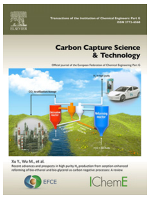
Carbon Capture Science & Technology 8 (2023) 100125

Contents lists available at ScienceDirect

Carbon Capture Science & Technology

journal homepage: www.elsevier.com/locate/ccst



Review

Assessing absorption-based CO_2 capture: Research progress and techno-economic assessment overview

Usman Khan[a], Chukwuma C. Ogbaga[b], Okon-Akan Omolabake Abiodun[c,d], Adekunle A. Adeleke[e], Peter P. Ikubanni[f], Patrick U. Okoye[g], Jude A. Okolie[h,*]

[a] Faculty of Chemical Engineering and Technology, Cracow University of Technology, Warszawska 24, Kraków 31-155, Poland
[b] Independent Researcher, Middlesbrough, North Yorkshire, United Kingdom
[c] Forestry Research Institute of Nigeria, Nigeria
[d] Wood and paper technology department, Federal College of Forestry, Ibadan, Nigeria
[e] Department of Mechanical Engineering, Nile University of Nigeria, Abuja 900001, Nigeria
[f] Mechanical Engineering Department, Landmark University, Omu Aran 251103, Nigeria
[g] Institutio de Energias Renovables, Universidad Nacional Autónoma de México, Temixco, Mexico
[h] Gallogly College of Engineering, University of Oklahoma, Norman United States

ARTICLE INFO

Keywords:
Carbon capture
Anthropogenic emission
Absorption
Adsorption
Techno-economic analysis
Lifecycle assessment

ABSTRACT

Rapid industrial developments and rising population are mounting concerns, leading to increased greenhouse gas (GHG) emissions and resultant climate change. Therefore, to curb such drastic trends, it is necessary to adopt and develop a sustainable environment. Among the most effective ways to lower GHG emissions is carbon capture. Absorption is one of the most mature methods of reducing CO_2 due to its high processing capacity, excellent adaptability, and reliability. This study aims to evaluate the most recent advancements in various CO_2 capture techniques, with an emphasis on absorption technology. The techno-economic analyses of absorption-based CO_2 capture processes were meticulously discussed. These include studies on solvent screening as well as techno-economic analysis methods. Economic estimators such as the payback period, rate of return and net present value are discussed. The research progress in absorption-based capture compared to other separation methods, is elucidated. Advances in the applications of various absorption solvents including aqueous, phase change solvents and deep eutectic solvents are presented. Finally, key recommendations are provided to tackle the challenges for efficient utilization of the absorption technique.

1. Introduction

The concentration of greenhouse gases (GHGs), including CO_2 has increased to unprecedented levels in the past few years, leading to critical pollution and global warming worldwide (Singh and Dhar, 2019). These unusual climatic changes, such as rising sea levels, unpredictable rainfall, storms, dry spells, and other catastrophic phenomena, collectively referred to as global warming, are primarily caused by excessive GHG emissions. The planetary temperature has risen by 0.85 °C from 1880 to 2012 and is ojected to increase by 1.4–5.8 °C by the end of the 21st century (De Silva et al., 2015). CO_2 emissions have risen to 32% since the industrial revolution, increasing from around 280 to 400 parts per million (Singh and Dhar, 2019). The dominant drivers for CO_2 emissions are the irrational use of fossil fuels and shifting land use patterns (Goldemberg, 2007). Higher atmospheric CO_2 concentrations not only contribute to global warming, but they also lead to about 30% increase in ocean acidity, which has a detrimental effect on biodiversity (Farrelly et al., 2013).

It is worth mentioning that the world's energy usage in 2018 increased by 2.3% compared to 2017, driven by economic expansion, technological innovation, and rising energy demand (Zhang et al., 2020). Moreover, coal-fired power plants are the largest contributors to CO_2 emissions, accounting for 30% of those associated with energy use (Zhang et al., 2020). Significant efforts have been made to reduce CO_2 emissions by transitioning from coal to gas power plants and increasing the use of renewable energy sources. However, renewable energy sources alone cannot meet the rising energy demand, leading to increased consumption of fossil fuels. For example, natural gas usage increased by 4.6% (Neagu, 2019). Moreover, CO_2 emissions rose by 1.7% to 33.1 Giga-tons (GT) (Neagu, 2019), highlighting the continued relationship between energy consumption and CO_2 emissions, which are both still rising concurrently. This calls for immediate response to

---

* Corresponding author.
E-mail address: Jude.okolie@ou.edu (J.A. Okolie).

https://doi.org/10.1016/j.ccst.2023.100125
Received 8 May 2023; Received in revised form 11 June 2023; Accepted 13 June 2023

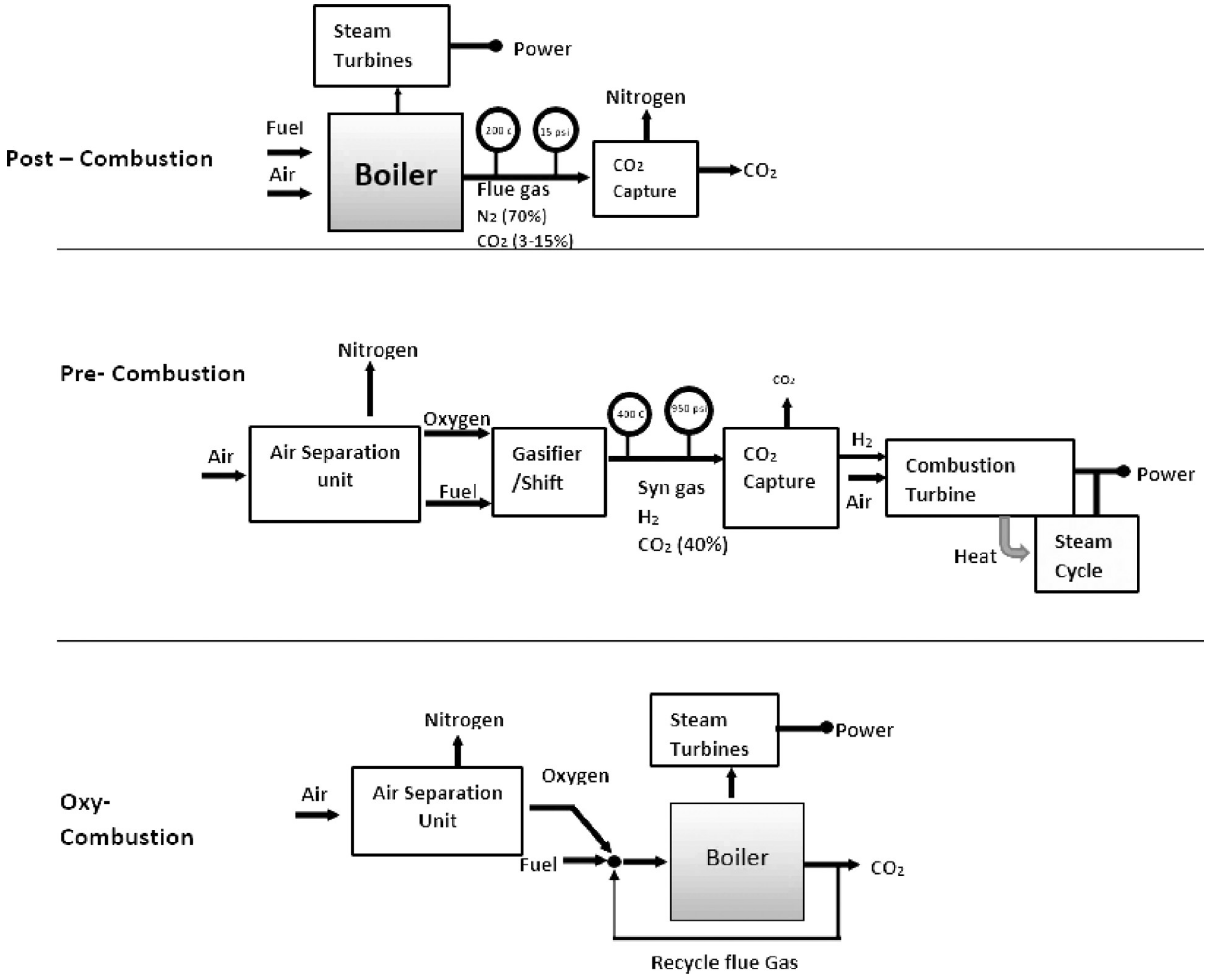


Fig. 1. An overview of different CO_2 capture technologies.

address carbon emission issues among researchers, countries, and policymakers.

The demand for a significant transition to a greener energy system and eco-friendly industrial production techniques is becoming more pressing because of the CO_2 emission challenges. To maintain the average temperature rise to 1.5 °C above pre-industrial levels, CO_2 emissions need to be decreased uniformly in every economic sector, in addition to modification of conventional techniques. Carbon capture, utilization, and storage (CCUS) is a practical technique to lower CO_2 emissions during a transitional period (Farrelly et al., 2013; Zhang et al., 2020). According to International Energy Agency (IEA) report, by 2050, carbon capture and sequestration (CCS) techniques will reduce GHG emissions by about 20% (Yadav and Mondal, 2019). Carbon capture (CC) can be carried out in the following three primary ways, i.e., pre-combustion, oxy-fuel combustion (OFC), and post-combustion as shown in Fig. 1 (Mukherjee et al., 2019). Pre-combustion involves the removal of CO_2 before combustion proceeds. On the contrary, post-combustion CO_2 capture refers to the separation of CO_2 after the combustion process using one of the following methods: cryogenic separation, membrane separation, adsorption, chemical looping combustion, and physical and chemical absorption (Samanta et al., 2012). In the case of oxy-fuel combustion, the flame temperature is lowered by recycling flue gas while only pure oxygen is used for burning purposes. CO_2 and water vapor make up the majority of the flue gas produced at the exhaust(De Mello et al., 2013). Consequently, CO_2 can be readily isolated by condensing water vapor.

Each process presents its advantages and limitations. For instance, the pre-combustion capture benefits from high CO_2 partial pressure and concentrated gas streams, leading to efficient absorption and reduced solvent usage (Mukherjee et al., 2019). However, its main limitation is the need for gasification, adding complexity and cost to the process. Post-combustion capture allows for retrofitting existing plants, making it attractive for immediate emission reduction. Yet, it faces challenges due to low CO_2 partial pressure and the presence of contaminants that may degrade solvents. Oxy-fuel capture simplifies the process by burning fuel in a high-purity oxygen environment, generating a concentrated CO_2 stream that facilitates absorption (Buhre et al., 2005; De Mello et al., 2013). Despite this advantage, the energy-intensive air separation process required for oxy-fuel combustion is a significant drawback.

Absorption is the most preferred method for CO_2 capture due to its versatility and adaptability to various processes, including pre-combustion, post-combustion, and oxy-fuel capture. Absorption's adaptability to various conditions and its maturity level make it the preferred choice for CO_2 capture. Several researchers have studied adsorption and absorption processes for CO_2 capture; however, few have focused on absorption. Mukherjee et al. performed a comprehensive techno-economic analysis of CO_2 capture via activated carbon (Mukherjee et al., 2022). The same authors also presented an excellent review of different activated carbon precursors for CO_2 capture (Mukherjee et al., 2019). Singh and Dhar. study outlined a literature overview of microalgae-based CO_2 capture (Singh and Dhar, 2019). Some researchers explored the

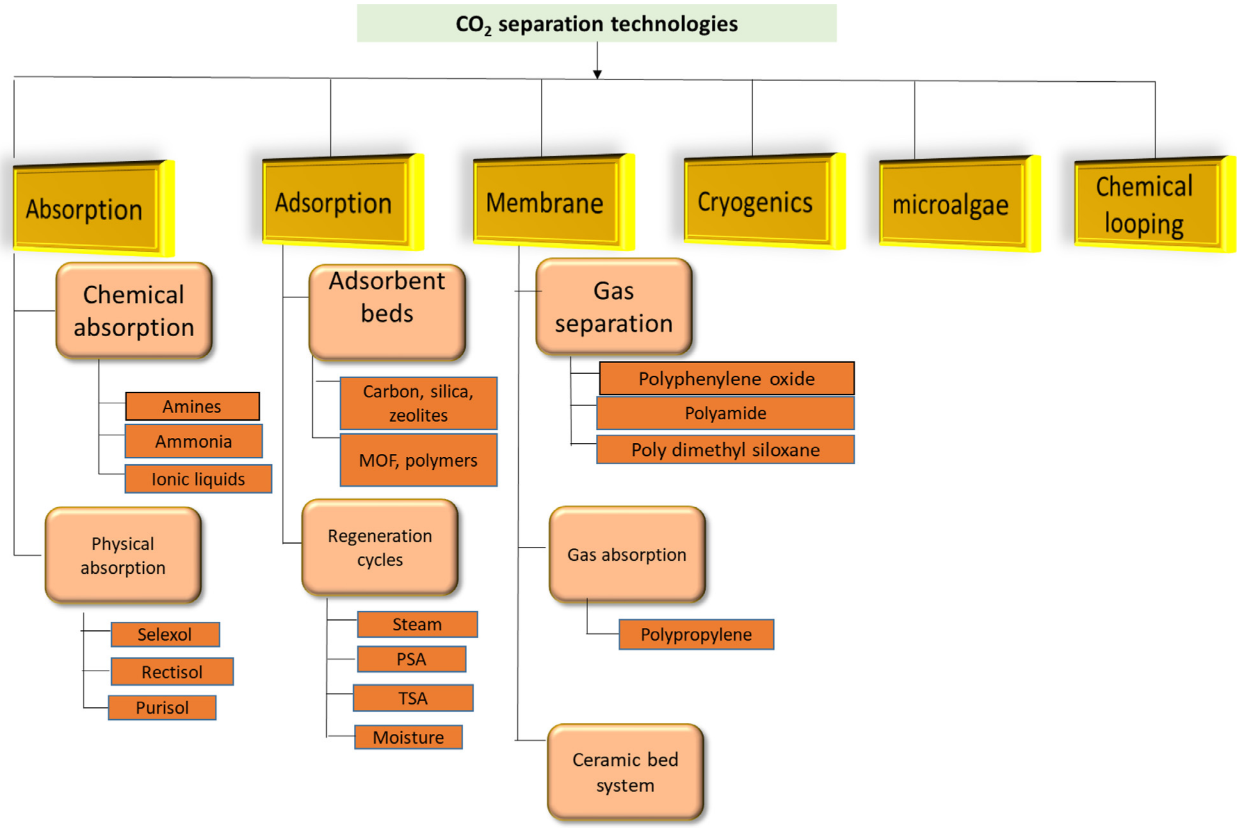


Fig. 2. An overview of CO_2 separation technologies.

environmental impacts of absorption-based CO_2 capture for the treatment of flue gas in a post-combustion plant (Thitakamol et al., 2007). In a recent study, Gambelli et al. reviewed CC and valorization technologies including the absorption methods (Gambelli et al., 2023). A recent study reported recent advances and progress related to the use of catalysts to reduce the energy cost of solvent regeneration during CO_2 absorption (Li et al., 2023). Another study showed that sepiolite (SEP) clay could be used as a promising support material for two metal oxides (Fe_2O_3, CuO) catalysts during CO_2 desorption processes (Zhang et al., 2022). He et al. compared the performance of four new dual-amine blends solvent as energy-efficient CO_2 capture solvents (He et al., 2023). Zhang et al. reported a comprehensive review of the advantages and limitations of phase change solvents as well as non-aqueous solvents for CO_2 capture (Zhang et al., 2019). Despite the widespread preference for absorption-based CO_2 capture, there is a limited body of research discussing its current status and progress, particularly in terms of a detailed techno-economic analysis methodologies. To enhance the adoption and performance of this technology, a comprehensive understanding of its economic feasibility and environmental impact is essential. This study presents an overview of the CC techniques, with more emphasis on absorption technology. The development of CO_2 capture by absorption, research progress and challenges in solvent selections and the procedure for carrying out the economic assessment are critically evaluated. The findings reported herein highlight the need for further investigation and interdisciplinary collaboration to advance the methodologies for assessing the cost-effectiveness of absorption-based CO_2 capture systems.

2. Overview of CO_2 capture techniques

Fig. 1 shows key CO_2 capture technologies while Fig. 2 presents different separation processes. The main CO_2 separation processes include absorption, adsorption, membrane separation, algae systems and cryogenic separation, each of which has its advantages and limitations summarized in Table 1.

2.1. Membrane capture

Membrane CO_2 capture is an innovative and energy-efficient technology designed to mitigate greenhouse gas emissions. It employs selective, permeable membranes to separate carbon dioxide from gas mixtures, such as flue gas from power plants or industrial processes. This method offers advantages over conventional CO_2 capture techniques, including lower energy consumption, reduced operational complexity, and minimal environmental impact. This method has high CO_2-capture efficiency due to its less-energy consumption, flexible configuration in industrial plants, and the capability potential of selective extraction of CO_2 from the streams of mixed gasses (Mondal et al., 2012a). In addition, the membrane technique is affordable and less energy-intensive compared to absorption processes for capturing CO_2. Table 2 enlists a detailed summary of CO_2 capture via the membrane separation method.

The common fabrication materials for membranes are either organic (polymeric membranes) or inorganic (ceramic membranes), or hybrid (consisting of both inorganic and organic membrane materials) (Abd et al., 2020). To improve the characteristics of the polymeric membranes, inorganic particles with a size in a scale of micro/nano are integrated into a polymeric matrix to synthesize the mixed matrix membranes. A polymeric membrane's potential for greater CO_2 removal from flue gasses is increased by the addition of inorganic particles, which also enhance the membrane's physical, thermal, and mechanical properties. Membrane uses materials that are permeable or semi-permeable to carry and isolate CO_2 from the components of another gas stream (Spigarelli and Kawatra, 2013). The CO_2 permeation through the membranes comprised of the following three steps: (i) CO_2 adsorption on the membrane's higher-pressure side, (ii) CO_2 diffusion through the

Table 1

Advantages and limitations of CO_2 separation technologies (Aaron and Tsouris, 2005; Gambelli et al., 2023; Mondal et al., 2012a; Tin et al., 2004; Yadav and Mondal, 2019).

CO_2 separation technologies	Advantages	Limitations
Adsorption	• Could produce high-purity CO_2 • Requires less heat and lower temperature for regeneration compared to absorption • Can be used in temperature or pressure swing operations	• The development of an efficient adsorbent is still an issue that requires further studies • High material costs for some adsorbents • Requires adsorbent regeneration
Absorption	• Versatile and adaptable to various processes. • High CO_2 capture efficiency • Matured technology	• Requires solvent regeneration which could be energy-intensive • There is a possibility of solvent degradation and environmental emissions
Cryogenic separation	• Can achieve very high purity CO_2 • Commercially matured and proven technology	• Highly energy-intensive process due to the need for extreme cooling • Expensive and often only cost-effective in niche applications requiring high-purity CO_2
Algae systems	• Uses photosynthesis, converting CO_2 into biomass or biofuels • Suitable for nutrient-rich wastewaters • Cost-effective in some cases	• Algae harvesting and dewatering can be challenging • Requires large land areas for cultivation • Variable efficiency due to environmental factors
Membrane separation	• Most membrane systems do not require thermal energy thereby reducing energy demand • Compact and modular design • Can achieve continuous separation	• Susceptible to membrane fouling and degradation • Requires high selectivity and permeability membranes for cost-effective operation

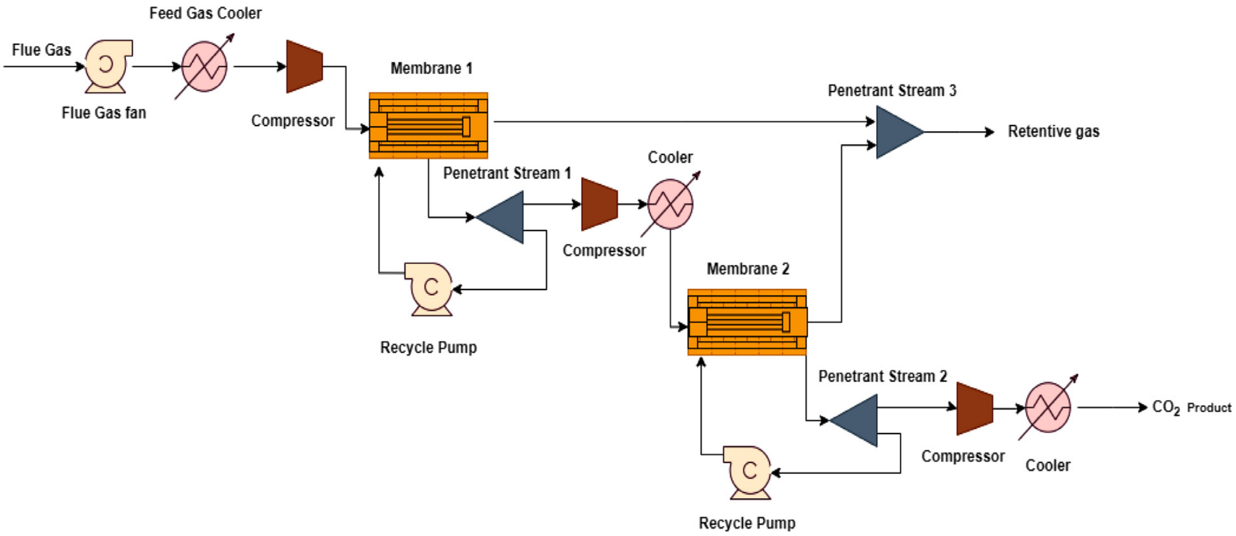


Fig. 3. Schematic flow diagram of a typical CO_2 capture from flue gas by membranes (recycled permeate).

membrane, and (iii) CO_2 desorption to the membrane's lower-pressure side (Wu et al., 2020).

The CO_2 capture through membrane technique has certain advantages as noted earlier, at the same time, the commercialized membranes are not appropriate for absorption using amine solutions because of their low permeation flux. Besides, when exposed to gas streams containing toxic impurities of acid gasses (NO_x and SO_2), the membrane has a shorter life span (Wu et al., 2020). The ongoing development of advanced membrane materials and configurations aims to enhance separation performance and reduce costs, making membrane CO_2 capture a promising solution for sustainable emissions reduction. Fig. 3 presents a schematic representation of the membrane capture system.

2.2. *Cryogenic separation*

Cryogenic CO_2 separation is a process used to purify and concentrate CO_2 from various gas streams. This method takes advantage of the different boiling points of the gases involved, cooling the gas mixture to extremely low temperatures (Font-Palma et al., 2021). At these low temperatures, CO_2 becomes a solid, allowing for easy separation from the remaining gas components. Once isolated, the solid CO_2 can be converted back to its gaseous state and collected, while the other gases are returned to their original state for further processing or release. This technique is energy-intensive but offers high purity and concentration levels of CO_2, making it suitable for applications in industries that require high-quality CO_2 or where other separation methods are ineffective (Babar et al., 2020).

This separation method is used for CO_2 capture due to its less harmful environmental effects. It involves using several condensation temperatures to successively cool and condense a gas combination (Babar et al., 2020). Furthermore, no chemical reagents are required, and the CO_2 from other gas streams is physically separated on account of the dew point and sublimation point (Spigarelli and Kawatra, 2013). The gas separation is influenced by the different boiling point values and the gas components' de-sublimation characteristics (Font-Palma et al., 2021). The flue gas was pretreated to confiscate various impurities (NO_x and SO_x) to increase the gas stream's CO_2 content. Therefore, the CO_2 de-sublimation temperature (up to which the gas stream should be cooled off) becomes a less harmful gas.

The cryogenic separation of CO_2 usually occurs in cryogenic distillation and cryogenic packed beds (Babar et al., 2020). Two different methods for CO_2 capture via cryogenics separation are as follows; (i) the release of CO_2 from the packing material after it has de-sublimated to create gaseous CO_2, and (ii) the regeneration of liquid CO_2 under high pressures, as well as the de-sublimation of gaseous CO_2 onto the fin surfaces of the heat exchangers (Spigarelli and Kawatra, 2013). Schematic

Table 2

Overview of literature studies on membrane-based CO_2 separation method.

Membrane type	Synthesis Method	Temperature (°C)	CO_2 permeance (GPU)	Pressure (kPa)	CO_2/N_2Selectivity	Key findings	Reference
Bipolar membrane	*in situ* mineralization	–	–	–	–	• The developed membrane was able to capture about 60% (for real seawater) up to 85% (for synthetic seawater) of the dissolved inorganic carbon present in the feed as well as minor $Mg(OH)_2$ precipitates. • Effective control of the applied current density and cell residence time can help significantly minimize the process energy requirement.	(Sharifian et al. (2022))
Highly selective hollow fiber membranes (HF)	*in-situ* layer-by-layer (LbL) surface functionalization		8341 Gas Permeation Unit (GPU)		1.1	• Polymer membrane showed high selectivity for CO_2:N_2 (240:1) at 1018 Barrer CO_2 permeability (101 GPU permeance). • Surface functionalization of the polymer improved the hydrophilicity and aided the layer-by-layer deposition.	(Mishra et al. (2021))
PDMS & MOF membrane	simple coordination modulation method	308 K	10,450	100	9.1	• Amorphous MOF nanosheets enhance thin-film composite (TFC) polymeric membranes by overcoming permeability and geometric limitations. • The innovative TFC membrane design exhibits superior CO_2/N_2 separation capabilities and improved processability.	(Liu et al., 2021)
Double-layered Pebax-1657/ PDMS nanomembranes	spin coating	298 K	1200–3500	300	23–72	• A CO_2-selective block copolymer, Pebax-1657, was used as a selective layer on a poly(dimethylsiloxane) gutter layer, defying conventional theoretical predictions for multilayer membranes and achieving more selective CO_2/N_2 separation with ultrathin layers. • Nanoscale blending at the interface between selective and gutter layers enhanced CO_2/N_2 selectivity, resulting in thin-film composite membranes suitable for CO_2 capture in post combustion processes and surpassing the separation ability of pristine Pebax-1657.	(Selyanchyn et al. (2020))
Continuous zeolitic imidazolate framework (ZIF-8) membranes on titania-functionalized porous polymeric supports	–	293 K	–	100	H_2/CO_2 selectivity: 7:1	• Ultrathin, continuous zeolitic imidazolate framework (ZIF-8) membranes were created on titania-functionalized porous polymeric supports using an immersion technique, resulting in flexible and adherent composite membranes. • The membranes demonstrated molecular sieving behavior with high hydrogen permeance and ideal H_2/CO_2 selectivity, opening opportunities for using MOFs in separation and sensing devices.	(Hou et al. (2016))
Zeolitic imidazolate framework-8 (ZIF-8)/graphene oxide (GO) membrane	Secondary growth method	298 K	104	100	7	• A defect-free zeolitic imidazolate framework-8 (ZIF-8)/graphene oxide (GO) membrane was prepared using hybrid nanosheets as seeds, resulting in a uniform seeding layer that facilitates fast crystal intergrowth during membrane formation. • The ultrathin membranes exhibit excellent molecular sieving gas separation properties, with high CO_2/N_2 selectivity, and this 2D nano-hybrid seeding strategy can be applied to other MOF or zeolite molecular sieving membranes for various separation applications.	(Hu et al., 2016)
Polycrystalline metal-organic framework (MOF) membranes		303 K	120–330	100	27.2–37.3	• A novel postsynthetic rapid heat treatment (RHT) drastically improves the carbon capture performance of ZIF-8 membranes, resulting in unprecedented CO_2/CH_4, CO_2/N_2, and H_2/CH_4 selectivities and complete blockage of C_3H_6. • RHT is a facile and versatile technique that enhances the gas separation performance of MOF membranes by increasing lattice stiffness without affecting the coordination environment or crystallinity.	(Babu et al. (2019))
High-performance ultrathin film composite (UTFC) membrane	Physical coating	25 °C	2860	0.2 MPa	28.2	• A facile interface-decoration-layer strategy using copper hydroxide nanofibers enables the formation of an ultrathin selective layer in a thin film composite membrane, leading to a 2.5-fold increase in gas permeance for CO_2 capture. • The as-prepared membrane demonstrates a high CO_2 permeance of 2860 GPU and a CO_2/N_2 selectivity of 28.2, outperforming state-of-the-art polymer membranes, with potential applications in various molecular separation processes.	(Ji et al. (2019))

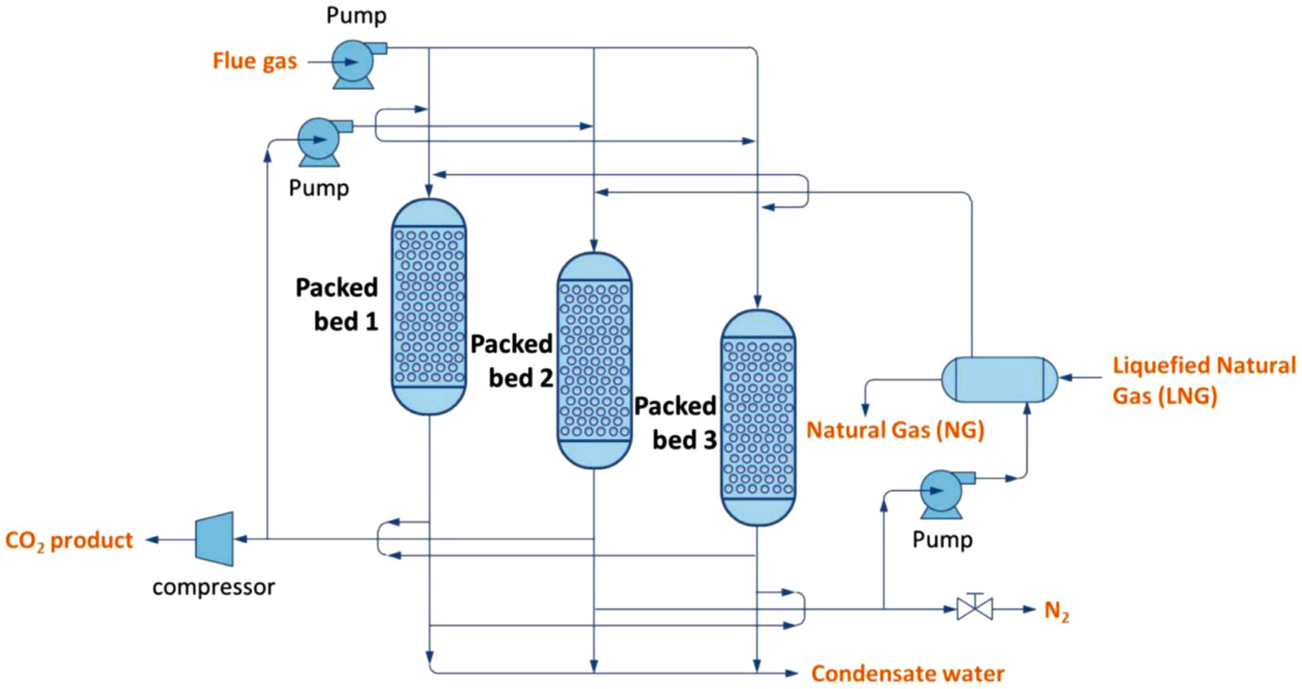


Fig. 4. A schematic of a low-temperature CO_2-packed bed designed for cryogenic separation. Adapted from (Tuinier et al., 2011).

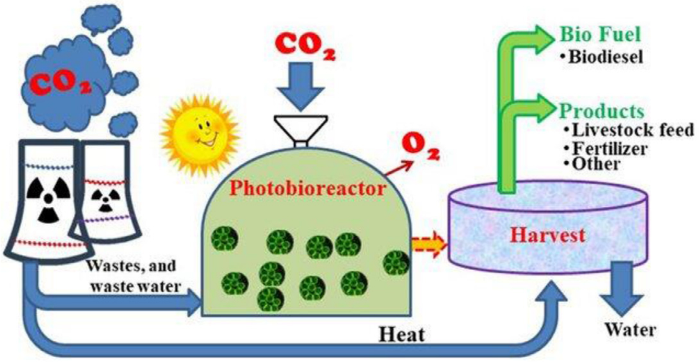


Fig. 5. Carbon by microalgae for biomass and value-added products production (Kondaveeti et al., 2020).

of a low-temperature CO_2-packed bed used for cryogenic separation is shown in Fig. 4.

2.3. CO_2 capture via microalgae

CO_2 capture via microalgae is an innovative and eco-friendly approach to mitigate greenhouse gas emissions, particularly carbon dioxide (Singh and Dhar, 2019). Microalgae are photosynthetic microorganisms that can efficiently utilize CO_2 as a carbon source to grow and produce valuable biomass. In this process, CO_2 is bubbled through a medium containing microalgae, which absorbs and converts the CO_2 into organic compounds during photosynthesis (Singh and Dhar, 2019). As the microalgae grow and reproduce, they remove CO_2 from the atmosphere, effectively sequestering the carbon in their cells. This method not only captures CO_2 but also generates useful biomass that can be harvested and processed into various bioproducts such as biofuels, animal feed, and bioplastics. An overview of CO_2 capture by microalgae is shown in Fig. 5.

Harnessing microalgae for CO_2 capture presents a promising and sustainable solution for reducing greenhouse gas emissions while simultaneously producing valuable resources. The bio-sequestration of CO_2 using micro-algal cell factories has gained rising potential in recycling CO_2 into biomass through photosynthesis that is consequently applied for the generation of bioenergy and other valuable products. Microalgae possess the ability to concentrate CO_2 for an effective photosynthesis process through the procurement of inorganic carbon even from low concentrations of atmospheric CO_2 (Singh and Dhar, 2019). In addition, microalgae are photosynthetic microorganisms that use light and CO_2 to create oxygen and produce high-value goods like biofuels.

The feasibility of this method is both the capture and utilization of CO_2 for obtaining valuable products. Therefore, such technological advancements have the added advantage of an environmentally friendly approach to capture hazardous CO_2 from the flue gasses. However, despite the widespread application of this technique, microalgae production for bulk products like biofuels and other low-value bulk products is not feasible. Using all of the biomass in a combined bio-refinery assembly, from which every single valuable component is collected, processed, and valorized, is the only method to scale the production.

2.4. Adsorption CO_2 capture

CO_2 capture via adsorption is a widely used method for separating and concentrating carbon dioxide from gas mixtures, such as flue gas or ambient air (Mukherjee et al., 2019). This process involves the use

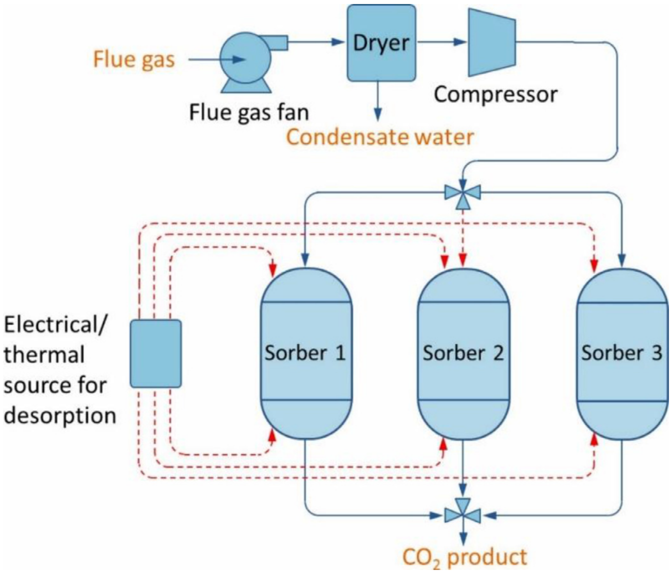


Fig. 6. Schematics of a typical adsorption process. Adapted from (Song et al., 2019).

of solid adsorbents, which are materials with a high affinity for CO_2 molecules. As the gas mixture comes into contact with the adsorbent, CO_2 molecules adhere to its surface, effectively separating them from the other gas components. A schematic representation of a typical adsorption process is shown in Fig. 6. The choice of adsorbent material is crucial for the efficiency of the CO_2 capture process (Ben-Mansour et al., 2017). Some of the most common adsorbents include activated carbon, zeolites, and metal-organic frameworks (MOFs) (Ben-Mansour et al., 2016). After the adsorption process reaches saturation, the adsorbent material can be regenerated by applying heat, pressure, or a combination of both, releasing the captured CO_2 for storage or further use. CO_2 capture via adsorption offers a flexible and efficient means of reducing greenhouse gas emissions from various industrial processes and can be tailored to meet specific separation and concentration requirements.

Adsorption-based capture generally requires less energy consumption because no additional chemical bonds are created between the adsorbent surface and the CO_2, which induces less-energy demand for the regeneration of CO_2. Table 3 outlines a summary of various adsorbents and their synthesis methods. Some of the commonly employed mechanisms of CO_2 adsorption are heterogeneous and surface adsorption, electrostatic excretion changes, electrostatic and acid-base interactions, chemical interactions, physisorption, diffusion, weak non-covalent complexes formation, molecular penetration, and H-bonding (Table 3) (Abd et al., 2020). Usually, narrow-pored porous materials doped with CO_2-public heteroatoms are suitable for CO_2-capture methods. In addition, the proficient materials for developing adsorbents to adsorb CO_2 should have good mechanical strength, better selectivity, thermal stability, lower preparation cost, and offer resistance in humid environments (Abd et al., 2020).

2.5. *CO_2 capture via absorption*

CO_2 capture via absorption is a prevalent method for removing carbon dioxide from various gas streams, including flue gas emitted by power plants and industrial processes. In this technique, a liquid solvent, known as the absorbent, is used to selectively dissolve CO_2 from the gas mixture. The process typically takes place in a gas-liquid contactor, such as an absorber column, where the gas stream is brought into contact with the absorbent (Fig. 7). As the CO_2-rich gas flows through the column, it interacts with the absorbent, and the CO_2 molecules are absorbed into the liquid phase, leaving the other gasses behind (Nwaoha et al., 2016). Once the CO_2 has been absorbed, the solvent is then transferred to a regeneration unit, where it is heated to release the captured CO_2 (de Meyer and Jouenne, 2022). The regenerated solvent can then be recycled back into the absorption process. The captured CO_2 can be compressed and stored or utilized for various applications, such as enhanced oil recovery or the production of valuable chemicals.

Absorption process has tremendous potential, higher selectivity for CO_2, and larger capacity and is usually employed for advanced CO_2 capture processes. However, certain limitations such as high-energy consumption, corrosion, toxicity, high solvent cost, and high mass loss of absorbent caused by the lower stability are some of the significant hurdles to the widespread utilization of this method in various power plants and several industries (Ochedi et al., 2020). Table 4 outlines the summary of various absorbents for successful CO_2 absorption.

Absorption uses both physical and chemical absorption as its two primary strategies for capturing CO_2. (Ochedi et al., 2020). The latter uses chemical solvents for CO_2 absorption whereas the former is based on Henry's law for CO_2 absorption into solvents. When CO_2 absorption is physical, it occurs at low temperature and high pressure, whereas solvent regeneration is accomplished either by increasing temperature or decreasing pressure, or by doing both. On the other hand, because CO_2 absorbs at high partial pressures, a lot of energy is required to pressurize the flue gasses. Whereas in chemical absorption, the solvents and CO_2 produce an intermediate molecule that is only weakly bound and, when heated, releases the trapped CO_2. Chemical absorption is extensively employed for separating different gases, and this technology is principally applied for CC at relatively lower values of partial pressure. Amine and carbonate solutions are considered the key solvents for chemical absorption (Shah et al., 2020).

The solvent at low temperatures and high partial pressure specifically binds to CO_2 thereby obeying Henry's law, which links the solubility of gases to their partial pressure, in the case of physical absorption (Spigarelli and Kawatra, 2013). Hence, for high-pressure streams, physical absorption is appropriate for capturing CO_2; for instance, CO_2 capture in a pre-combustion stage of the integrated coal gasification combined cycle (IGCC) plants. Here the molecules of CO_2 dissolved into the bulk of the material in absorption.

After CO_2 separation from the mixture, H_2-rich syngas is burned to produce power, and the solvent is subsequently regenerated either through flash desorption or stripping after being loaded with CO_2. With flash desorption, a series of pressure reduction phases is used to degas the loaded solvent. Just the CO_2 can separate from the solvent when the pressure is decreased. Regeneration of the loaded solvent is carried out in this manner. Similar to flash desorption, the CO_2-rich solvent is initially degassed in the case of solvent regeneration through stripping; however, the stripping of solvent is carried out after degassing with an inert gas (N_2) to flush out any remaining CO_2 (Spigarelli and Kawatra, 2013).

3. Advances in absorption CO_2 capture

Absorption-based CO_2 capture, in particular, has seen significant progress in recent years. CO_2 capture through absorption has been studied using different physical, chemical or combined solvents (Borhani and Wang, 2019). While the physical solvents rely on weak van der Waals forces to capture CO_2 by dissolving it in the solvent (examples of physical solvents include rectisol, propylene carbonate and Selexol), the chemical solvents (monoethanolamine (MEA), Diethanolamine (DEA), Methyl diethanolamine (MDEA)) form chemical bonds with CO_2, enhancing their selectivity and capacity. It should be mentioned that screening and selection of the most efficient solvent is one of the most important parts of the absorption process.

Chemical solvents offer benefits such as relative indifference to acid gas partial pressure, the ability to capture acid gases down to ppm levels, and high absorption and desorption mass transfer coefficients (Borhani et al., 2019). However, they also have drawbacks,

Table 3
Overview of literature studies on adsorption-based CO_2 separation method.

Adsorbents	Fabrication method/process	Specific surface area (m^2/g)	Diffusion coefficient D(CO_2) ($m^2.s^{-1}$)	Amount of CO_2 capture (CO_2 adsorption uptake)	Experimental conditions/regeneration cycles	Adsorption mechanism	Reference
biomass-pyrolysis derived char	–		–	~1–1.6 mol/kg	30 °C, 1 atm, and 100 min	Electrostatic attraction and acid-base interaction	(Jiang et al. (2023))
WDPC-KOH–HNO_3		755.74					
WDPC-KOH–CO_2		1618.94					
WDPC-KOH		970.29					
Temperature swing adsorption (TSA) process operated on a metal-organic framework (MOF) adsorbent UTSA-16	Temperature swing adsorption	–	–	–	25–40 °C	–	(Peh et al. (2023))
nitrogen-groups modified porous carbon microspheres materials (PCS)	ethanol-assisted hydrothermal technology		CO_2/N_2 (15:85) separation coefficient: 56.9	3.02 mmol/g	313 K, 1 bar, and 20 min/30 cycles	Physical adsorption, chemical adsorption	(An et al. (2023))
(MNPCS)				4.77 mmol/g			
Covalently tethered amines were in-situ polymerized into mesoporous silica support, namely PE-SBA-15	in-situ polymerization	235.0 ± 1.5	–	0.27 mmol/g for 400 ppm CO_2 concentration	25 °C/10 cycles	Diffusion, chemical interactions, weak non-covalent complexes formation, and physisorption	(Al-Absi et al., 2023)
				0.86 mmol/g for 5% ppm CO_2 concentration			
				0.9 mmol/g for 10% ppm CO_2 concentration			
				0.94 mmol/g for 15% ppm CO_2 concentration			
Magnetic biodegradable adsorbent (NaOH@Chitosan-Fe_3O_4)	Alkali post-treatment	3.2838	Diffusion coefficient: 2.850 m^2/s	3.21 mmol/g	25 °C and 9 bar/10 cycles	Heterogeneous and surface adsorption, adsorbent carbonation, electrostatic excretion changes, chemical interactions, molecular penetration, and H-bonding	(Helmi et al. (2023))
			Mass flux: 0.0042 mol/m^2s Mass transfer coefficient: 10.324 m/s				
Corn starch	Chemical activation	711	–	3.805 mmol/g	–	–	(Nazir et al. (2021))
		1747		4.278 mmol/g			
Sugarcane bagasse	Physical and chemical activation	622	–	2.55	–	–	(Guo et al. (2020))
		873		2.68			
		1149		4.28			
A400 Purolite as a solid resin base (solid adsorbent)	Impregnation method	–	PCO_2 (bar): 0.004 bar	58 mg/g	20 °C, 24 h, and 0.5 g loading/3 cycles	diffusion of CO_2 molecules into the adsorbent pores	(Samaddoost et al. (2023))
10% surfactants and 40% amines (T40/S10) sample		1.07		84 mg/g			
ZrO2-stabilized CaO nanoadsorbent	one-pot MWCNT-template method		–	0.1 g CO_2/g adsorbent	-/15 cycles	Physical adsorption	(Mousavi et al. (2023))
CaZr		1.75					
CaZr-CNT2.5		2.53	–	0.09 g CO_2/g adsorbent			
CaZr-CNT5		6.03	–	–			
CaZr-CNT10		4.99	–	0.18 g CO_2/g adsorbent -			

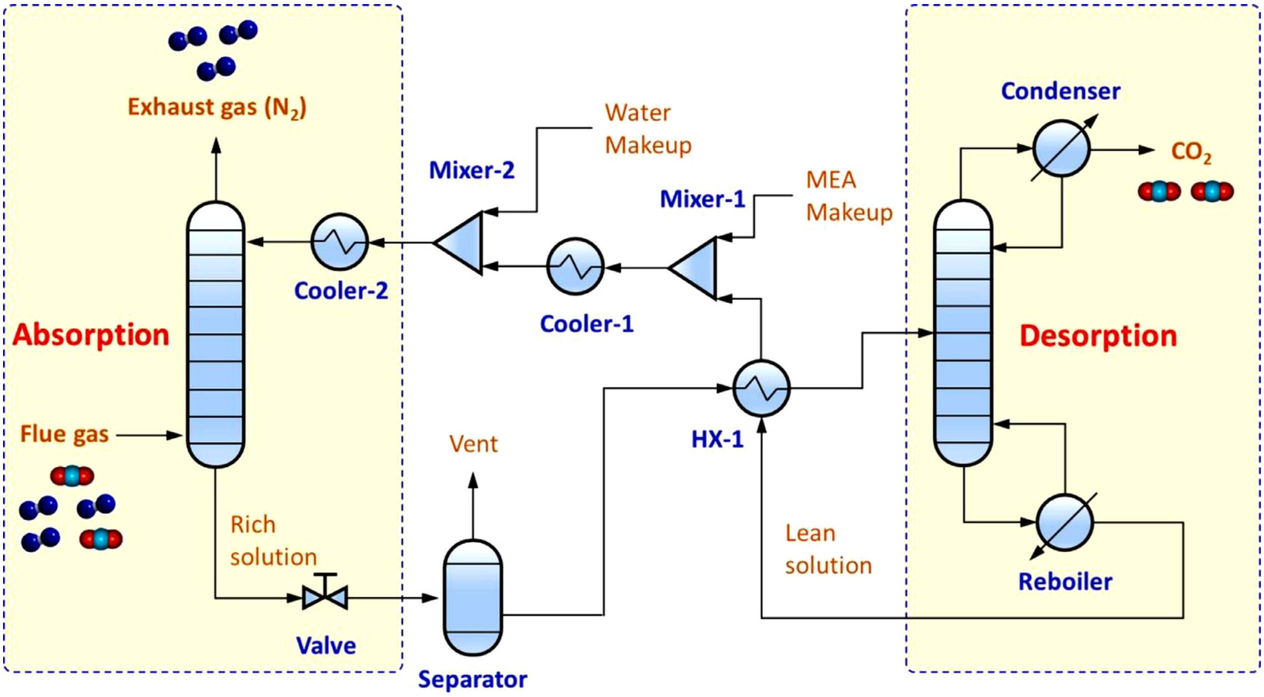


Fig. 7. Schematic of conventional chemical CO_2 absorption process (Song et al., 2019).

Table 4
Studies on Carbon dioxide capture via absorption method.

Absorbents	Concentration	Diffusion coefficient D(CO_2) ($m^2.s^{-1}$)	Amount of CO_2 capture (Absorption capacity)	Temperature (°C)	Adsorption equilibrium (min)	Reference
Secondary and tertiary amines: 2EAE-TMPAD, 2EAE-DEAB, 2EAE-1DMA2P, 2MAE-2DMAE, 2EAE-2DMAE, DMCA-MCA	–	1.01E-09 0.98E-09 0.92E-09 0.92E-09 0.85E-09 0.61E-09	–	333 K	–	(Sharif et al. (2023))
Deep eutectic solvents (DESs): 1,5-diazabicyclo[4.3.0]non-5-ene (DBN) and 1,2,4-triazole (Tz) DES [2DBN:Tz]	100 kPa	–	0.19 g CO_2/g DES	25	60	(Ruan et al. (2023))
[3DBN:Tz]			1.89 mol CO_2/mol DES		30	
[DBN:3Tz]			–		180	
Methyldiethanolamine (MDEA)	300 kPa recovered CO_2 pressure	–	–	–	–	(Hara et al. (2023))
tertiary amine TEMDA (N,N,N′,N′-Tetramethylethylenediamine) and space hindered amine DACH (trans-1,4-Diaminocyclohexane) with Chlorella sp. L166		–	carbon sequestration capacity: 123.27 mg L^{-1} d^{-1}	–	–	(Yin et al. (2023))
anhydrous multi-hybrid absorbent from tetraethylenepentamine-modified porous silica	Specific surface area: 669.54 m^2/g	–	0.419 mmol/g at 20% CO_2 Or 0.377 mmol/g @ 0.15 bar and 27 °C	57	95% regeneration efficiency after 5 cycles	(Ding et al. (2023))
I-liquid-D-I NOHM	50 bar	–	3.890 mmol/g	20	–	(Bai et al. (2016))
H-ZSM-5-liquid/[P66614][Br]	10 bar	–	0.460 mmol/g	25	–	(Li et al. (2019))

including high energy demands for solvent regeneration, limited selectivity among acid gasses, expensive materials, substantial heat of absorption, increased corrosion, the presence of side reactions, and potential environmental harm (N.Borhani and Wang, 2019). Additionally, using aqueous solutions can sometimes result in the treated gas becoming saturated with water. In contrast, physical solvents provide benefits such as lower energy requirements for regeneration, better selectivity between acid gasses, and reduced heat of absorption compared to chemical solvents (N Borhani and Wang, 2019). However, physical solvents also have limitations, including sensitivity to acid gas partial pressure, lower CO_2 capture capacities, and slower absorption and desorption mass transfer coefficients (Gui et al., 2010). Furthermore, some physical solvents may have higher material costs, increased corrosion, and potential environmental impacts (Smith et al., 2022).

Mixture solvents or solvent blends are used in absorption-based CO_2 capture to combine the benefits of different solvents and improve the overall performance of the process (N Borhani and Wang, 2019). Mixed solvents can enhance CO_2 absorption capacity, selectivity, and energy efficiency during the regeneration stage. These blends often comprise a physical solvent and a chemical solvent or a combination of various chemical solvents (N Borhani and Wang, 2019).

Solvent screening has been the focus of several research studies (N.Borhani and Wang, 2019; Ochedi et al., 2020). Nwaoha et al. examined highly concentrated tri-solvent blends of 2-amino-2-methyl-1-propanol (AMP), piperazine (PZ), and monoethanolamine (MEA) for CO_2 capture (Nwaoha et al., 2016). Their results showed higher cyclic capacities, initial desorption rates, and 50–54.5% lower heat duties of solvent blends compared to 5 kmol/m^3 MEA. Blends with AMP/PZ molar ratios of 1 and 2 had higher initial absorption rates. These findings highlight the potential of AMP-PZ-MEA blends in CO_2 capture applications.

In another study, CO_2 solubility and absorption rate in pure and promoted potassium carbonate (K_2CO_3) solutions at elevated temperatures were comprehensively studied (Grimekis et al., 2019). Experiments were conducted at 80 ˚C, 100 ˚C, and 120 ˚C with 1.81 M and 2.53 M K_2CO_3 concentrations. Results were validated against electrolyte-NRTL model predictions. Four additives—MDEA, MEA, PZ, and Glycine—were tested in 1.81 M K_2CO_3 solutions at 100–120 ˚C. PZ and MEA-promoted K_2CO_3 solutions increased solvent capacity and absorption rate (Grimekis et al., 2019). Glycine improved the absorption rate at low loadings without affecting capacity. MDEA negatively impacted solvent capacity at higher concentrations and showed no positive effect on the absorption rate. Another study explores enhancing CO_2 capture in ionic liquids (ILs) like $[Bmim]^+[BF4]^-$ and $[Bmim]^+[PF6]^-$, comparing them to conventional amine solvents MEA and MDEA. Although amines have higher CO_2 loadings, IL-Amine blends combine the reactive nature of amines with the non-volatile nature of ILs. The $[Bmim]^+[BF4]^-$-MEA blend showed higher CO_2 loading than pure IL or aqueous amine solutions, with the 80% $[Bmim]^+[BF4]^-$–20% MEA blend performing best. Adding piperazine (PZ) as a promoter further improved CO_2 loading, and kinetic studies were conducted to evaluate the parameters of various blends.

Solvent regeneration in conventional aqueous amine-based CO_2 capture is energy-intensive. Some researchers proposed a novel water-lean amino acid salt-based biphasic absorbent to enhance CO_2 capture performance and energy efficiency (H. Li et al., 2020). Potassium prolinate (ProK) and potassium sarcosinate (SarK) were used as active components, and 2-alkoxyethanols acted as physical antisolvents, triggering solid phase formation during CO_2 absorption. The study found that weak polar solvents, such as 2-methoxyethanol and 2-ethoxyethanol, favored solid precipitate formation. Solid slurry captured 50–80% of the absorbed CO_2, with ionic products being the main composition (H. Li et al., 2020). Compared to aqueous 5.0 M MEA, the 3.0 M ProK/EGME system showed comparable cyclic capacity, higher desorption efficiency, and a 40–50% reduction in regeneration energy, demonstrating its potential for advanced CO_2 capture technology.

Deep eutectic solvents (DESs) are gaining interest for various applications, including carbon dioxide (CO_2) capture. A recent research study proposes a novel set of DESs created by complexing ethylenediamine (EDA), monoethanolamine (MEA), tetraethylenepentamine (TEPA), triethylenetetramine (TETA), and diethylenetriamine (DETA) with monoethanolamide hydrochloride (EAHC) salt for CO_2 capture (Pishro et al., 2020). CO_2 absorption capacity was evaluated at 313.15 K and 0.8 MPa. The highest CO_2 solubility was observed in 1EAHC:9DETA, 1EAHC:9TETA, and 1EAHC:9TEPA systems, with CO_2 solubility increasing with the molar ratio of hydrogen bond donor and alkyl chain length (Pishro et al., 2020). The study suggests that these DESs could potentially serve as alternatives to conventional solvents in CO_2 capture processes.

The efficiency of CO_2 absorption through absorption can also be improved by adding a surfactant to the solvent used. One study, for instance, demonstrated that the addition of frothers as a surfactant to the Na_2CO_3 solution resulted in an increase in CO_2 absorption efficiency from 55.6% to 99.9% (Valluri and Kawatra, 2021). This enhancement was attributed to the increased surface area available for the transport of CO_2 within the packed bed (Valluri and Kawatra, 2021). Additionally, frothers can prevent the formation of coalesced bubbles by reducing surface tension, which creates smaller and uniform bubbles that improve physical mass transfer, leading to faster absorption of additional CO_2 molecules.

Lately, there has been an increasing interest in the use of a category of solvents, known as phase change solvents, due to their ability to drastically decrease energy consumption in the capture of CO_2 (Zhang et al., 2019). These solvents exist as a single-phase solution under standard conditions, but they transform into a dual-phase system when subjected to alterations in aspects like polarity, hydrophilicity, ionic intensity, or the strength of hydrogen bonds. This transformation results in the creation of two distinct phases: a liquid phase with low CO_2 concentration and another phase (liquid or solid) that is rich in CO_2 (Zhang et al., 2019). Phase change solvents studied in literature include those that undergo chemically or thermally triggered phase changes, non-aqueous or aqueous systems, and those forming either a CO_2-enriched solid or a liquid phase (Su et al., 2013).

Several studies have explored the use of phase change solvents including the aqueous and non-aqueous solvents for CO_2 capture (Liang, 2015; Oexmann and Kather, 2010). Non-aqueous solvents, which replace water with organic solubilizers or ionic liquids and require a relatively low temperature for solvent regeneration (Ma et al., 2023; Ping et al., 2020), can mitigate several drawbacks typically associated with aqueous absorbents including amine degradation and evaporation losses, equipment corrosion and the high heat duty required for solvent regeneration (Liang, 2015). The large-scale use of non-aqueous amine solutions for CO_2 capture is hindered by high viscosity and insoluble substances, causing fouling and blockages (Ma et al., 2023). A recent study proposes using polyamine 1,5-diamino-2-methyl-pentane (DA2MP) as the main absorbent for high absorption load, and 2-amino-2-methyl-1-propanol (AMP) as a regulator to reduce viscosity and dissolve insoluble substances. The novel absorbent demonstrated a CO_2 absorption load of 0.95 mol·mol^{-1} and significantly lower viscosity. After four regeneration cycles, it maintained 97% initial CO_2 absorption capacity. The regulation mechanism involved hydrogen bond network changes, leading to viscosity reduction and insoluble product elimination. The total regeneration energy consumption was only 50.27% compared to an MEA-based solution, making it a promising candidate for CO_2 capture (Ma et al., 2023).

Various CO_2 absorption methods utilizing distinct phase change solvents have been suggested. These encompass the "self-concentration" procedure, the iCap method, the DMX system, the TBS process, and the DECAB technique (Zhang et al., 2019). The self-concentration process involves a nonaqueous solvent consisting of a mixture of amine and alcohol (Zhang et al., 2019). CO_2 absorption takes place at a temperature of 35 ˚C, resulting in the formation of two liquid phases in the solvent.

The lower phase, known as the rich phase, is separated using a decanter and then subjected to solvent regeneration in a stripper operating at 115–125 °C. The regenerated solvent is combined with the upper phase, called the lean phase, and returned to the absorber for CO_2 absorption. In contrast, the iCap process employs a phase transitional aqueous solution composed of a blend of MAPA (2 M) and DEEA (5 M) (Pinto et al., 2014). Similar to the self-concentration process, a liquid-liquid phase transition occurs during CO2 absorption, and only the liquid from the rich phase is directed to the stripper for regeneration.

Ternary amine blends are also promising absorption solvents for CO_2 capture. By merging various alkanolamines, the benefits of each alkanolamine can be synergistically harnessed, creating sorbents that exhibit exceptional CO_2 capture capabilities (Chen et al., 2022). This performance is notably superior to that of aqueous MEA under comparable operational conditions. Numerous studies indicate that an aqueous blended system, typically consisting of a primary (or secondary) amine combined with a tertiary (or sterically hindered) amine, can demonstrate a quicker CO_2 reaction rate than a solitary tertiary (or sterically hindered) amine(Conway et al., 2015; Sema et al., 2012). Additionally, this blended system may necessitate less energy for regeneration compared to a single primary (or secondary) amine. specifically, the primary (or secondary) amine accelerates the reaction rate and facilitates mass transfer, whereas the tertiary (or sterically hindered) amine functions as a base (proton acceptor), thereby improving the efficiency of desorption (Chen et al., 2022).

3.1. CO_2 desorption enhancement techniques

CO_2 desorption enhancement techniques are crucial in carbon capture and storage (CCS) technology, aimed at mitigating climate change. These techniques focus on improving the efficiency and speed of releasing captured CO_2 from absorbent materials. CO_2 is a challenging gas to break down and remove due to its strong chemical and thermodynamic stability, which results from the double bond between its carbon and oxygen atoms. Therefore, several methods have been evaluated for improving CO_2 separation in bulk molecules (Tavakoli et al., 2022). CO_2 desorption enhancement methods include the use of nanofluids, solid acid-catalyzed processes, biocatalysts, and the use of ionic liquids.

Nanofluids have demonstrated immense potential in enhancing CO_2 desorption as reported by previous studies. Nanofluids are colloidal suspensions of nanoparticles in a base fluid, often water or oil. The nanoparticles used in nanofluids can vary widely, with materials such as metals, oxides, carbides, or carbon nanotubes (Tavakoli et al., 2022). The main reason nanofluids are used for CO_2 desorption enhancement lies in their superior thermophysical properties compared to conventional fluids. Lee et al.'s study demonstrated that adding SiO_2 nanoparticles at certain concentrations to a solution improved CO_2 regeneration by up to 11.8% (Lee et al., 2016). However, the addition of Al_2O_3 nanoparticles reduced the performance, with a decrease as high as −14.7%. This decline is attributed to the Al_2O_3 surface's reactions with CO_2, creating adsorbed bicarbonate and carbonate species, making CO_2 desorption difficult. SiO_2 didn't display this effect. The researchers also improved CO_2 absorption and regeneration in methanol using these nanoparticles during the physical absorption process (Lee et al., 2016).

Hafizi and colleagues investigated the regeneration of nanofluids infused with amine-functionalized Fe_3O_4 nanoparticles, using both traditional heat-based processes and a novel sonication (bath) method (Hafizi et al., 2020). They discovered that the sonication technique could desorb CO_2 in under a minute with little impact on absorption efficiency. This suggests that ultrasonic-based regeneration is a more effective approach than traditional heating.

Solid acid catalysts have also attracted interest in enhancing CO_2 desorption process due to their surface reactivity, regenerability ability and chemical stability (Bhatti et al., 2020; Guo et al., 2023). Solid catalysts permit an equal CO_2 desorption rate at a minimal temperature in comparison to the non-catalytic system thereby improving the energy efficiency of the system (Guo et al., 2023). Moreover, solid acid catalysts can enhance the generation of CO_2 and support a solid-liquid separation. This ensures that the CO_2-depleted solution retains its absorption capability, thus resolving the compromise between absorption and desorption.

Some researchers explored the use of a solid acid catalyst (HZSM-5) in an α-Al_2O_3 ceramic membrane to improve CO_2 desorption from an aqueous MEA Solution (Guo et al., 2023). Various tests were conducted to assess the influence of different variables on the rate of CO_2 removal and energy usage. The system proved to be effective in CO_2 removal and displayed enduring stability across 60 test cycles, suggesting that the incorporation of a solid acid catalyst with a porous ceramic membrane could enhance CO_2 removal rates and lessen energy demands. Bhatti et al. studied the use of mesoporous HZSM-5 catalysts to improve CO_2 desorption from an MEA solution (Bhatti et al., 2020). Despite the potential for CO_2 capture, such methods have been hindered by high energy needs and slow desorption. The synthesized catalysts, showing increased surface area and mesoporosity, improved desorption rates significantly (up to 580% at 82 °C), increased total desorbed CO_2 by 60%, and reduced heat duty by 37%. This highlights catalysts' role in optimizing CO_2 capture and gives insights for future catalyst design. Table 5 presents previous studies on CO_2 enhancement methods

4. Techno-economic analysis of absorption CO_2 capture

Techno-economic analysis (TEA) of absorption CO_2 capture is essential for determining the feasibility and effectiveness of carbon capture technologies. This evaluation considers both the technical performance and economic factors of the process, examining factors such as capital costs, operational expenses, energy consumption, and CO_2 capture efficiency. By analyzing these elements, researchers and industry stakeholders can identify optimal absorption methods, optimize system design, and reduce costs. TEA supports the development of sustainable, cost-effective solutions for reducing greenhouse gas emissions and mitigating climate change (Okolie et al., 2021).

In assessing the feasibility of CO_2 capture through absorption, the cost analysis is a critical factor to compare absorption with other technologies. There are several economic estimators used to appraise the TEA of absorption processes, each with its advantages and limitations as illustrated in Table 6.

4.1. Techno-economic analysis methodology

Assessing the techno–economic analysis of absorption-based CO_2 capture involves several steps each of which is described in Fig. 8. Notably, the steps are grouped into technological and economic evaluation. During the technological evaluation, a reference process simulation is presented for estimating the mass and energy balance, especially if the proposed process is new and complex. The simulation is often appraised with the help of process simulator software which could be open source (DWSIM) or commercial software (Aspen Plus/Aspen Hysys) (Okolie et al., 2021). Process simulation helps in technological scale-up in such a way that the economy of scale could be similar to the economy of a production process. It also helps in equipment sizing. Although a proper techno – economic appraisal is dependent on accurate estimation of the equipment sizing and cost. The latter is complex and requires several parameters related to the proposed CO_2 capture plant.

To design the process and equipment required for a techno-economic analysis study, both thermodynamic properties and transport properties, along with kinetic parameters, must be considered (Ortiz and J, 2020). Thermodynamics typically constrain a process's performance factors, such as maximum product yield or energy efficiency, which can impact its feasibility. Meanwhile, the dimensions of process units like reactors, heat exchangers, or separation units rely on kinetic and transport properties. As a result, accurate modeling of thermodynamics, kinetics, and

Table 5
Overview of different solid catalysts used for CO_2 desorption enhancement.

Solid acid catalyst	Process conditions	Key findings	References
Mesoporous HZSM-5 catalysts, synthesized through alkaline desilication and surfactant-induced re-assembly of dissolved species from the parent HZSM-5 crystals.	CO_2 desorption from 30 wt.% MEA solution under mild temperature conditions (40–82 ˚C).	• The synthesized catalysts significantly enhanced the CO_2 desorption rate at low temperatures (up to 350–580% increase at ≤82 ˚C), improved the total amount of desorbed CO_2 by up to 60%, and reduced the heat duty by 24–37%. • The improved desorption rate was attributed to the synergistic effect of increased mesoporosity and a higher number of Lewis acid sites (LAS) and Brønsted acid sites (BAS).	(Bhatti et al. (2020))
HZSM-5 catalyst	The absorption and desorption performance of various single and blended solvents, including MEA, PZ, BEA, AMP, BDEA, and MDEA, were studied. These were used at a specified concentration of 2.5 M. The initial desorption rate was evaluated by varying the temperature, weight of the solid catalyst, and initial rich CO_2 loading.	• All the chosen blank solvent blends showed better absorption and desorption performance than the blank benchmark solution (2.5 M MEA). • Catalyst-aided CO_2 desorption performance was significantly influenced by the rich loading and operating temperature.	(T. Li et al., 2022)
SnO_2 modified attapulgite (SnO_2/ATP) solid acid catalyst	CO_2 desorption in a rich 5 M MEA solution at 88 ˚C	• The use of the SnO_2/ATP catalyst, which had improved Brønsted acid sites and strong acid sites, increased the CO_2 desorption rate and amount of desorbed CO_2 by 265% and 222%, respectively, compared to desorption without a catalyst. • The catalyst showed superior performance to most reported solid catalysts.	(Tan et al. (2023))
Fe promoted SO_4^{2-}/ZrO_2 supported on MCM-41 (SZMF) catalysts with different iron oxide content (5%, 10%, and 15%)	Regeneration process of rich monoethanolamine solution at 98 ˚C	The use of SZMF significantly enhanced CO_2 desorption performances (desorption factor by 260–388%) and reduced the heat duty by about 28–40%, performing better than most reported catalysts.	(Zhang et al. (2019))
Ni-HZSM-5 catalyst, with varying nickel content from 2.16 to 9.80 wt% in HZSM-5	CO_2 desorption of rich amine solvent at 90 ˚C	• The introduction of nickel increased the acid sites of the catalysts compared to parent HZSM-5, which played a key role in improving the CO_2 desorption rate. • The 7.85-Ni-HZ catalyst displayed excellent catalytic activity for the CO_2 desorption: it increased the amount of desorbed CO_2 up to 36%, reduced the relative heat duty by 27.07% with the same reaction time, and showed high stability during five cyclic tests.	(Sun et al. (2022))
SO_4^{2-}/ZrO_2_HZSM-5 (SZ@H), with improved Lewis's acid sites (LASs) and Bronsted acid sites (BASs)	The CO_2 desorption temperature was decreased to less than 98 ˚C	The improved LASs and BASs of the SZ@H catalyst enhanced the amount and rate of CO_2 desorption from spent monoethanolamine by more than 40% and 37% respectively, compared to non-catalyzed desorption. As a result, energy consumption was reduced by approximately 31%.	(Xing et al. (2020))
Composite catalyst, CeO2-MOF-HPW (CeM-HPW), combines cerium-based MOFs materials with heteropolyacids to increase acid sites	The CO_2 desorption temperature was decreased to less than 98 ˚C	• The CeM-HPW composite catalyst improved CO2 desorption performance, with the desorption capacity and rate increased by 38.1% and 166% respectively compared to the non-catalytic process. • Furthermore, desorption energy consumption was reduced by 29.4%.	(Wei et al. (2022))

Table 6
Advantages and limitations of different economic estimators used for absorption-based CO_2 capture (Ortiz and J, 2020; Kiani et al., 2020; Yun et al., 2021).

Economic estimators	Definition	Advantages	Limitations
Net present value	Represents the sum of the present values of all cash flows, including the initial investment	• Provide a single value for economic analysis comparison. • Considers time value of money.	• Sensitive to discount rate. • Needs an accurate cash flow projection.
Payback period	Defined as the duration required to pay off the initial investment with revenues from the beginning of the project.	• Suitable for evaluating the profitability of conceptual design with a relatively short lifespan.	• The performance of the project after the payback period is often neglected. • Does not consider the time value of money.
Internal rate of return	Measures the difference between revenues, once discounted the expenses and investment in relation to the investment	• Considers the time value of money • Easier for non-financial stakeholders to understand	• Not ideal for projects with unconventional cash flows • Sometimes issues of ambiguity might arise due to multiple internal rates of return.
Levelized Cost of CO_2 Capture	It indicates the average cost per unit of CO_2 captured over the lifetime of the capture system.	• Considers capital, operating, and maintenance costs • Allows for comparison between different technologies	• Sensitive to assumptions about future costs and performance • Simplifies complex costs into a single value, which may not reflect reality

transport phenomena in process units is essential for generating precise simulation results (Yun et al., 2021).

After equipment sizing, the cost of equipment is determined through several methods including the CAPCOST software (Turton et al., 2008), correlations from literature, or published books. There are also some good websites for equipment cost appraisal such as the Peters and Timmerhaus (Peters and Timmerhaus, 2023) or a commercial simulator such as Aspen Capital Cost Estimator.

In certain situations, equipment capacity may fall outside the scope of the sources and tools mentioned previously. In such cases, estimates can be derived from open literature or commercial catalogs, combined with the application of the six-tenths-factor rule

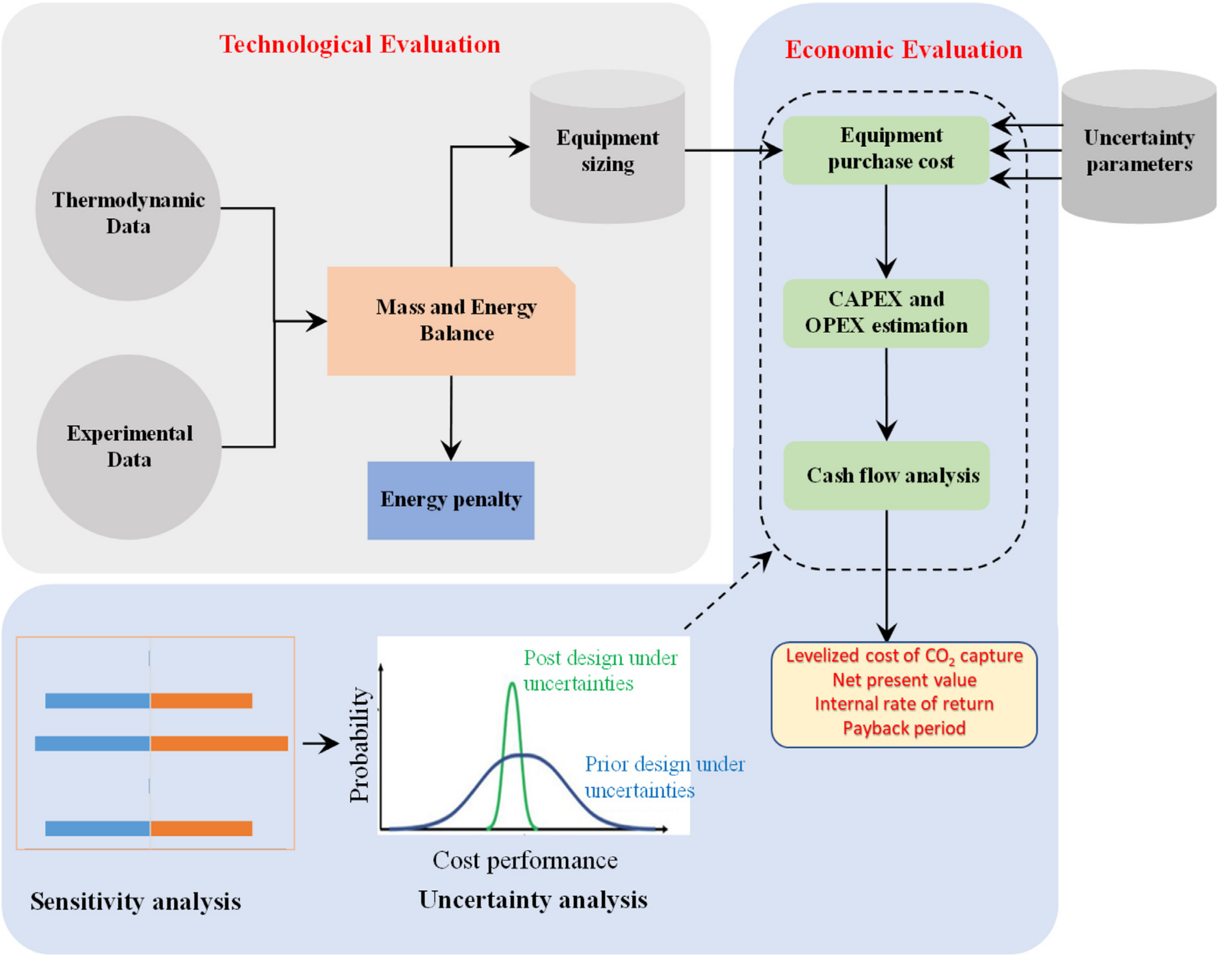


Fig. 8. Methodology for estimating the techno-economic analysis of absorption-based CO_2 capture.

(Omoarukhe et al., 2023). Since the equipment purchase cost is typically sourced from previous years and tends to change over time, it is necessary to update it to the current year (Omoarukhe et al., 2023). This can be achieved by using the Chemical Engineering Plant Cost Index (CEPCI).

The economic evaluation follows the technological evaluation, and it involves the calculations of capital expenditure (CAPEX) and operating expenses (OPEX). After this, a discounted and undiscounted cash flow analysis is performed to determine any of the economic estimators listed in Table 5. To identify and quantify the impact of variations in key input parameters on the outcome of the techno-economic analysis, sensitivity and uncertainty analyses are often performed. These analyses help determine which factors have the most significant influence on the project's economic viability and highlight potential risks associated with uncertain inputs. By understanding these uncertainties, decision-makers can develop more robust strategies, prioritize mitigation measures, and make more informed investment decisions. The sensitivity analysis method is used to assess how the variation in input parameters affects the output of a model or system (Okolie et al., 2021). By changing one input parameter at a time while keeping others constant, it helps identify the most influential factors and assess their impact on the results. In contrast, uncertainty analysis is a method used to evaluate the range of possible outcomes and the associated probabilities due to uncertainties in input variables (Omoarukhe et al., 2023). Detailed information on the uncertainty and sensitivity analysis methods can be found elsewhere (Oke et al., 2021; van der Spek et al., 2017; Yates et al., 2020)

4.2. Research progress in the techno-economic analysis of absorption CO_2 capture

Although TEA of several CO_2 capture systems has been widely documented in the literature, limited research has reported the cost analysis and economic assessment for absorption-based-CO_2 capture. When capturing high volumes of CO_2, large equipment is often needed to handle the flow. As a result, the capital expenses for heavy machinery and strong solvents may exhibit reverse economies of scale. Additionally, the high energy needed to regenerate additional solvents could result in operating and maintenance cost models that also exhibit reverse economies of scale (Hasib-ur-Rahman et al., 2010).

Some researchers reported the cost analysis of mini-channel absorbers, taking into account the Present Net Value of capital and operating costs, which suggested that mini-channel absorbers are an economically feasible option compared to other conventional technological methods (Yang et al., 2018). For plants with capacities in a range of 5–50 MMSCFD, the system yielded savings ranging from 50% to 3% for low CO_2 capture capacity, mainly because of low capital cost. On the other hand, the increased operational cost of the small channel absorbers overwhelms their NPVC at higher plant capacities, frequently causing them to lose their competitiveness (Yang et al., 2018).

The feasibility of CO_2 capture and sequestration (CCS) at PacifiCorp's Hunter Plant was assessed, evaluating performance, capital, and operating costs for implementing CCS on Unit 3, which burns low-sulfur, subbituminous coal (Panja et al., 2022). Using the MHI KM-CR Process® with KS-1^{TM} solvent, the cost of capture decreases with larger capture rates and ranges from \$50, \$61, and \$74 per ton of CO_2 removed for 90%, 65%, and 1000 lbs/MWh-g of CO_2 capture, respectively, with CO_2 purity greater than 95% (Panja et al., 2022).

In another study, a techno-economic assessment was conducted for capturing CO_2 using MEA and a new absorbent, both interconnected dynamically with a power plant (Yun et al., 2020). According to the study, the cost of CO_2 capture using the MEA-based technology in the Republic of Korea is anticipated to be roughly \$35.5/ton of CO_2, which consumes 3.5 GJ/ton of CO_2 for regeneration. Meanwhile, using the new absorbent, which requires 2.17 GJ per ton of CO_2 regeneration of solvent, results in a CO_2 capture cost of about \$25.7 per ton of CO_2. In a similar study, there was also a techno-economic analysis of employing aqueous piperazine to capture CO_2 after combustion that was based on the CO_2 concentration, flue gas flow rate, and CO_2 capture efficiency (Yun et al., 2020). In this case, the optimum CO_2 capture efficiency improved as the inlet flue gas CO_2 concentration grew i.e., the optimal CO_2 capture efficiency reached 95% for an inlet flue gas CO_2 concentration of 33 vol%, resulting in the lowest CO_2 capture cost.

Several absorption processes for CO_2 capture have demonstrated relatively lower cost performance compared to conventional techniques, indicating those to be the superior options for capturing CO_2 (Chang et al., 2021; Mondal et al., 2012b). However, most of the studies on these processes have been conducted at the laboratory scale, and further assessment of the cost analysis of CO_2 capture through absorption is still needed. A recent study explores an advanced pre-combustion CO_2 absorption process using a novel solvent looping system for steam methane reforming (SMR), which significantly reduces reboiler duties compared to conventional post-combustion capture processes (Kum et al., 2023). The techno-economic analysis of the MDEA/PZ blended solvent shows that the CO_2 capture cost per ton decreases as the capture rate increases, and the novel system requires lower energy consumption and operational expenditure (Kum et al., 2023).

Siefart et al. synthesized and evaluated two new hydrophobic physical solvents for CO_2 capture from pre-combustion syngas streams at integrated gasification combined cycle (IGCC) power plants: PEG-Siloxane-1 and [aPy][Tf2N] (Siefert et al., 2016). The levelized cost of capturing CO_2 (LCOC) for these solvents is estimated using Aspen Plus and a detailed techno-economic analysis. The results indicate that PEG-Siloxane-1 is cost-competitive with the baseline solvent, Selexol, and [aPy][Tf2N] could potentially lower CO_2 capture costs, depending on the commercial-scale synthesis cost (Siefert et al., 2016). Kotamreddy et al. developed a detailed model for microencapsulated carbon capture solvents (MECS) using sodium carbonate solution and conducts a techno-economic analysis (Kotamreddy et al., 2019). The results indicate that optimal residence time minimizes bed volume and heat recovery is crucial for low-energy regeneration. The equivalent annual operating cost (EAOC) for the MECS fixed bed configuration is 1.8–2.7 times higher than a conventional monoethanolamine (MEA) solvent system with 85% heat recovery. However, improvements to the MECS capsules and contactor technologies are expected to decrease the system cost and make it more competitive.

Direct air capture (DAC) is an emerging technology that addresses dispersed CO_2 emissions, which traditional CCS methods cannot capture. Barzagli et al. study explored various alkanolamines, particularly those used in CCS, for DAC efficiency (Barzagli et al., 2020). The results indicate that aqueous primary unhindered amines are as efficient as aqueous alkali hydroxides in CO_2 capture, with the potential for lower regeneration energy, and that high yield production of amine carbamate is crucial for effective CO_2 capture.

Some researchers proposed a hybrid system combining membrane and enzymatic-absorption processes to remove CO_2 from flue gas emitted by a 600 MWe power plant (Gilassi et al., 2021). The absorption technology was based on the use of an amine solvent. This hybrid approach overcomes the high investment cost and energy consumption associated with standalone processes. Optimization results show that the hybrid system reduces total electricity loss by 124 MW and total annual cost by \$139 million, which is 10% and 37% lower than a standalone membrane process, respectively. This approach offers a more efficient and cost-effective alternative to traditional amine-based absorption technology.

5. Challenges and recommendations

In recent years, absorption processes have emerged as sustainable and economically favorable methods for capturing GHG emissions, due to the rapid advancement in CO_2-capturing technology. However, to fully comprehend the potential of these processes for practical applications, there are still significant challenges and restrictions that need to be overcome. Definite observations must be prioritized to direct future research on the development and industrialization of CO_2 capture via absorption. These include the resolution of technological, economic, environmental, and safety issues, as well as the development of different approaches to improve the effectiveness of the absorption process. The most important factor for the absorption technique for CO_2 capture is solvent selection, which should have high selectivity, minimal environmental impacts, and technical limitations.

Moreover, cost estimation analysis and economic assessment for post-CO_2 capture also remain a challenge for researchers as only a few studies have reported these aspects. Therefore, integrated research is required to couple the technical perspective and economic dimensions of the absorption processes for CO_2 capture. Moreover, in chemical absorption, more than 60% of the total energy used in the process is used in a stripper for the thermal regeneration of chemical absorbents, which is high in the case of CO_2. So, to maximize the effectiveness of chemical absorption, future research should be focused on improving the absorbent composition and process efficiency. Additionally, future research should also address issues such as lower efficiency, high-energy requirements, complete removal of CO_2, and the regeneration of the used solvents in absorption processes for further treatments.

Solvent degradation and evaporation are key considerations that should be included in future TEA studies. Over time, the chemical reactions and exposure to CO_2 can lead to solvent degradation, reducing its effectiveness in capturing CO_2. This degradation can result in a decrease in the solvent's absorption capacity and efficiency, requiring more frequent solvent replacement or regeneration. The need for additional solvent replacement or regeneration can increase operating costs, including the cost of purchasing new solvent, disposal of degraded solvent, and the energy required for regeneration. Solvent evaporation can result in the loss of solvent from the capture system, reducing its overall efficiency and effectiveness. The loss of solvent through evaporation can lead to decreased CO_2 capture rates and increased solvent makeup requirements. This can result in higher operating costs, including the need for additional solvent purchases and increased energy consumption for solvent regeneration. Solvent degradation and evaporation can both lead to increased costs associated with maintaining optimal CO_2 capture performance. Regular monitoring and maintenance of the solvent system are necessary to mitigate these effects and ensure efficient and cost-effective CO_2 capture. Strategies such as solvent regeneration, solvent recovery systems, and proper system design can help minimize the impact of solvent degradation and evaporation on overall capture costs.

6. Conclusions

The issue of climate change has put CC technology at the forefront of current research globally. This review aimed to highlight recent advances in various CC techniques, with a particular emphasis on absorption technology as a means to remove CO_2 from the environment. The review focused on the different operational CC processes and highlighted the advantages and drawbacks of various solvents used in the absorption process. Additionally, this review synchronized various research works from the literature to analyze the economic assessment of the absorption process. Various challenges facing the technology were identified, and recommendations were provided to address the challenges. This comprehensive review covered the background, status, and future perspectives of CO_2 capture via absorption technology at various levels, making it beneficial for future research work.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to improve the quality and flow of English language grammar and also to identify/correct any grammatical errors. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

Acknowledgment

The authors would like to thank the editor and reviewers for providing insightful comments that helped improve the manuscript. The authors also acknowledge Elsevier for providing publication fees waiver for this article. Special appreciation to Nile University of Nigeria for supporting the research.

References

Aaron, D., Tsouris, C., 2005. Separation of CO_2 from flue gas: a review. Sep. Sci. Technol. 40 (1–3), 321–348. doi:10.1081/SS-200042244.

Abd, A.A., Naji, S.Z., Hashim, A.S., Othman, M.R., 2020. Carbon dioxide removal through physical adsorption using carbonaceous and non-carbonaceous adsorbents: a review. J. Environ. Chem. Eng. 8 (5), 104142. doi:10.1016/J.JECE.2020.104142.

Al-Absi, A.A., Domin, A., Mohamedali, M., Benneker, A.M., Mahinpey, N., 2023. CO_2 capture using in-situ polymerized amines into pore-expanded-SBA-15: performance evaluation, kinetics, and adsorption isotherms. Fuel 333, 126401. doi:10.1016/J.FUEL.2022.126401.

An, X., Yang, J., Qi, G., Li, T., Zhao, K., Fu, D., 2023. Functional molecular engineering hierarchical pore-interface based on thermodynamic-kinetic synergy strategy for efficient CO_2 capture and separation. Fuel 332, 126243. doi:10.1016/J.FUEL.2022.126243.

Babar, M., Bustam, M.A., Maulud, A.S., Ali, A., Mukhtar, A., Ullah, S., 2020. Enhanced cryogenic packed bed with optimal CO_2 removal from natural gas; a joint computational and experimental approach. Cryogenics 105, 103010. doi:10.1016/J.CRYOGENICS.2019.103010, (Guildf).

Babu, D.J., He, G., Hao, J., Vahdat, M.T., Schouwink, P.A., Mensi, M., Agrawal, K.V., 2019. Restricting lattice flexibility in polycrystalline metal–organic framework membranes for carbon capture. Adv. Mater. 31 (28), 1900855. doi:10.1002/ADMA.201900855.

Bai, H., Zheng, Y., Yang, R., 2016. Recyclable liquid-like POSS derivatives with designed structures and their potential for CO_2 capture. Mater. Des. 99, 145–154. doi:10.1016/J.MATDES.2016.03.010.

Barzagli, F., Giorgi, C., Mani, F., Peruzzini, M., 2020. Screening study of different amine-based solutions as sorbents for direct CO_2 capture from air. ACS Sustain. Chem. Eng. 8 (37), 14013–14021. doi:10.1021/ACSSUSCHEMENG.0C03800/ASSET/IMAGES/LARGE/SC0C03800_0005.JPEG.

Ben-Mansour, R., Basha, M., Qasem, N.A.A., 2017. Multicomponent and multi-dimensional modeling and simulation of adsorption-based carbon dioxide separation. Comput. Chem. Eng. 99, 255–270. doi:10.1016/j.compchemeng.2017.01.040.

Ben-Mansour, R., Habib, M.A., Bamidele, O.E., Basha, M., Qasem, N.A.A., Peedikakkal, A., Laoui, T., Ali, M., 2016. Carbon capture by physical adsorption: materials, experimental investigations and numerical modeling and simulations - a review. Appl. Energy 161, 225–255. doi:10.1016/j.apenergy.2015.10.011.

Bhatti, U.H., Shah, A.K., Hussain, A., Khan, H.A., Park, C.Y., Nam, S.C., Baek, I.H., 2020. Catalytic activity of facilely synthesized mesoporous HZSM-5 catalysts for optimizing the CO_2 desorption rate from CO_2-rich amine solutions. Chem. Eng. J. 389, 123439. doi:10.1016/J.CEJ.2019.123439.

Borhani, T.N., Oko, E., Wang, M., 2019. Process modelling, validation and analysis of rotating packed bed stripper in the context of intensified CO_2 capture with MEA. J. Ind. Eng. Chem. 75, 285–295. doi:10.1016/J.JIEC.2019.03.040.

Buhre, B.J.P., Elliott, L.K., Sheng, C.D., Gupta, R.P., Wall, T.F., 2005. Oxy-fuel combustion technology for coal-fired power generation. Prog. Energy Combust. Sci. 31 (4), 283–307. doi:10.1016/j.pecs.2005.07.001.

Chang P.T., Ng Q.H., Ahmad A.L., & Low S.C. (2021). A critical review on the techno-economic analysis of membrane gas absorption for CO2 capture. 10.1080/00986445.2021.1977926, 209 (11), 1553–1569. doi:10.1080/00986445.2021.1977926.

Chen, G., Chen, G., Peruzzini, M., Zhang, R., Barzagli, F., 2022. Understanding the potential benefits of blended ternary amine systems for CO2 capture processes through 13C NMR speciation study and energy cost analysis. Sep. Purif. Technol. 291, 120939. doi:10.1016/J.SEPPUR.2022.120939.

Conway, W., Bruggink, S., Beyad, Y., Luo, W., Melián-Cabrera, I., Puxty, G., Feron, P., 2015. CO_2 absorption into aqueous amine blended solutions containing monoethanolamine (MEA), N,N-dimethylethanolamine (DMEA), N,N-diethylethanolamine (DEEA) and 2-amino-2-methyl-1-propanol (AMP) for post-combustion capture processes. Chem. Eng. Sci. 126, 446–454. doi:10.1016/J.CES.2014.12.053.

De Mello, L.F., Gobbo, R., Moure, G.T., Miracca, I., 2013. Oxy-combustion technology development for fluid catalytic crackers (FCC) – large pilot scale demonstration. Energy Procedia 37, 7815–7824. doi:10.1016/J.EGYPRO.2013.06.562.

de Meyer, F., Jouenne, S., 2022. Industrial carbon capture by absorption: recent advances and path forward. Curr. Opin. Chem. Eng. 38, 100868. doi:10.1016/J.COCHE.2022.100868.

De Silva, G.P.D., Ranjith, P.G., Perera, M.S.A., 2015. Geochemical aspects of CO_2 sequestration in deep saline aquifers: a review. Fuel 155, 128–143. doi:10.1016/J.FUEL.2015.03.045.

Ding, Y., Ma, L., Yang, X., Zhu, X., Wang, H., Cheng, M., Liao, Q., 2023. Anhydrous multi-hybrid absorbent with low viscosity and high regeneration efficiency for post-combustion CO_2 capture. Energy 263, 125742. doi:10.1016/J.ENERGY.2022.125742.

Farrelly, D.J., Everard, C.D., Fagan, C.C., McDonnell, K.P., 2013. Carbon sequestration and the role of biological carbon mitigation: a review. Renew. Sustain. Energy Rev. 21, 712–727. doi:10.1016/J.RSER.2012.12.038.

Font Palma C., Cann D., Udemu C., García O. (2021). Review of cryogenic carbon capture innovations and their potential applications. C 2021 Vol. 7 Page 58, 7 (3), 58. doi:10.3390/C7030058.

Gambelli, M., Podder, J., Patra, B.R., Pattnaik, F., Nanda, S., Dalai, A.K., 2023. A review of carbon capture and valorization technologies. Energies 16 (6), 2589. doi:10.3390/EN16062589, 2023, Vol. 16, Page 2589.

Gilassi, S., Taghavi, S.M., Rodrigue, D., Kaliaguine, S., 2021. Techno-economic analysis of a hybrid system for flue-gas separation: combining membrane and enzymatic-absorption processes. Chem. Eng. Process. Process Intensif. 159, 108222. doi:10.1016/J.CEP.2020.108222.

Goldemberg, J., 2007. Ethanol for a sustainable energy future. Science 315 (5813), 808–810. doi:10.1126/SCIENCE.1137013/ASSET/DF795B22-5631-48DE-AE36-3535A165725A/ASSETS/GRAPHIC/315_808_F2.JPEG.

Grimekis, D., Giannoulidis, S., Manou, K., Panopoulos, K.D., Karellas, S., 2019. Experimental investigation of CO_2 solubility and its absorption rate into promoted aqueous potassium carbonate solutions at elevated temperatures. Int. J. Greenh. Gas Control 81, 83–92. doi:10.1016/J.IJGGC.2018.12.008.

Gui, X., Tang, Z., Fei, W., 2010. CO_2 capture with physical solvent dimethyl carbonate at high pressures. J. Chem. Eng. Data 55 (9), 3736–3741. doi:10.1021/JE1002708/ASSET/IMAGES/LARGE/JE-2010-002708_0003.JPEG.

Guo, Y., Tan, C., Sun, J., Li, W., Zhang, J., Zhao, C., 2020. Porous activated carbons derived from waste sugarcane bagasse for CO_2 adsorption. Chem. Eng. J. 381, 122736. doi:10.1016/J.CEJ.2019.122736.

Guo Y., Zhang H., Fu K., Chen X., Qiu M., & Fan Y. (2023). Integration of solid acid catalyst and ceramic membrane to boost amine-based CO2 desorption. *Energy, 274*, 127329. doi:10.1016/J.ENERGY.2023.127329.

Hafizi, A., Rajabzadeh, M., Khalifeh, R., 2020. Enhanced CO_2 absorption and desorption efficiency using DETA functionalized nanomagnetite/water nano-fluid. J. Environ. Chem. Eng. 8 (4), 103845. doi:10.1016/J.JECE.2020.103845.

Hara, N., Taniguchi, S., Yamaki, T., Nguyen, T.T.H., Kataoka, S., 2023. Bi-objective optimization of post-combustion CO_2 capture using methyldiethanolamine. Int. J. Greenhouse Gas Control 122, 103815. doi:10.1016/J.IJGGC.2022.103815.

Hasib-ur-Rahman, M., Siaj, M., Larachi, F., 2010. Ionic liquids for CO_2 capture—development and progress. Chem. Eng. Process. 49 (4), 313–322. doi:10.1016/J.CEP.2010.03.008.

He X., He H., Barzagli F., Amer M.W., Li C., & Zhang R. (2023). Analysis of the energy consumption in solvent regeneration processes using binary amine blends for CO2 capture. *Energy, 270*, 126903. doi:10.1016/J.ENERGY.2023.126903.

Helmi, M., Moazami, F., Ghaemi, A., Hemmati, A., 2023. Synthesis, characterization and performance evaluation of NaOH@Chitosan-Fe3O4 as an adsorbent for CO2 capture. Fuel 338, 127300. doi:10.1016/J.FUEL.2022.127300.

Hou, J., Sutrisna, P.D., Zhang, Y., Chen, V., 2016. Formation of ultrathin, continuous metal–organic framework membranes on flexible polymer substrates. Angew. Chem. Int. Ed. 55 (12), 3947–3951. doi:10.1002/ANIE.201511340.

Hu, Y., Wei, J., Liang, Y., Zhang, H., Zhang, X., Shen, W., Wang, H., 2016. Zeolitic imidazolate framework/graphene oxide hybrid nanosheets as seeds for the growth of ultrathin molecular sieving membranes. Angew. Chem. 128 (6), 2088–2092. doi:10.1002/ANGE.201509213.

Ji, Y., Zhang, M., Guan, K., Zhao, J., Liu, G., Jin, W., 2019. High-performance CO_2 capture through polymer-based ultrathin membranes. Adv. Funct. Mater. 29 (33), 1900735. doi:10.1002/ADFM.201900735.

Jiang, D., Li, H., Wang, S., Cheng, X., Bartocci, P., Fantozzi, F., 2023. Insight the CO2 adsorption onto biomass-pyrolysis derived char via experimental analysis coupled with DFT calculation. Fuel 332, 125948. doi:10.1016/J.FUEL.2022.125948.

Kiani, A., Jiang, K., Feron, P., 2020. Techno-economic assessment for CO_2 capture from air using a conventional liquid-based absorption process. Front. Energy Res. 8, 92. doi:10.3389/FENRG.2020.00092/BIBTEX.

Kondaveeti, S., Abu-Reesh, I.M., Mohanakrishna, G., Bulut, M., Pant, D., 2020. Advanced routes of biological and bio-electrocatalytic carbon dioxide (co2) mitigation toward carbon neutrality. Front. Energy Res. 8, 94. doi:10.3389/FENRG.2020.00094/BIBTEX.

Kotamreddy, G., Hughes, R., Bhattacharyya, D., Stolaroff, J., Hornbostel, K., Matuszewski, M., Omell, B., 2019. Process modeling and techno-economic analysis of a CO_2 capture process using fixed bed reactors with a microencapsulated solvent. Energy Fuels 33 (8), 7534–7549. doi:10.1021/ACS.ENERGYFUELS.9B01255/SUPPL_FILE/EF9B01255_SI_001.PDF.

Kum, J., Oh, H.T., Park, J., Kang, J.H., Lee, C.H., 2023. Techno-economic analysis and optimization of a CO_2 absorption process with a solvent looping system at the absorber using an MDEA/PZ blended solvent for steam methane reforming. Chem. Eng. J. 455, 140685. doi:10.1016/J.CEJ.2022.140685.

Lee, J.W., Torres Pineda, I., Lee, J.H., Kang, Y.T., 2016. Combined CO2 absorption/regeneration performance enhancement by using nanoabsorbents. Appl. Energy 178, 164–176. doi:10.1016/J.APENERGY.2016.06.048.

Li, H., Guo, H., Shen, S., 2020. Low-Energy-Consumption CO_2 capture by liquid-solid phase change absorption using water-lean blends of amino acid salts and 2-alkoxyethanols. ACS Sustain. Chem. Eng. 8 (34), 12956–12967. doi:10.1021/ACSSUSCHEMENG.0C03525/ASSET/IMAGES/LARGE/SC0C03525_0008.JPEG.

Li, P., Chen, H., Schott, J.A., Li, B., Zheng, Y., Mahurin, S.M., Jiang, D.E., Cui, G., Hu, X., Wang, Y., Li, L., Dai, S., 2019. Porous liquid zeolites: hydrogen bonding-stabilized H-ZSM-5 in branched ionic liquids. Nanoscale 11 (4), 1515–1519. doi:10.1039/C8NR07337F.

Li, T., Yang, C., Tantikhajorngosol, P., Sema, T., Tontiwachwuthikul, P., 2022. Experimental investigations of CO_2 absorption and catalyst-aided CO_2 desorption performance of several different amines blending with a promoter. Chem. Eng. Sci. 264, 118177. doi:10.1016/J.CES.2022.118177.

Li, T., Yu, Q., Barzagli, F., Li, C., Che, M., Zhang, Z., Zhang, R., 2023. Energy efficient catalytic CO_2 desorption: mechanism, technological progress and perspective. Carbon Capture Sci. Technol. 6, 100099. doi:10.1016/J.CCST.2023.100099.

(Henry) Liang, Z., Rongwong, W., Liu, H., Fu, K., Gao, H., Cao, F., Zhang, R., Sema, T., Henni, A., Sumon, K., Nath, D., Gelowitz, D., Srisang, W., Saiwan, C., Benamor, A., Al-Marri, M., Shi, H., Supap, T., Chan, C., … Tontiwachwuthikul, P.(PT)., 2015. Recent progress and new developments in post-combustion carbon-capture technology with amine based solvents. Int. J. Greenh. Gas Control 40, 26–54. doi:10.1016/J.IJGGC.2015.06.017.

Liu, M., Xie, K., Nothling, M.D., Zu, L., Zhao, S., Harvie, D.J.E., Fu, Q., Webley, P.A., Qiao, G.G., 2021. Ultrapermeable composite membranes enhanced via doping with amorphous MOF nanosheets. ACS Cent. Sci. 7 (4), 671–680. doi:10.1021/ACSCENTSCI.0C01711/ASSET/IMAGES/LARGE/OC0C01711_0006.JPEG.

Ma, M., Liu, Y., Chen, Y., Jing, G., Lv, B., Zhou, Z., Zhang, S., 2023. Regulatory mechanism of a novel non-aqueous absorbent for CO2 capture using 2-amino-2-methyl-1-propanol: low viscosity and energy efficient. J. CO_2 Util. 67, 102277. doi:10.1016/J.JCOU.2022.102277.

Mishra, N.K., Patil, N., Yi, S., Hopkinson, D., Grunlan, J.C., Wilhite, B.A., 2021. Highly selective hollow fiber membranes for carbon capture via in-situ layer-by-layer surface functionalization. J. Memb. Sci. 633, 119381. doi:10.1016/J.MEMSCI.2021.119381.

Mondal, M.K., Balsora, H.K., Varshney, P., 2012a. Progress and trends in CO_2 capture/separation technologies: a review. Energy 46 (1), 431–441. doi:10.1016/J.ENERGY.2012.08.006.

Mondal, M.K., Balsora, H.K., Varshney, P., 2012b. Progress and trends in CO_2 capture/separation technologies: a review. Energy 46 (1), 431–441. doi:10.1016/J.ENERGY.2012.08.006.

Mousavi, S.B., Heidari, M., Rahmani, F., Akbari Sene, R., Clough, P.T., Ozmen, S., 2023. Highly robust ZrO_2-stabilized CaO nanoadsorbent prepared via a facile one-pot MWCNT-template method for CO2 capture under realistic calcium looping conditions. J. Clean. Prod. 384, 135579. doi:10.1016/J.JCLEPRO.2022.135579.

Mukherjee, A., Okolie, J.A., Abdelrasoul, A., Niu, C., Dalai, A.K., 2019. Review of post-combustion carbon dioxide capture technologies using activated carbon. J. Environ. Sci. 83, 46–63. doi:10.1016/J.JES.2019.03.014.

Mukherjee, A., Okolie, J.A., Niu, C., Dalai, A.K., 2022. Techno – Economic analysis of activated carbon production from spent coffee grounds: comparative evaluation of different production routes. Energy Convers. Manag. 14, 100218. doi:10.1016/j.ecmx.2022.100218.

Nazir, G., Rehman, A., Park, S.J., 2021. Role of heteroatoms (nitrogen and sulfur)-dual doped corn-starch based porous carbons for selective CO2 adsorption and separation. J. CO_2 Util. 51, 101641. doi:10.1016/J.JCOU.2021.101641.

N.Borhani, T., Wang, M., 2019. Role of solvents in CO2 capture processes: the review of selection and design methods. Renew. Sustain. Energy Rev. 114, 109299. doi:10.1016/J.RSER.2019.109299.

Neagu, O., 2019. The link between economic complexity and carbon emissions in the european union countries: a model based on the environmental kuznets curve (EKC) approach. Sustainability 11 (17), 4753. doi:10.3390/SU11174753, 2019, Vol. 11, Page 4753.

Nwaoha, C., Saiwan, C., Tontiwachwuthikul, P., Supap, T., Rongwong, W., Idem, R., AL-Marri, M.J., Benamor, A., 2016. Carbon dioxide (CO2) capture: absorption-desorption capabilities of 2-amino-2-methyl-1-propanol (AMP), piperazine (PZ) and monoethanolamine (MEA) tri-solvent blends. J. Nat. Gas Sci. Eng. 33, 742–750. doi:10.1016/J.JNGSE.2016.06.002.

Ochedi, F.O., Yu, J., Yu, H., Liu, Y., Hussain, A., 2020. Carbon dioxide capture using liquid absorption methods: a review. Environ. Chem. Lett. 19 (1), 77–109. doi:10.1007/S10311-020-01093-8, 2020 19:1.

Oexmann, J., Kather, A., 2010. Minimising the regeneration heat duty of post-combustion CO_2 capture by wet chemical absorption: the misguided focus on low heat of absorption solvents. Int. J. Greenh. Gas Control 4 (1), 36–43. doi:10.1016/J.IJGGC.2009.09.010.

Oke, E.O., Okolo, B.I., Adeyi, O., Adeyi, J.A., Ude, C.J., Osoh, K., Otolorin, J., Nzeribe, I., Darlinton, N., Oladunni, S., 2021. Process design, techno-economic modelling, and uncertainty analysis of biodiesel production from palm kernel oil. Bioenergy Res. 1, 1–15. doi:10.1007/s12155-021-10315-y.

Okolie, J.A., Nanda, S., Dalai, A.K., Kozinski, J.A., 2021. Techno-economic evaluation and sensitivity analysis of a conceptual design for supercritical water gasification of soybean straw to produce hydrogen. Bioresour. Technol. 331, 125005. doi:10.1016/J.BIORTECH.2021.125005.

Omoarukhe, F.O., Epelle, E.I., Ogbaga, C.C., Okolie, J.A., 2023. Stochastic economic evaluation of different production pathways for renewable propylene glycol production via catalytic hydrogenolysis of glycerol. React. Chem. Eng. doi:10.1039/D2RE00281G.

Ortiz, G., J, F., 2020. Techno-economic assessment of supercritical processes for biofuel production. J. Supercrit. Fluids 160, 104788. doi:10.1016/J.SUPFLU.2020.104788.

Panja, P., McPherson, B., Deo, M., 2022. Techno-economic analysis of amine-based CO_2 capture technology: hunter plant case study. Carbon Capture Sci. Technol. 3, 100041. doi:10.1016/J.CCST.2022.100041.

Peh, S.B., Farooq, S., Zhao, D., 2023. Techno-economic analysis of MOF-based adsorption cycles for postcombustion CO_2 capture from wet flue gas. Chem. Eng. Sci. 268, 118390. doi:10.1016/J.CES.2022.118390.

Peters and Timmerhaus, 2023. Equipment Costs for Plant Design and Economics for Chemical Engineers, 5th Edition (n.d.). Peters and Timmerhaus Retrieved May 7from.

Ping, T., Dong, Y., Shen, S., 2020. Energy-efficient co2capture using nonaqueous absorbents of secondary alkanolamines with a 2-butoxyethanol cosolvent. ACS Sustain. Chem. Eng. 8 (49), 18071–18082. doi:10.1021/ACSSUSCHEMENG.0C06345/ASSET/IMAGES/LARGE/SC0C06345_0007.JPEG.

Pinto, D.D.D., Knuutila, H., Fytianos, G., Haugen, G., Mejdell, T., Svendsen, H.F., 2014. CO2 post combustion capture with a phase change solvent. Pilot plant campaign. Int. J. Greenh. Gas Control 31, 153–164. doi:10.1016/J.IJGGC.2014.10.007.

Pishro, K.A., Murshid, G., Mjalli, F.S., Naser, J., 2020. Investigation of CO_2 solubility in monoethanolamine hydrochloride based deep eutectic solvents and physical properties measurements. Chin. J. Chem. Eng. 28 (11), 2848–2856. doi:10.1016/J.CJCHE.2020.07.004.

Ruan, J., Ye, X., Wang, R., Chen, L., Deng, L., Qi, Z., 2023. Experimental and theoretical study on efficient CO2 absorption coordinated by molecules and ions of DBN and 1,2,4-triazole formed deep eutectic solvents. Fuel 334, 126709. doi:10.1016/J.FUEL.2022.126709.

Samaddoost, L., Soltani, M., Fatehifar, E., Abbasi Asl, E., 2023. Design of amine-functionalized resin via a facial method with efficient CO2 capture from air. Process Saf. Environ. Prot. 171, 18–27. doi:10.1016/J.PSEP.2023.01.008.

Samanta, A., Zhao, A., Shimizu, G.K.H., Sarkar, P., Gupta, R., 2012. Post-combustion CO_2 capture using solid sorbents: a review. Ind. Eng. Chem. Res. 51 (4), 1438–1463. doi:10.1021/IE200686Q/ASSET/IMAGES/LARGE/IE-2011-00686Q_0013.JPEG.

Selyanchyn, O., Selyanchyn, R., Fujikawa, S., 2020. Critical role of the molecular interface in double-layered pebax-1657/PDMS nanomembranes for highly efficient CO2/N2Gas separation. ACS Appl. Mater. Interfaces 12 (29), 33196–33209. doi:10.1021/ACSAMI.0C07344/ASSET/IMAGES/LARGE/AM0C07344_0004.JPEG.

Sema, T., Naami, A., Fu, K., Edali, M., Liu, H., Shi, H., Liang, Z., Idem, R., Tontiwachwuthikul, P., 2012. Comprehensive mass transfer and reaction kinetics studies of CO2 absorption into aqueous solutions of blended MDEA–MEA. Chem. Eng. J. 209, 501–512. doi:10.1016/J.CEJ.2012.08.016.

Shah, S., Shah, M., Shah, A., Shah, M., 2020. Evolution in the membrane-based materials and comprehensive review on carbon capture and storage in industries. Emergent Mater. 3 (1), 33–44. doi:10.1007/S42247-020-00069-2/METRICS.

Sharif, M., Fan, H., Wu, X., Yu, Y., Zhang, T., Zhang, Z., 2023. Assessment of novel solvent system for CO2 capture applications. Fuel 337, 127218. doi:10.1016/J.FUEL.2022.127218.

Sharifian, R., Boer, L., Wagterveld, R.M., Vermaas, D.A., 2022. Oceanic carbon capture through electrochemically induced *in situ* carbonate mineralization using bipolar membrane. Chem. Eng. J. 438, 135326. doi:10.1016/J.CEJ.2022.135326.

Siefert, N.S., Agarwal, S., Shi, F., Shi, W., Roth, E.A., Hopkinson, D., Kusuma, V.A., Thompson, R.L., Luebke, D.R., Nulwala, H.B., 2016. Hydrophobic physical solvents for pre-combustion CO2 capture: experiments, computational simulations, and techno-economic analysis. Int. J. Greenh. Gas Control 49, 364–371. doi:10.1016/J.IJGGC.2016.03.014.

Singh, J., Dhar, D.W., 2019. Overview of carbon capture technology: microalgal biorefinery concept and state-of-the-art. Front. Mar. Sci. 6 (FEB), 29. doi:10.3389/FMARS.2019.00029/BIBTEX.

Smith, K.H., Ashkanani, H.E., Morsi, B.I., Siefert, N.S., 2022. Physical solvents and techno-economic analysis for pre-combustion CO2 capture: a review. Int. J. Greenh. Gas Control 118, 103694. doi:10.1016/J.IJGGC.2022.103694.

Song, C., Liu, Q., Deng, S., Li, H., Kitamura, Y., 2019. Cryogenic-based CO2 capture technologies: state-of-the-art developments and current challenges. Renew. Sustain. Energy Rev. 101, 265–278. doi:10.1016/J.RSER.2018.11.018.

Spigarelli, B.P., Kawatra, S.K., 2013. Opportunities and challenges in carbon dioxide capture. J. CO2 Util. 1, 69–87. doi:10.1016/J.JCOU.2013.03.002.

Su, X., Cunningham, M.F., Jessop, P.G., 2013. Switchable viscosity triggered by CO_2 using smart worm-like micelles. Chem. Commun. 49 (26), 2655–2657. doi:10.1039/C3CC37816K.

Sun, Q., Gao, H., Mao, Y., Sema, T., Liu, S., Journal, Z.L.-Aundefined, 2022. Efficient nickel-based catalysts for amine regeneration of CO_2 capture: from experimental to calculations verifications. Wiley Online Libr. (8) 68. doi:10.1002/aic.17706.

Tan, Z., Zhang, S., Zhao, F., Zhang, R., Tang, F., You, K., Luo, H., Zhang, X., 2023. SnO2/ATP catalyst enabling energy-efficient and green amine-based CO2 capture. Chem. Eng. J. 453, 139801. doi:10.1016/J.CEJ.2022.139801.

Tavakoli, A., Rahimi, K., Saghandali, F., Scott, J., Lovell, E., 2022. Nanofluid preparation, stability and performance for CO_2 absorption and desorption enhancement: a review. J. Environ. Manag. 313, 114955. doi:10.1016/J.JENVMAN.2022.114955.

Thitakamol, B., Veawab, A., Aroonwilas, A., 2007. Environmental impacts of absorption-based CO_2 capture unit for post-combustion treatment of flue gas from coal-fired power plant. Int. J. Greenh. Gas Control 1 (3), 318–342. doi:10.1016/S1750-5836(07)00042-4.

Tin, P.S., Chung, T.S., Liu, Y., Wang, R., 2004. Separation of CO2/CH4 through carbon molecular sieve membranes derived from P84 polyimide. Carbon N Y 42 (15), 3123–3131. doi:10.1016/j.carbon.2004.07.026.

Tuinier, M.J., Hamers, H.P., Van Sint Annaland, M., 2011. Techno-economic evaluation of cryogenic CO_2 capture—A comparison with absorption and membrane technology. Int. J. Greenh. Gas Control 5 (6), 1559–1565. doi:10.1016/J.IJGGC.2011.08.013.

Turton R., Bailie R., Whiting W., & Shaeiwitz J. (2008). Analysis, Synthesis and Design of Chemical Processes. https://books.google.com/books?hl=en™lr=™id=kWXyhVXztZ8C™oi=fnd™pg=PT3™ots=p_pSrzrRvy™sig=M9-QGxscO6yMBwxwlKVsjdLnyb8

Valluri, S., Kawatra, S.K., 2021. Use of frothers to improve the absorption efficiency of dilute sodium carbonate slurry for post combustion CO2 capture. Fuel Process. Technol. 212, 106620. doi:10.1016/J.FUPROC.2020.106620.

van der Spek, M., Sanchez Fernandez, E., Eldrup, N.H., Skagestad, R., Ramirez, A., Faaij, A., 2017. Unravelling uncertainty and variability in early stage techno-economic assessments of carbon capture technologies. Int. J. Greenh. Gas Control 56, 221–236. doi:10.1016/j.ijggc.2016.11.021.

Wei, K., Xing, L., Li, Y., Xu, T., Li, Q., Wang, L., 2022. Heteropolyacid modified Cerium-based MOFs catalyst for amine solution regeneration in CO_2 capture. Sep. Purif. Technol. 293, 121144. doi:10.1016/J.SEPPUR.2022.121144.

Wu, Y., Xu, J., Mumford, K., Stevens, G.W., Fei, W., Wang, Y., 2020. Recent advances in carbon dioxide capture and utilization with amines and ionic liquids. Green Chem. Eng. 1 (1), 16–32. doi:10.1016/J.GCE.2020.09.005.

Xing, L., Wei, K., Li, Q., Wang, R., Zhang, S., Wang, L., 2020. One-step synthesized SO42−/ZrO2-HZSM-5 solid acid catalyst for carbamate decomposition in CO_2 capture. Environ. Sci. Technol. 54 (21), 13944–13952. doi:10.1021/ACS.EST.0C04946/ASSET/IMAGES/MEDIUM/ES0C04946_M008.GIF.

Yadav, S., Mondal, S.S., 2019. A complete review based on various aspects of pulverized coal combustion. Int. J. Energy Res. 43 (8), 3134–3165. doi:10.1002/ER.4395.

Yang, Z., Khan, T.S., Alshehhi, M., AlWahedi, Y.F., 2018. Economic assessment of carbon capture by minichannel absorbers. AlChE J. 64 (2), 620–631. doi:10.1002/AIC.15919.

Yates, J., Daiyan, R., Patterson, R., Egan, R., Amal, R., Ho-Baille, A., Chang, N.L., 2020. Techno-economic analysis of hydrogen electrolysis from off-grid stand-alone photovoltaics incorporating uncertainty analysis. Cell Rep. Phys. Sci. 1 (10), 100209. doi:10.1016/J.XCRP.2020.100209.

Yin, Q., Mao, W., Chen, D., Song, C., 2023. Effect of adding tertiary amine TMEDA and space hindered amine DACH on the CO_2 chemical absorption-microalgae conversion system. Energy 263, 125726. doi:10.1016/J.ENERGY.2022.125726.

Yun, S., Jang, M.G., Kim, J.K., 2021. Techno-economic assessment and comparison of absorption and membrane CO_2 capture processes for iron and steel industry. Energy 229, 120778. doi:10.1016/J.ENERGY.2021.120778.

Yun, S., Oh, S.Y., Kim, J.K., 2020. Techno-economic assessment of absorption-based CO_2 capture process based on novel solvent for coal-fired power plant. Appl. Energy 268, 114933. doi:10.1016/J.APENERGY.2020.114933.

Zhang, R., Li, Y., Zhang, Y., Li, T., Yang, L., Li, C., Barzagli, F., Zhang, Z., 2022. Energy-saving effect of low-cost and environmentally friendly sepiolite as an efficient catalyst carrier for CO_2 capture. ACS Sustain. Chem. Eng. 11, 4353–4363. doi:10.1021/ACSSUSCHEMENG.2C06739/ASSET/IMAGES/LARGE/SC2C06739_0012.JPEG.

Zhang, X., Zhu, Z., Sun, X., Yang, J., Gao, H., Huang, Y., Luo, X., Liang, Z., Tontiwachwuthikul, P., 2019. Reducing energy penalty of CO_2 capture using fe promoted SO42-/ZrO2/MCM-41 catalyst. Environ. Sci. Technol. 53 (10), 6094–6102. doi:10.1021/ACS.EST.9B01901/ASSET/IMAGES/LARGE/ES-2019-01901Y_0006.JPEG.

Zhang, Z., Wang, T., Blunt, M.J., Anthony, E.J., Park, A.H.A., Hughes, R.W., Webley, P.A., Yan, J., 2020. Advances in carbon capture, utilization and storage. Appl. Energy 278, 115627. doi:10.1016/J.APENERGY.2020.115627.