydrotalc like derived adsorbent materials	Mg30Al1	100%CO_2, 90 min, 300 °C, 5 h, 1 atm	14.9	400 °C, N_2, 30 min, 1atm		Kim et al. (2023)
High-temperature solid CO_2 absorbents						
Alkaline titanate based absorbent	$KNaTiO_3$	20%CO_2, 10%H_20, 700 °C,1 atm, 30 min, 40 mL/min	3.7	700 °C, N_2, 40 mL/min, 30 min		Zheng et al. (2020)
Alkaline silicate based absorbent	Li_4SiO_4	20%CO_2, 580 °C, 3 h	4.1	800 °C N_2, 60 mL/min	−121.43	Hernández-Palomares et al. (2023)
CaO-based sorbents	Carbide slag	100%CO_2, 20mL/min, 750 °C	12.3	900 °C, He, 40 mL/min		Liu et al. (2020a)
	LAC-C	30%CO_2/N_2, 100 mL/min, 750 °C, 20 min	11.8	750 °C N_2, 100 mL/min, 30 min		Liu et al. (2023)

that molecules with significant dipole and quadrupole moments, such as CO_2 molecules, are attracted to the strong electric fields within the zeolite framework. Because of its high capacity, selectivity, stability, durability, regenerability, availability and low toxicity, it is a promising candidate for CO_2 capture and storage (Zhou et al., 2021; Liao et al., 2023).

The adsorption performance and desorption behavior of four commercial zeolites at different temperatures and CO_2 concentrations were investigated, leading to the proposal of two temperature-dependent desorption processes (Chen et al., 2023a). At a CO_2 pressure of 1.0 bar, the adsorption capacities for 13X, 5A, NaY, and HY zeolites are 18.4, 15.6, 19.3, and 3.3 wt%, respectively (Li et al., 2023). Furthermore, products with CO_2 purity exceeding 70% can be obtained with just one adsorption

step, with CO_2 recovery rates reaching up to 90% (Siegelman et al., 2021).

4.2.3.2 Carbonaceous sorbents

Carbonaceous sorbents are materials primarily consisting of carbon atoms in their structure. Compared to noncarbonaceous materials, they possess several advantages. First, carbonaceous materials demonstrate excellent chemical and thermal stability. Additionally, they exhibit high pore volumes and specific surface areas, making them ideal for adsorption processes. Moreover, carbonaceous sorbents can be easily regenerated, thereby increasing their reusability. Examples of carbonaceous sorbents are pyrogenic carbon materials such as biochar, charcoal, and carbonized biomass, as well as activated carbon, carbon fibers, and ordered carbon nanostructured materials such as graphene aerogels and nanotubes (Ahmed et al., 2020).

Carbon-based materials, while known for their high stability and cost-effectiveness, exhibit limitations such as low adsorption capacity and poor selectivity in the presence of nitrogen. Moreover, their adsorption capacity decreases notably at elevated temperatures due to the significant influence of operating temperature and pressure (Abd et al., 2020).

4.2.3.3 Silicon based sorbents

Mesoporous silica has emerged as the preferred choice for an adsorbent due to its exceptional structural characteristics, which include a large pore volume, adjustable pore diameter, high surface area, and ease of modification (Fatima et al., 2021). However, it exhibits a low adsorption rate for CO_2. Fortunately, the properties of silica allow for modification by the introduction of new functional groups. Given that amines are inherently basic, incorporating amine groups into silica carriers creates high-affinity CO_2 capture sites. To date, several amine-silica composites have been developed for CO_2 capture through methods such as physical impregnation, chemical grafting, or direct single-step processes (Zhang et al., 2019).

4.2.3.4 MOF based sorbents

MOF-based materials are emerging as an effective sorbent for CO_2 adsorption due to their large surface areas, variety of structural and compositional features, high porosities and large pore sizes (Younas et al., 2020; Lin et al., 2021).

However, stable MOF sorbents with high CO_2 capture ability and selectivity, rapid adsorption cycle kinetics and low energy demand for regeneration are required. The incorporation of a functional group that strongly interacts with CO_2 into the MOF structure will increase the affinity of the framework, resulting in an increase in CO_2 adsorption capacity. A new kind of molecular structure and metal adsorption site has been developed (Lei et al., 2022; Sedighi et al., 2023), and MOF-74 (Ni) can be controlled efficiently by precise preparing steps. Under the same condition (0 °C, 1.0 bar), the trapping ability could reach 8.29 mmol/g, which was higher than the conventional solid adsorption (2.00–6.50 mg/g). This shows excellent CO_2 capture capability, favorable selectivity, and adequate CO_2 adsorption heat.

4.2.3.5 Amine-based sorbents

Solid amine sorbents are produced by coating organic amines on the surface of a porous solid material. These adsorbents are highly efficient and rapidly selective in their adsorption of CO_2. For this purpose, porous materials such as silicon, zeolites, active carbon, resins, and MOFs are commonly used. Commonly used amines include polyethyleneimine (PEI), tetraethylenepentamine (TEPA), diethanolamine (DEA), monoethanolamine (MEA), and others (Lin et al., 2023).

Based on the preparation method and resulting bond structure, materials loaded with amines can be classified into three subclasses: impregnated amine, grafted amine, and *in situ* polymerized amine (Gelles et al., 2020). Impregnated FSS is commonly manufactured by the physical infusion of amine groups into the porous support (Zhang et al., 2023a). These extensively studied amine groups, known as unique low-temperature chemical sorbents, exhibit exceptional sorption selectivity under environmental conditions. They spontaneously remove CO_2 from gas sources at low concentrations and can regenerate under mild conditions. Yan et al. (2022) reported that HMS-4h was impregnated with TEPA, achieving the highest adsorption capacity at 90 °C and 1.0 bar with 75% TEPA, reaching 6.04 mmol/g. In addition, Al-Absi et al. (2022) synthesized linear polyethylene amine bound to mesoporous silica foam and tested the CO_2 adsorption performance at different temperatures (relative humidity of 0–60%) and low CO_2 concentration (400 ppm), with a maximal uptake of 1.50 mmol/g.

4.2.3.6 Alkali carbonate based sorbents

Alkali-metal carbonate-based sorbents, such as K_2CO_3 and Na_2CO_3, have been extensively researched for their ability to capture CO_2. They are cost-effective, have a high adsorption capacity, and can operate at low temperatures. These characteristics make them a promising option for use in fossil fuel power plants.

Alkali metal carbonates are typically deposited on stable porous supports like metal oxides (Al_2O_3, TiO_2), activated carbon and zeolites to enhance their properties. As reported by Cai et al. (2020), they prepared a series of Na_2CO_3-based solid sorbents (Na_2CO_3/γ-AlOOH) loaded with boehmite using initial wet impregnation technology. The CO_2 sorption performance of the chosen sorbent,

$NaAlH_2$, has been investigated under conditions with 10% CO_2 and 10% H_2O, resulting in a maximum CO_2 sorption capacity of 2.25 mmol/g.

4.3 Membrane separation

In the 1980s, as an alternative to amine solvents, membrane separation technology was first used to capture CO_2 in the purification of natural gas. Membrane separation offers notable advantages, including low capital costs and minimal energy consumption. This technology exploits the selectivity and permeability of the membrane to separate gas mixtures. The process drives gas separation or enrichment using the pressure differential across the separation membrane. In recent years, researchers have made significant strides in enhancing the performance of these membranes through various optimizations. The following section provides an overview of the latest research advancements in these three types of membranes, as depicted in Fig. 7.

4.3.1 Organic (polymeric) membranes

4.3.1.1 Polyamide (PA) membranes

Traditional interfacial polymerization (IP) methods for producing PA membranes typically result in dense microstructures with a unique configuration of functional groups, making it difficult to achieve both high CO_2 permeability and selectivity. However, a new approach uses a double-modulation strategy to enhance the CO_2 separation efficiency of PA membranes (Li et al., 2023). This strategy involves optimisation of the preparation process and modification of the filler. The resulting membranes exhibit exceptional CO_2 separation performance.

4.3.1.2 Polyimide (PI) membranes

Polyimide membranes are a type of glassy polymer separation membrane known for their exceptional properties, including high-temperature resistance, corrosion resistance, and robust mechanical strength. The

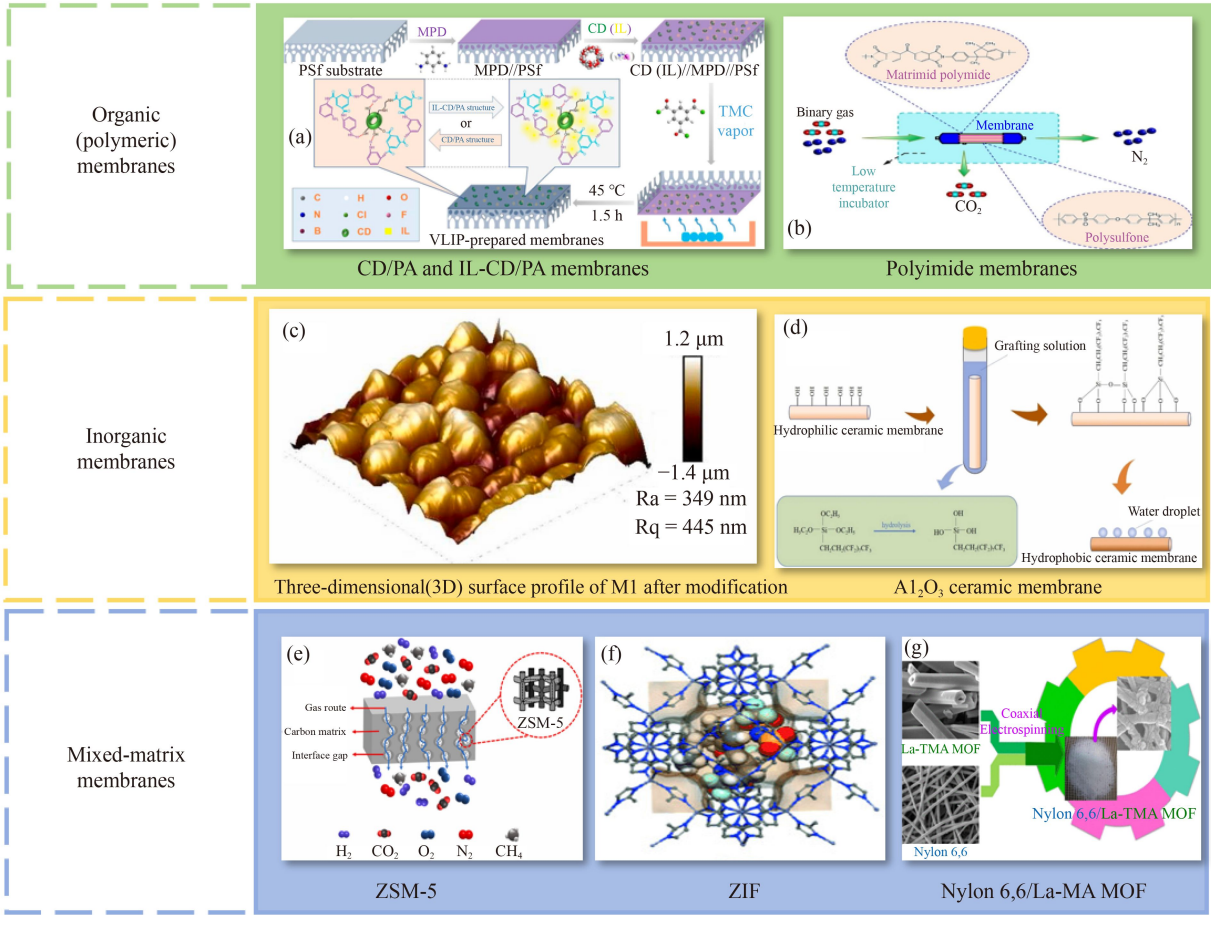

Fig. 7 Membrane separation technology for CO_2 capture: (a) CD/PA and IL-CD/PA membranes. Copyright 2023, American Chemical Society (Li et al., 2023); (b) Polyimide membranes. Copyright 2018, Elsevier (Song et al., 2018); (c) Three-dimensional (3D) surface profile of M1 after modification. Copyright 2023, Elsevier (Fu et al., 2023a); (d) Al_2O_3 ceramic membrane. Copyright 2023, Elsevier (Fu et al., 2023b); (e) ZSM-5. Copyright 2022, Elsevier (Zhang et al., 2022); (f) ZIF. Copyright 2015, John Wiley and Sons (Ban et al., 2015); (g) Nylon 6,6/La-MA MOF. Copyright 2023, American Chemical Society (Fateminia et al., 2023).

introduction of suitable filler materials can enhance the selectivity of polyimide films. In a previous study, polyimide membranes were filled with porous CO_2 nanocomposites (Waqas Anjum et al., 2015). The results show a significant increase in the separability and transmissivity of CO_2 over N_2 and CO_2 over CH_4 gas mixtures. Additionally, Xie et al. (2022) have reported on two new series of polyimides, one being benzimidazole functionalized polyimides and the other ionic polyimides. These materials have been developed for the creation of highly selective membranes, further advancing the field of membrane separation technology.

4.3.2 Inorganic membranes

The application of membrane absorption for CO_2 capture has encountered challenges related to membrane wetting (Park et al., 2017). To address this issue, Fu et al. (2023b) undertook hydrophobic modification of Al_2O_3 ceramic membranes by grafting 1H,1H,2H,2H-perfluorodecyl-triethoxysilane. The modification led to a substantial enhancement in the wettability of the ceramic membranes. The angle of contact has increased from an initial 49.8° to 130.9°. When ethanolamine (MEA) was used as the absorbent, a CO_2 mass transfer rate of 46.6 × 10^{-3} mol/(m^2·s) and a separation efficiencies of 98.0% were achieved with the modified hydrophobic ceramic membrane.

4.3.3 Mixed-matrix membranes (MMMs)

Challenges have been identified in relation to MMMs for CO_2 capture. These potential polymer/inorganic phase interface defects should be considered, as well as issues such as particle agglomeration, sedimentation and poor dispersion, which can adversely affect membrane selectivity. Carbon molecular sieves (CMS) membranes possess a rigid pore structure with a bimodal porosity structure (Sanyal et al., 2020; Wang et al., 2023c). Compared to polymeric membranes, they offer superior gas separation efficiency and chemical and thermal stability (Cheng et al., 2014; Dasgupta et al., 2022). A study demonstrated an approach to enhance the efficiency of mixed-matrix CMS membranes by optimising the filler design and incorporating a hierarchical zeolite 5A filler into the membrane (Li et al., 2019)

This section discusses the use of MOF membranes for capturing CO_2, with a focus on strategies for improving their microstructural performance. Unfortunately, defects are often present in MMMs due to their unique properties, and can have a negative impact on separation efficiency (resulting in lower selectivity or reduced durability). Typically, defects arise from the phase interface (Gkotsis et al., 2023). One potential solution is to decorate MOFs with functional groups. The interplay between the MOF and the matrix can be enhanced by decorating MOFs with specific groups (Nik et al., 2012; Waqas Anjum et al., 2015). Using anodic electrodeposition, Yao et al. (2023a) incorporated different types of MOFs into graphene oxide (GO) nanochannels *in situ*. The objective was to develop a new layer-by-layer structure that is confined by GO layers This led to the formation of membranes with a broader range of pore sizes and a substantial increase in both elastic modulus and hardness. These membranes showed high CO_2 capture performance and selective efficiency, providing a viable approach for the fabrication of mechanically robust and functional MOFs suitable for real-world applications.

4.4 Emerging carbon capture technologies

4.4.1 Chemical looping combustion

Solid oxygen carriers, including metal oxides, are used in CLC technology to help transport oxygen from air to fuel; thus, enabling combustion without direct interaction between the fuel and air. This process leads to the internal separation of CO_2 during combustion (Liu et al., 2022b). In Fig. 8, it shows the oxygen transport pathway of oxygen carrier during CLC. Oxide ions (O^{2-}) migrate to the oxygen carrier's surface, where they react with the fuel, resulting in the production of H_2O and CO_2 due to energy excitation. As a result, a chemical potential gradient is created inside the oxygen carrier as well as on its surface, which causes an increase in the migration of O^{2-} ions to the surface. Simultaneously, electrons (e^-) relocate to the particle's center to maintain local charge balance. To supplement the oxygen vacancy created during the reduction process, when the particles of the reduced oxygen carrier are exposed to the air, electrons move from their interior to the surface and react with O_2 to produce an O^{2-} ligand. This action renews oxygen carrier oxidation.

Creating appropriate oxygen carriers with ideal characteristics, such as high oxygen transport capacity, reactivity, and stability, is the primary obstacle to scaling up the CLC process. Natural ores have been widely used as low cost and high availability oxygen carriers for CLC. The primary natural ore oxygen carriers under investigation for CLC include calcium sulfate, manganese ores such as Colormax, Tinforss and Elkem, and iron ores such as Ilmenite, Hematite and Malmbergret. Their CO_2 capture efficiencies are shown in Table 5.

Ilmenite is a naturally occurring mineral that has been used in the CLC process. Consists primarily of iron and titanium oxide ($FeTiO_3$) (Leion et al., 2009; Azis et al., 2010). Ilmenite has a high oxygen transfer capacity of 5% (0.05 kg/kg) (Khakpoor et al., 2019). However, the loss of oxygen transport capacity (OTC) and reactivity after extended redox cycles brought on by the iron's separation from titanium oxide is a major drawback of utilizing ilmenite (Chen et al., 2017; Keller et al., 2019).

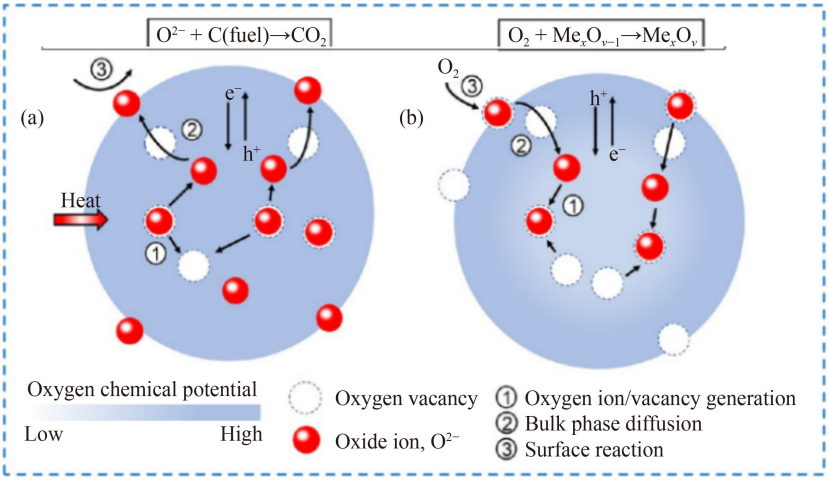

Fig. 8 Oxygen transfer mechanism of the oxygen carrier during the (a) reduction process and (b) the oxidization process. Copyright 2022, Elsevier (Liu et al., 2022b).

Therefore, to improve the reactivity and stability of ilmenite, small adjustments such the inclusion of alkaline earth metals are required.

Fe_2O_3 is the main component of hematite, along with alumina and silica as impurities. Because of its economical and ecologically beneficial character, this oxygen carrier (OC) shows great promise for CLC. However, hematite has demonstrated less reaction stability than ilmenite. Due to improvements in porosity in the OC, certain samples have shown greater reactivity with an increasing number of cycles (Xiao et al., 2010). Hematite and other iron ores often have poor OTC and thermodynamic constraints, particularly when reducing agent CH_4 is used (Gu et al., 2011).

Because manganese ores are more readily available, less expensive, and have a greater OTC as iron ore, they are also thought to be appropriate oxygen carriers. They typically consist of 30%–60% manganese oxide and various impurities, including iron, alumina, and silica, that are important in improving the OC's chemical and physical characteristics (Sundqvist et al., 2015). Manganese ores resist sintering, although attrition is the primary issue when using them as oxygen carriers. The process of attrition is the result of micropores growing into macropores, which weakens the structure (Schmitz et al., 2016). Therefore, in order to enhance the physical structure of manganese ores and mitigate the negative impacts of attrition, it is recommended to use an additional metal as a support, such as calcium and iron (Xu et al., 2016; Liu et al., 2020b).

In the CLC process, copper ores show promise as oxygen carriers. These materials are excellent choices for organic compounds because of their high OTC concentration, rapid reaction rate, and lack of thermodynamic limitations. Copper ores are the priciest of all the ores ($1.60/kg) (Tian et al., 2015). These ore sources vary in their copper composition; generally speaking, a higher CuO content results in a higher fuel conversion rate of about 95% (Zhao et al., 2014). On the other hand, lower copper concentrations in ores lead to lower combustion efficiency (Tian et al., 2013). However, the relatively low melting point of these high-copper ores poses an

Table 5 CO_2 capture efficiency by oxygen carriers in CLC

Oxygen carrier	Fuel	CO_2 capture efficiency	Refs.
$CaSO_4$	Coal	N.A.	Andrus et al. (2010)
NiO	CH_4/natural gas	94.5%–99%	Linderholm et al. (2008); Linderholm et al. (2009); Berguerand & Lyngfelt (2008)
ilmenite	Coal, petroleum coke	68%–96%	Berguerand & Lyngfelt (2009); Lyngfelt (2011)
CuO	CH_4	~100%	Adánez et al. (2006); de Diego et al. (2007)
NiO	Coal biomass	95%	Shen et al. (2009b)
Fe_2O_3		76%–87%	Shen et al. (2009a)
Fe_2O_3	Coal syngas	>97%	Fan & Li (2010)
Fe_2O_3		99.80%	Sridhar et al. (2012)
NiO	Syngas	~95%	Kolbitsch et al. (2009); Kolbitsch et al. (2010)
Ilmenite		~65%	Pröll et al. (2009a); Pröll et al. (2009b)

important concern for particle agglomeration and sintering in high-temperature processes such as CLC. Long-term CLC cycles are adversely affected by this in terms of the stability and reactivity of copper ores (Tian et al., 2013; Zhao et al., 2014). Thus, using ores with less copper concentration might help avoid agglomeration, but greater OC loadings are needed (Wen et al., 2012).

4.4.2 Electrochemical capture

In recent years, the electrochemical capture technology has become increasingly popular as a research area in the quest for CO_2 emission reduction and carbon neutrality, primarily due to its capacity for energy efficiency, adaptability, and environmental sustainability. To achieve CO_2 uptake and release, electrochemical carbon sequestration typically relies on redox capture media or pH swing. However, practical use is hampered by the low capture rate (typically below 10 mA/cm^2) and sensitivity to oxygen in most CO_2 sources. In this section, we introduce two innovative electrochemical capture techniques: 1) Combining O_2/H_2O electrolysis with Porous Solid Electrolyte (PSE) Reactor; 2) Novel electrochemical CO_2 capture based on bionic electrochemical protons.

Continuous and modular CO_2 capture with a unique design from various sources has been reported by Hao-Tian Wang's group, coupling O_2/H_2O Porous Solid Electrolyte (PSE) Reactor Electrolysis (Xia et al., 2019). The reactor demonstrates impressive remarkable Faraday efficiency (> 90%), carbon capture rates (440 mA/cm^2, 0.137 mmol CO_2/(min·cm^2) or 86.7 kg CO_2/(d·m^2)), outstanding simulated flue-gas decarbonization efficiency (> 98%), and remarkably low energy consumption (approximately ~150 kJ/mol CO_2). Figure 9(a) illustrates the solid electrolyte reactor comprises an oxygen reduction reaction (ORR) cathode ($O_2 + 2H_2O + 4e^- = 4OH^-$) and an oxygen evolution reaction (OER) anode ($2H_2O = O_2 + 4H^+ + 4e^-$), separated by a solid-electrolyte layer that is permeable but compact to facilitate efficient ionic conduction (Zhu et al., 2023). The system neither consumes nor produces any chemicals through this OER/ORR redox electrolysis, in order to preserve stoichiometric equilibrium, the anode's created material can be returned to the cathode. An anion exchange membranes (AEM) and a cation exchange membranes (CEM) are positioned between the electrodes and the PSE layer to prevent flooding. While an active ORR catalyst (e.g., commercial Pt/C) reduces O_2 molecules at the cathode, significant hydroxide (OH^-) is produced at the interface of the catalyst and membrane. These ions swiftly combine with the stream's CO_2 molecules to produce bicarbonate or carbonate (Fig. 9(b)). Subsequently, powered by the magnetic field, through AEM, these carbonate ions go into PSE. In the meantime, on the anode side, the water has become oxidized. An equivalent amount of O_2 is produced and protons (H^+) are released, which allow charge equalization to pass through the CEM and into the middle layer. The combination of these carbonate and proton ions yields CO_2 gas, which may be collected and discharged in its purest form by water flow circulation across the PSE layer (Fig. 9(c)).

In comparison to previously reported electrochemical carbon capture methods, this approach offers advantages such as high capture rate, high energy efficiency, insensitivity to oxygen, ease of scalability, and adaptability. Ultimately, their PSE device makes it possible to capture and release CO_2 continuously, synchronously, and integratedly, simplifying the carbon capture system for a wide range of field applications (Fig. 9(d)).

Academician Xie Heping's team discovered that by incorporating the highly efficient proton-coupled electron transfer reaction (PCET) in living organisms into membrane electrolysis and integrating it with the CO_2 absorption and desorption process (Xie et al., 2020), it is possible to achieve CO_2 capture at room temperature, atmospheric pressure, and with low energy use. This innovation results in a new electrochemical CO_2 capture technology based on biomimetic electrochemical plasmonic carriers, effectively addressing the technological challenges associated with electrolysis in electrochemical CO_2 capture processes. The technology achieved a remarkable 94.3% Faraday efficiency and a 97.5% CO_2 desorption rate. The power consumption for CO_2 desorption was approximately 9.8 kJ/mol, marking a significant advancement toward achieving low energy consumption in the CO_2 capture process (Li et al., 2022c). There are other achievements for electrochemical carbon dioxide capture technology as shown in Table 6.

4.4.3 Direct air capture

Differing from traditional CO_2 capture methods, DAC represents a prominent "negative emission" technology capable of directly removing CO_2 from the atmosphere. It is currently being widely explored as a means of achieving negative carbon emissions (Qiu et al., 2022). As depicted in Fig. 10, numerous DAC companies have emerged worldwide in recent years, employing various technical approaches for CO_2 capture. For commercial applications, DAC can be broadly categorized into two major types: liquid DAC and solid DAC. Table 7 compares two different DAC technologies.

4.4.3.1 Liquid DAC

The most recent benchmark sorbents utilized in DAC systems feature the use of aqueous solutions containing potassium hydroxide or sodium hydroxide (Bistline and Blanford, 2021). However, many studies have focused on

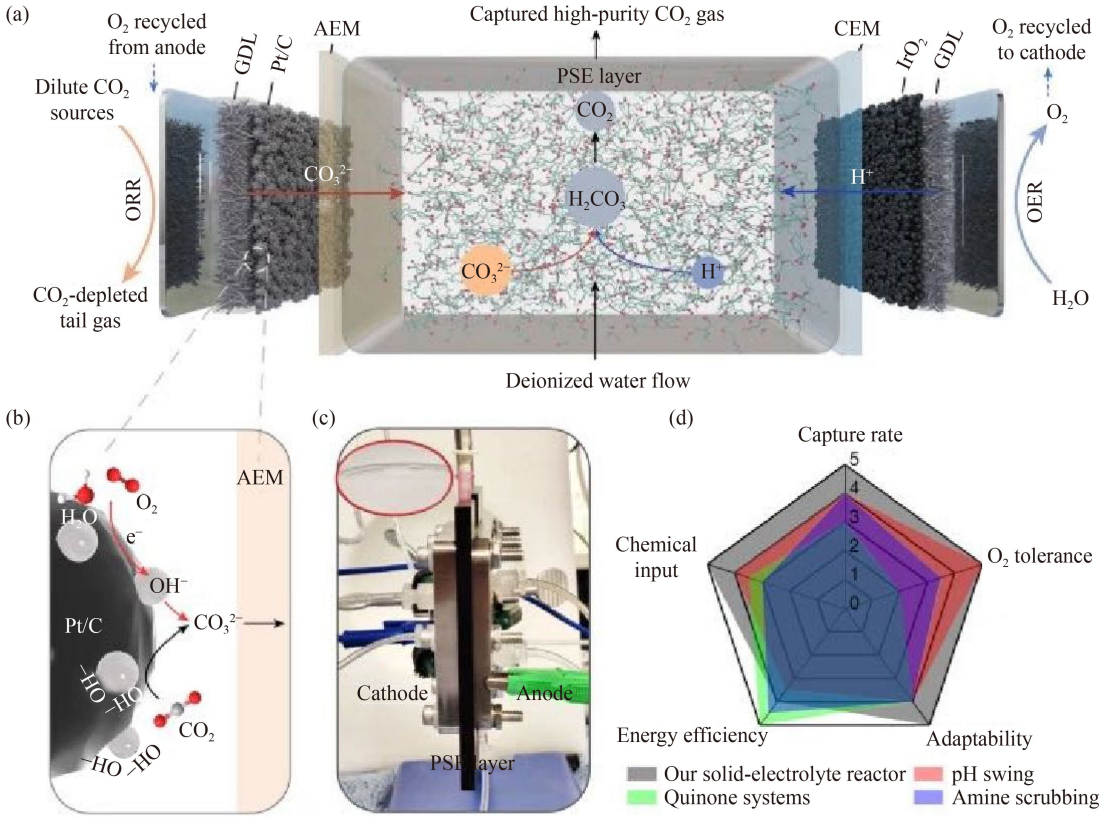

Fig. 9 Solid electrolyte reactor design for carbon capture from different CO_2 sources: (a) Schematic of the solid-electrolyte reactor for carbon capture; (b)Schematic of the reaction mechanism at the catalyst–membrane interface; (c) Photograph of the solid-electrolyte reactor and captured CO_2 gas (inset) flowing out of the solid-electrolyte layer; (d) A radar plot comparison of different carbon-capture technologies. Copyright 2023, Springer Nature (Zhu et al., 2023).

developing more efficient and cost-effective CO_2 capture systems to overcome the limitations caused by the strong CO_2 binding capacity of alkaline hydroxides (Chatterjee & Huang, 2020).

Aqueous amines are commonly used as CO_2 absorbents because of their high absorption capacity, low volatility, large CO_2 uptake capacity, high chemical stability and low cost. Amine scrubbing with alkanol amines, generally using MEA or DEA, is recognized as the most established and cost effective CO_2 capture technology for industrial processes, and has been shown to be effective for larger sources of emissions (Galán-Martín et al., 2021).

ILs are a promising option for CO_2 absorption because of their favorable properties, including low regenerative heat requirement, low volatility, minimal degradability and good stability (Hospital-Benito et al., 2023). Nonetheless, ILs face certain challenges, such as their relatively high cost compared to amines and their greater affinity for binding to H_2O over CO_2 in ambient air. These limitations constrain the broader application of ILs in DAC field.

The application of phase change absorbers in DAC of CO_2 is still in its early development, leaving ample room for advancements. There is a need to enhance the CO_2 capture capacity, improve the recyclability of the absorbers, and reduce their overall cost. Currently, the phase change absorbers used in DAC predominantly utilize guanidine compounds and amino acid solvents (Brethomé et al., 2018; Meckling and Biber, 2021).

4.4.3.2 Solid DAC

The main solid sorbents used for direct air CO_2 capture are carbon-based materials, zeolites, MOFs, and alkali metals (McQueen et al., 2020). Carbon-based materials are commonly used as sorbents for CO_2 extraction due to their high surface area and cost effectiveness. However, carbon materials have some drawbacks, such as poor adsorption capacity at low partial pressures of CO_2 and poor selectivity for N_2 and moisture, which also affect their performance in capturing CO_2 from air (Realmonte et al., 2019). Zeolites can react with CO_2 due to the influence of alkali cations on their surface and perform better than carbon-based sorbents at low CO_2 partial pressures. MOFs are a novel class of nanocrystalline porous materials composed of transition metal nodes and bridging organic ligands. Due to the special properties of their chemical components and void structure, they have a broad application in direct air capture. Compared to other types of sorbents, alkali metals offer superior adsorption

Table 6 Description of electrochemical CO_2 capture technologies

Capture method	Feed	Energy consumption (kJ/mol CO_2)	Current efficiency	Product	Current density (mA/cm^2)	Ref.
Fuel-cell	Air + H_2	350	23%	CO_2(g)	0.5	Eisaman et al. (2009)
Electrolysis	Air	290–350 (kJ/mol KOH)	>95%	CO_2(g) + H_2(g)	100	Stucki et al. (1995)
Electrolysis	Air + mined $CaCO_3$(s)	266	–	CO_2(g) + H_2(g)	–	Rau (2008)
Electrolysis	Synthetic flue gas + cement kiln dust	4634–1276 (kJ/mol $CaCO_3$)	60%–90%	$CaCO_3$(s)	100–200	Youn et al. (2019)
Bipolar membrane electrodialysis (BPMED)	$NaHCO_3$/NaOH	160–500	65%–80%	CO_2(g)	5–20	Iizuka et al. (2012)
BPMED	$KHCO_3$/K_2CO_3	100–450	95% ($KHCO_3$), 50% (K_2CO_3)	CO_2(g)	5–100	Eisaman et al. (2011a)
BPMED	$KHCO_3$	200–500	70%–90%	CO_2(g)	22–139	Eisaman et al. (2011b)
BPMED	Artificial seawater	250–400	<70%	CO_2(g)	1–3	Eisaman et al. (2012)
BPMED	Artificial seawater + NaCl	390–640	60%–95%	CO_2(g) or $CaCO_3$(s)	100	de Lannoy et al. (2018)
BPMED	Artificial seawater + CO_2(g)	1080–2880 (kJ/mol $CaCO_3$)	–	$CaCO_3$(s)	–	Zhao et al. (2020)
EDI + BPMED	Synthetic flue gas	–	–	CO_2(g)	2–16	Datta et al. (2013)
EDI + electrolysis	Natural seawater	2775–6940	–	CO_2(g)/H_2(g)	20–61	Dimascio et al. (2010); Willauer et al. (2017); Willauer et al. (2014); Willauer et al. (2011)
MCDI	Synthetic flue gas	40–50	60%–80%	CO_2(g)	0.02–0.06	Legrand et al. (2020)
Redox-active carriers + pH-swing	Synthetic flue gas	106	90%	CO_2(g)	18	Huang et al. (2019)
Redox-active carriers	Synthetic flue gas	56	>75%	CO_2(g)	0.5	Liu et al. (2020c)

performance and better selectivity in low CO_2 and water vapor conditions. Solid amine is a promising CO_2 adsorbent for capturing CO_2 from the air. Amines have high reactivity and selectivity with CO_2, and they are not volatile or corrosive when loaded into porous materials. Researchers are currently working on enhancing the performance of amine-based solid adsorbents by synthesising them, screening appropriate amines, modifying them, and optimizing supports.

In a study conducted by (Kumar et al., 2023), an efficient adsorbent for DAC was developed using amine-impregnated octahedral zeolite (FAU) to capture 400 ppm of CO_2 in simulated air. Six different types of amines were employed for modification. The adsorption capacity of FAU samples impregnated with PEI was enhanced (1.54 mmol/g) under humid conditions. Both PEI and DETA impregnated FAU zeolites demonstrated excellent regeneration stability over ten adsorption cycles.

In summary, DAC technology is currently in its early stages, and there is significant potential for improvement in the development of sorbents and processing technology. Future research should focus on the development of new and effective CO_2 capture agents, as well as further improvements in the performance of existing sorbents. This pursuit will contribute to improving the overall capability of CO_2 capture methods and advancing their effectiveness in addressing environmental challenges.

5 Remarks and perspectives

Carbon capture technology has made significant progress in recent decades, but economically attractive commercialization has yet to be achieved. The primary challenges ahead revolve around the creation of new materials with enhanced CO_2 capture capacity and reduced energy consumption, as well as the implementation of streamlined processes to decrease costs and equipment space requirements. In this context, we believe that future research should focus on data-driven material design, comprehensive process simulation, and the simultaneous removal of CO_2 and gaseous pollutants. These approaches hold great promise for addressing the evolving demands of CO_2 capture technology.

5.1 Design of data-driven materials for carbon capture

The traditional development of capture materials is typically based on intensive experimental screening, which is inefficient and costly. However, subtle changes in the composition and structural properties of capture materials, whether they are absorbents, sorbents, or membranes, can significantly impact their capture performance. This poses a formidable challenge to traditional experimental screening (Yang et al., 2023). Machine learning (ML) is considered a promising new

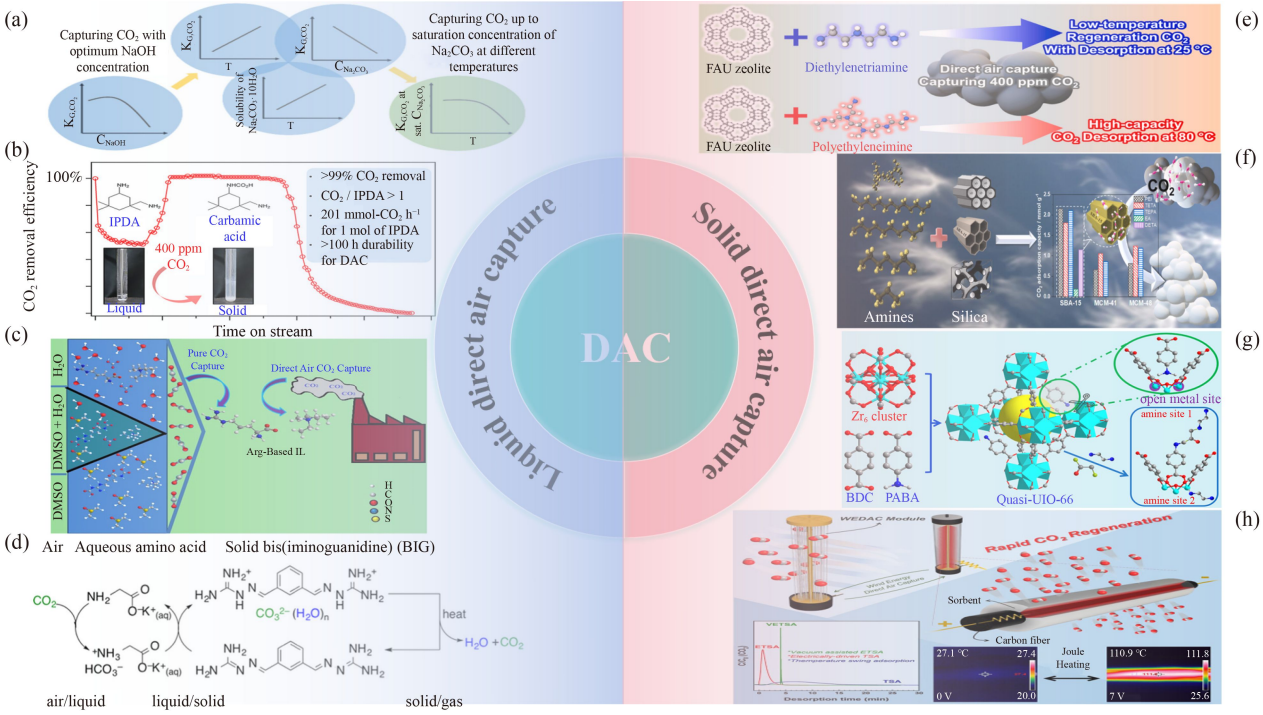

Fig. 10 Different technologies for DAC. (a) NaOH aqueous solution absorbent. Copyright 2023, American Chemical Society (Ghaffari et al., 2023). (b) Liquid amine absorbent. Copyright 2022, American Chemical Society (Kikkawa et al., 2022). (c) ILs absorbent. Copyright 2024, American Chemical Society (Bera et al., 2024). (d) Aqueous amino acids absorbent. Copyright 2019, American Chemical Society (Custelcean et al., 2019). (e) Amine-functionalized FAU zeolites adsorbent. Copyright 2023, Elsevier (Kumar et al., 2023). (f) Amine-functionalized mesoporous silica adsorbent. Copyright 2022, Elsevier (Kumar et al., 2022). (g) Amine-functionalized MOF adsorbent. Copyright 2023, American Chemical Society (Dong et al., 2023). (h) Amine-functionalized carbon fibers adsorbent. Copyright 2023, Elsevier (Lee et al., 2023).

Table 7 A technology comparison of different technologies for DAC

Adsorption type	Adsorbent	Adsorption capacity/efficiency	Adsorption conditions	Desorption conditions	Regenerative energy consumption	Ref.
Solid DAC						
Zeolites+amine	PEI50/FAU300	1.54 mmol/g	0.04%CO_2/N_2, 25 °C, 100 mL/min, 4 h, 60%RH	80 °C, 80% N_2/ 20% O_2, 100 mL/min, 30 min		Kumar et al. (2023)
MOF+amine	2-UIO-EDA	0.44 mmol/g	0.04%CO_2/Ar, 25 °C, 10 mL/min, 30%RH			Dong et al. (2023)
MOF+SIL	Ni-MOF/IL-3	2.54 mmol/g	0.04%CO_2/He, 25 °C, 10%RH	90 °C		Qiu et al. (2023)
Silica+amine	PEI50/SBA-15	2.16 mmol/g	0.04%CO_2/He, 25 °C, 100 mL/min, 60%RH	80 °C, wet He, 30 mL/min, 30 min		Kumar et al. (2022)
Fibers+amine	PF-15-DETA	0.8 mmol/g	0.04%CO_2, 25 °C, 50%RH	70 °C N_2		Sekizkardes et al. (2023)
Liquid DAC						
Amino Acids	Potassium glycinate, potassium sarcosinate	0.12–0.20 mol/mol amine	0.04%CO_2, 25 °C	60–120 °C	8.2 GJ/ ton CO_2	Custelcean et al. (2019)
Liquid amine	IPDA	99%, 201 mmol/h for 1 mol of amine	0.04%CO_2/N_2, 25 °C	60 °C N_2		Kikkawa et al. (2022)

paradigm for material development because it can quantitatively analyze the property–performance relationships of different capture materials. Several researchers have designed specific molecular or material structures with high CO_2 capture capacity through ML analysis of publicly available databases (Zhang et al., 2021b; Chen et al., 2023b).

A persistent challenge in this research field is the

scarcity of extensive and reliable data, which hinders the effectiveness of ML applications. Although the potential of machine learning for CCUS has been acknowledged, many studies lack substantial experimental data and are often limited to a few hundred data points (Yan et al., 2021). This is significantly smaller compared to the vast data sets generated from theoretical computations. For instance, various strong CO_2 binding sites were identified by Boyd et al. (2019) through data mining over 300000 MOFs computational screening libraries, resulting in the development of a novel adsorption material, Al-PyrMOF. Obviously, finding an appropriate high-performance material in such a large database through traditional experimental methods is challenging. Therefore, the employment of data-driven approaches to design special structures is crucial for the development of novel materials with superior CO_2 capture performances.

5.2 Simulation and optimization of the capture process

Recent studies have demonstrated that the performance of capture materials is intimately linked to the process in which they are deployed (Rajendran et al., 2023). Any meaningful screening should thus consider the complexity of the process. Process simulation and optimization can provide engineers with more accurate and reliable data and decision support, helping optimize process design, product performance, and production cost reduction. For instance, a rigorously validated process simulation method for operational optimization of MDEA, PZ, and tetramethylene sulfone blends on an industrial scale was proposed by Zhan et al. (2023). Most process models presently prioritize the simulation and optimization of absorption, adsorption, and membrane processes. However, process models for emerging capture technologies such as CLC, electrochemical capture, and DAC urgently need development.

On the other hand, current process simulations often concentrate on individual performance indicators of capture materials in large-scale applications. The prediction of crucial criteria, including scalability and stability, becomes imperative. An exemplary instance is the recent achievement of Calgary Framework-20 (CALF-20) (Lin et al., 2021), possibly the inaugural MOF scaled up for industrial carbon capture. CALF-20s CO_2/N_2 separation capability is not remarkable, but it meets all criteria. However, none of the simulation studies identified this MOF as a potential candidate. Thus, future process simulation and optimization should prioritize comprehensive performance rather than individual indicators.

5.3 Environmental impact and monitoring

Sustainability issues should be considered before large-scale deployment of CO_2 capture technologies, notably environmental impacts. Currently, most large-scale carbon capture uses amine solvent absorption, which can emit secondary pollutants such as volatile organic compounds (VOCs) due to amine degradation. Through complex atmospheric chemical reactions, these VOCs facilitate the formation of ozone and fine particulate ($PM_{2.5}$), exacerbating environmental pollution. Accurate analysis of environmental impacts helps to assess the applicability of carbon capture technologies. In general, life cycle assessment can be used to analyze these environmental impacts of carbon capture, such as $PM_{2.5}$ emissions, ecological toxicity, photochemical pollution (Cruz et al., 2021; Antzaras et al., 2023; Xie et al., 2023). The accuracy of life cycle assessment outcomes is fundamentally dependent on the precision of input data. However, obtaining high-precision emission data remains a challenge, especially for secondary pollutants. It is noteworthy that monitoring technology of secondary pollutants in the carbon capture field is still in emerging stage, with some key challenges requiring attention and improvement. Environmental factors such as humidity may interfere with sensor readings, leading to errors. High sensitivity methods should be used to demonstrate secondary pollutants less than 100 ppb (Rochelle, 2024). Therefore, there is an urgent need to develop customized secondary pollutants sensors, providing accurate input data for the environmental impact of carbon capture technology.

5.4 Simultaneous control of CO_2 and gaseous pollutants

The tradeoff between the CO_2 reduction and the air pollution prevention should be emphasized. In general, the combustion of fossil fuels generates not only CO_2 but also gaseous pollutants such as SO_2 and NO_x. Typically, SO_2 and NO_x are commonly removed by the wet scrubbing and the selected catalytic reduction, respectively. However, the presence of trace quantities of SO_2 or NO_x can result in the deactivation of the amine-based solvent for CO_2 capture, consequently diminishing their cyclic CO_2 capture capacity. Therefore, the simultaneous control of CO_2 and gaseous pollutants faces challenges. Novel solvents and their corresponding processes should be developed. Noting that all of the CO_2, SO_2, and NO_x are acidic gas, the wet scrubbing process can be an option for their simultaneous control. Due to the low solubility of NO in water, increasing the NO solubility or converting NO into NO_2 with a high solubility is important. For example, as reported, a urea-$NaClO_2$-$Ca(OH)_2$ mixed solvent was proposed for their simultaneous removal from flue gas (Lu et al., 2024). Among them, $NaClO_2$ served to oxidize NO into NO_2, and urea efficiently captured SO_2 and NO_x. Concurrently, $Ca(OH)_2$ was used to capture CO_2, facilitating the simultaneous control of CO_2, SO_2, and NO_x. Additionally, an alternative approach was proposed to

convert the CO_2, SO_2, and NO_x into chemical raw materials or products rather than the conventional abatement process. For instance, aqueous ammonia absorbents are considered capable of absorbing CO_2, SO_2 and NO_x, converting them into ammonium bicarbonate or ammonium sulfate (Qi and Wang, 2017). This process not only prevents deactivation of CO_2 capture materials but also enhances its economic feasibility. Therefore, it is urgent to develop novel processes for the simultaneous control of CO_2 and gaseous pollutants to cut down the overall cost for the CO_2 and gaseous pollutant treatment.

5.5 Assessment of technical and economic feasibility

The cost of CO_2 capture is influenced by the capture capacity of demonstrations. The power, oil and gas industries have a substantial number of carbon capture projects, and most of them have capture capacity exceeding one million tons. In relative terms, the capture costs are higher in the steel and other industries with the smaller capture scale (NEA, 2023). This can be attributed to larger scale carbon capture effectively sharing the initial equipment cost and making it easier to achieve the recycling and utilization of multiple energy sources. In the future, as technology maturity improves and economies of scale come into play, opportunities for low-cost or investment-worthy CCUS projects are expected to increase. Additionally, the substantial economic benefits derived from the utilization of CO_2 in chemical, biological, and geological processes can enhance the economic feasibility of CCUS technologies. For instance, the geological utilization of CO_2 can generate revenue while achieving carbon emission reductions. Furthermore, converting CO_2 into high-value-added chemical products can also offset the costs of carbon capture.

Due to the development of carbon capture technologies, the focus will shift from technical demonstrations and testing to industrial implementation in the coming decades. It is reasonable to consider choosing technologies with higher maturity and lower implementation costs to avoid pitfalls such as over budget and schedule associated with the megaprojects (Flyvbjerg, 2014). Some CO_2 capture technologies are commercially available now, while others are still in development, and this further contributes to the large range in costs. Currently, absorption technologies represent the largest demonstrated method for CO_2 capture. However, high energy consumption, solvent volatilization and degradation, and equipment corrosion render it expensive. The cost ranged from 15–25 \$/t CO_2 for industrial processes producing "pure" or highly concentrated CO_2 streams (such as ethanol production or natural gas processing) to 40–120 \$/t CO_2 for processes with "dilute" gas streams, such as cement production and power generation (Baylin-Stern and Berghout, 2021). Compared to absorption, other energy-efficient carbon capture technologies, such as adsorption and membrane, are still under the bench- or pilot-scales. Some emerging carbon capture technologies such as CLC and electrochemical capture are only laboratory developments. These technologies generally exhibit lower energy consumption, rendering them more economically feasible in theory. However, the lack of scale-up demonstrations means that the actual costs of carbon capture remain to be further assessed.

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Conflict of Interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acronym list

AEM	Anion exchange membranes
AMP	Amphetamine
BPMED	Bipolar membrane electrodialysis
CCUS	Carbon capture, utilisation and storage
CCS	Carbon capture and storage
CLC	Chemical looping combustion
CMS	Carbon molecular sieves
DAC	Direct air capture
DEEA	Diethylethanolamine
DEA	Ethylene glycol amine
EOR	Enhance oil recovery
GO	Graphene oxide
IPCC	The Intergovernmental Panel on Climate Change
IL	Ionic liquid
MEA	monoethanolamine
MDEA	Methyldiethanolamine
MMEA	Methylethanolamin
MMM	Mixed matrix membrane

ML	Mechanical learning
MOF	Metal-organic framework
NO_x	Nitrogen oxide
OC	Oxygen carrier
OER	Oxygen evolution reaction
OTC	Oxygen transport capacity
ORR	Oxygen reduction reaction
PA	Polyamide
PEI	Polyvinylamine
PI	Polyimide
PSE	Porous Solid Electrolyte
PCET	Proton-coupled electron transfer
PZ	Piperazine
TETA	Triethylenetetramine
TEPA	Tetraethylenepentamine
WMO	The World Meteorological Organization
WoS	Web of Science

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