Review of Applied Science and Technology
Volume 02, Issue 01 (2023)
Page No: 113 – 141
Doi: 10.63125/9p690n14

COMPREHENSIVE INSIGHTS INTO CO_2 CAPTURE: TECHNOLOGICAL PROGRESS AND CHALLENGES

Tamanna Rashid[1]; Dipongkar Ray Sobuj[2];

[1]. Master of Science in Chemistry, Lamar University, Texas, USA;
Email: trshormi@gmail.com

[2]. Master in Pharmacy, Daffodil International University, Dhaka, Bangladesh;
Email: raydipongkar@gmail.com

Abstract

In response to the urgent global imperative to mitigate anthropogenic climate change, carbon dioxide (CO_2) capture technologies have become critical components of decarbonization strategies across the energy, industrial, and infrastructure sectors. This systematic review provides a comprehensive and comparative analysis of current CO_2 capture methodologies, drawing from 98 peer-reviewed studies published between 2010 and 2023. The review encompasses the full spectrum of capture technologies, including chemical absorption, physical adsorption, membrane separation, cryogenic methods, direct air capture (DAC), and hybrid or integrated systems. A structured search and selection process was conducted using the PRISMA 2020 framework, retrieving literature from major databases such as Scopus, Web of Science, PubMed, IEEE Xplore, and ScienceDirect. Key performance metrics—including capture efficiency, regeneration energy, operational scalability, environmental impact, and lifecycle emissions—were synthesized thematically and compared across technologies. Chemical absorption, particularly using monoethanolamine (MEA) and blended amines, remains the most mature technology, demonstrating high removal efficiency but incurring significant energy and environmental costs due to solvent degradation, corrosion, and thermal regeneration. Solid adsorption systems utilizing porous materials such as zeolites, activated carbon, and metal-organic frameworks (MOFs) showed promising low-energy alternatives, although scale-up constraints and moisture sensitivity limit current deployment. Membrane-based systems exhibited operational simplicity and adaptability in high-pressure environments but were limited by fouling and the permeability–selectivity trade-off. Cryogenic separation demonstrated high-purity CO_2 recovery and viability in niche applications, yet was hindered by its thermodynamic intensity and infrastructure demands. DAC technologies offered unique potential for atmospheric CO_2 removal, but their high energy requirements and material costs present substantial barriers to economic scalability. Hybrid systems, integrating complementary mechanisms, emerged as effective configurations for industrial decarbonization, though they entail higher capital investment and control complexity. Lifecycle assessment across all technologies revealed that environmental performance is highly dependent on energy source, material durability, and system integration. The review concludes that no single technology is universally optimal; rather, selection and implementation must be context-specific, guided by techno-economic evaluations, environmental trade-offs, and long-term system integration potential.

Keywords
CO_2 Capture Technologies; Carbon Utilization; Chemical Absorption; Direct Air Capture (DAC); Climate Change Mitigation

Citation:
Rashid, T. & Sobuj, D. R., (2023). Comprehensive insights into co_2 capture: technological progress and challenges. *Review of Applied Science and Technology*, 2(1), 113–141. https://doi.org/10.63125/9p690n14

Received:
May 20, 2023

Revised:
June 14, 2023

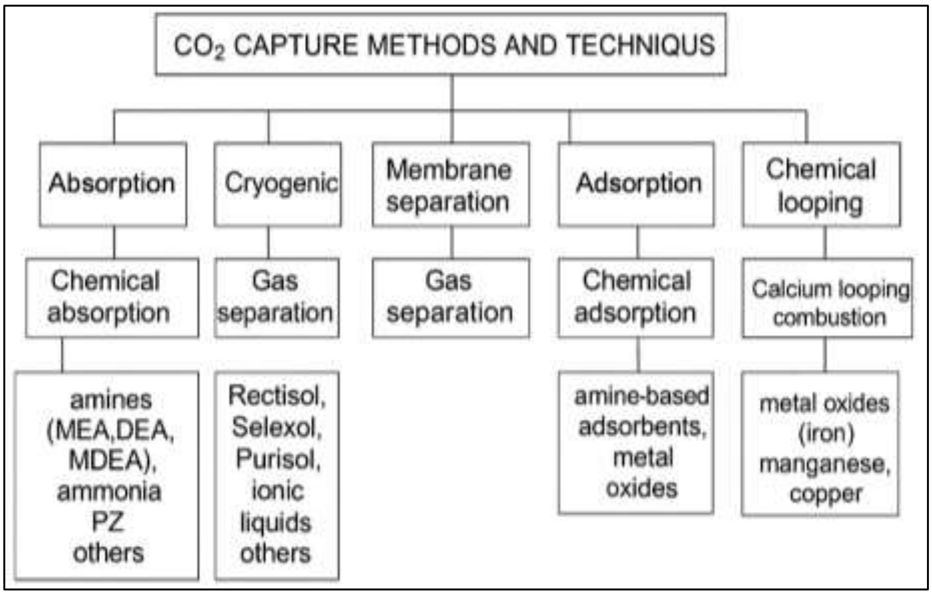
Accepted:
July 18, 2023

Published:
August 25, 2023

INTRODUCTION

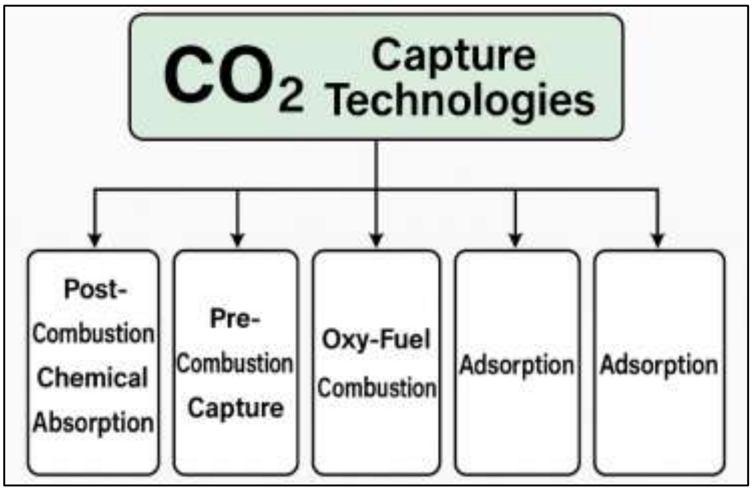
Carbon dioxide (CO_2) capture refers to the suite of technological processes aimed at separating CO_2 from industrial and energy-related sources before or after its release into the atmosphere (Raganati et al., 2021). It constitutes a foundational element in the global effort to mitigate anthropogenic climate change by directly reducing CO_2 emissions from fossil fuel combustion and industrial processes (Zukal et al., 2010). The Intergovernmental Panel on Climate Change classifies carbon capture as one of the essential mechanisms for achieving net-zero emissions within this century, particularly in hard-to-abate sectors such as cement, steel, and chemical manufacturing. Carbon capture does not only relate to post-combustion systems but also encompasses pre-combustion capture, oxy-fuel combustion, and more recently, direct air capture (Siriwardane et al., 2005). It is distinct from carbon sequestration, which refers to the long-term geological or biological storage of CO_2 after its capture. Since the Kyoto Protocol and subsequently the Paris Agreement, international policy frameworks have consistently highlighted the role of carbon capture technologies in stabilizing atmospheric greenhouse gas concentrations (Knowles et al., 2005). Moreover, international collaborations such as Mission Innovation and the Carbon Sequestration Leadership Forum have mobilized research and funding for capture technologies. CO_2 capture is central to strategies of climate mitigation, particularly in scenarios involving continued fossil fuel use with emissions control. Various terminologies including carbon capture and storage (CCS), carbon capture and utilization (CCU), and carbon dioxide removal (CDR) reflect the breadth and diversification of the field (Yongwei et al., 2018). These technologies have evolved from concept to pilot to commercial-scale demonstration in several regions including North America, Europe, and parts of Asia, illustrating their global significance and operational complexity (Sharma & Dhir, 2020).

Figure 1: Overview of Carbon dioxide (CO_2) capture



The technological landscape of CO_2 capture comprises several core methodologies categorized by the state of the source stream and the point of capture. The most established form is post-combustion chemical absorption, typically using aqueous amine-based solvents such as monoethanolamine (MEA) or diethanolamine (DEA) to selectively bind CO_2 from flue gas streams. Pre-combustion capture, often applied in integrated gasification combined cycle (IGCC) systems, involves removing CO_2 from syngas before combustion, using solvents like Selexol or Rectisol (Simmons et al., 2011). Oxy-fuel combustion captures CO_2 by burning fuels in pure oxygen rather than air, producing a concentrated stream of CO_2 and water vapor that can be easily separated. Adsorption techniques, such as pressure swing adsorption (PSA) and temperature swing adsorption (TSA), utilize solid porous materials like activated carbon, zeolites, and more recently, metal-organic frameworks (MOFs) to selectively trap CO_2 molecules. Membrane-based separations employ polymers or hybrid materials with selective permeability to CO_2, enabling energy-efficient separation from flue gas or syngas. Cryogenic distillation leverages differences in boiling points to separate CO_2 at low temperatures and is particularly suited for high-concentration streams (Hauchhum & Mahanta, 2014). Each technique operates under distinct thermodynamic, economic, and operational constraints, necessitating tailored application to specific industrial conditions (Al-Shargabi et al., 2022). Furthermore, hybrid systems combining different mechanisms are increasingly explored to optimize capture efficiency and reduce regeneration penalties. These categories represent not just academic constructs but the foundation for industrial implementation, forming the basis of numerous pilot and commercial-scale initiatives globally.

Figure 2: Conceptual Framework of CO_2 Capture Technologies



Chemical absorption remains the most extensively deployed technology due to its maturity, modularity, and compatibility with retrofitted coal and gas-fired power plants (Knowles et al., 2005). However, its widespread application is often constrained by the high thermal energy required for solvent regeneration, degradation of solvents over time, and associated operational emissions such as nitrosamines and aerosols. In response, alternative solvents—such as blended amines, ammonia-based systems, amino acid salts, and ionic liquids—have been investigated for improved thermal stability, lower regeneration energy, and enhanced absorption rates. Phase-change solvents and encapsulated absorbents represent an innovation aimed at reducing energy use by leveraging thermodynamically favorable reactions and improving reaction kinetics. The industrial deployment of amine systems continues in several countries, supported by projects such as Boundary Dam in Canada, Petra Nova in the U.S., and Longship in Norway (IEAGHG, 2019). These efforts have informed not only the technical feasibility but also the logistical and economic requirements of commercial-scale chemical absorption (Yongwei et al., 2018). Furthermore, process intensification strategies such as microchannel reactors and membrane-assisted contactors have emerged to reduce equipment footprint and enhance mass transfer efficiency. Nonetheless, extensive research continues to refine solvents, reduce corrosion, and implement effective process controls. These operational and chemical insights serve as the groundwork for assessing viability across diverse industrial scenarios, including petrochemical plants, cement kilns, and waste-to-energy facilities.

Direct air capture (DAC) represents a novel and increasingly studied domain within CO_2 capture, targeting atmospheric concentrations of CO_2 typically around 420 ppm (Sharma & Dhir, 2020). Unlike flue gas systems, DAC operates independently of emission sources and can be co-located with storage or utilization sites, offering logistical flexibility. DAC systems generally employ liquid alkaline solutions such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), or solid sorbents functionalized with amines, hydroxides, or metal oxides. Liquid systems require high-temperature regeneration, typically via calcination, while solid systems often employ low-grade heat for desorption. Techno-economic analyses reveal that DAC remains more expensive than point-source capture, with cost estimates ranging from $100 to $600 per ton of CO_2 depending on technology maturity, energy source, and system design (Simmons et al., 2011). Operational projects such as Climeworks (Switzerland) and Carbon Engineering (Canada) demonstrate the technical feasibility of

DAC under diverse climate and economic conditions. However, these implementations require significant infrastructure, including air contactors, heat exchangers, and integration with renewable energy systems to maintain net carbon negativity. Material durability, regeneration cycles, and land use intensity are additional constraints under scrutiny. Although DAC offers a pathway for negative emissions, particularly in the context of carbon offsetting, its viability rests on continual refinement of capture media, process optimization, and integration into industrial ecosystems.

The objective of this comprehensive review is to provide a detailed and structured evaluation of current carbon dioxide (CO_2) capture technologies, focusing on their operational principles, engineering performance, material design, and technological maturity across different industrial contexts. The review aims to systematically explore the dominant capture mechanisms, including chemical absorption, physical adsorption, membrane separation, cryogenic techniques, and direct air capture, outlining how each operates in post-combustion, pre-combustion, and ambient conditions. By dissecting these technologies, the paper seeks to highlight their respective advantages, limitations, and areas of optimization, with attention to parameters such as energy consumption, scalability, material stability, and environmental footprint. In addition to the scientific and engineering perspectives, the paper also investigates the integration potential of capture technologies with carbon utilization systems, such as those involved in the synthesis of fuels, chemicals, and construction materials, as a means to establish circular carbon pathways. An equally important goal is to identify the critical challenges hindering large-scale deployment, including cost barriers, degradation issues, infrastructure compatibility, and technical bottlenecks related to gas purity, pressure conditions, and regeneration techniques. The review is structured to enable comparison across methods while recognizing the diversity in capture scenarios, from large stationary sources like power plants and cement kilns to distributed systems and atmospheric extraction. Furthermore, the review intends to offer a classification of technologies based on their readiness levels and practical application domains, distinguishing between those already implemented at commercial scale and those still in experimental or pilot phases. In sum, this review serves as a comprehensive resource for researchers, engineers, and policymakers aiming to assess the current landscape of CO_2 capture and make informed decisions on deployment strategies, research investments, and technology development aimed at reducing industrial carbon emissions and facilitating the transition to a low-carbon economy.

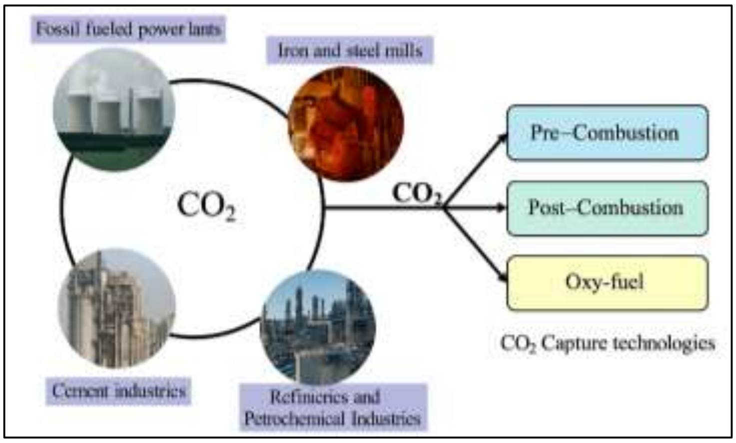
LITERATURE REVIEW

The academic discourse on carbon dioxide (CO_2) capture technologies has evolved significantly over the past two decades, shaped by growing global recognition of the environmental, economic, and industrial necessity to mitigate greenhouse gas emissions. This literature review critically examines the trajectory of research surrounding CO_2 capture systems, with particular attention to the scientific foundations, material innovations, process configurations, and techno-economic assessments presented in peer-reviewed journals, technical reports, and governmental publications. The progression from conventional post-combustion absorption to advanced direct air capture and hybrid solutions reflects an increasingly interdisciplinary landscape encompassing chemical engineering, materials science, environmental policy, and systems integration. This section dissects both established and emergent technologies, uncovering the breadth of experimentation with solvents, adsorbents, membranes, and thermodynamic cycles that form the technological backbone of current CO_2 capture systems. Moreover, it contextualizes these developments within the wider framework of industrial decarbonization and climate governance, highlighting not only technical feasibility but also deployment constraints and lifecycle implications. Through thematic segmentation, the literature review delineates the state-of-the-art methodologies and comparative performance metrics associated with each capture approach, tracing their evolution, current applications, and optimization strategies. In doing so, the review seeks to identify critical research gaps, standardization deficiencies, and unresolved operational challenges that warrant deeper scientific inquiry. Each subsection integrates findings from laboratory-scale studies, pilot projects, and industrial-scale deployments to form a coherent narrative around technological maturation and real-world implementation. Rather than merely cataloging technologies, the review aims to synthesize insights into their systemic roles, illustrating how various capture strategies align with sector-specific emissions profiles and regional infrastructure contexts. This structure allows for a multifaceted understanding of CO_2 capture as not only a technological intervention but also a dynamic component of low-carbon innovation pathways.

CO_2 Capture Research

Research into CO_2 capture technologies has developed over decades in response to rising concerns over anthropogenic climate change and the role of carbon dioxide as a dominant greenhouse gas. The conceptual foundations of CO_2 separation date back to industrial gas purification processes, where early solvent-based techniques such as chemical absorption with monoethanolamine (MEA) were used in natural gas processing long before their climate mitigation potential was explored (Dasgupta et al., 2015). Early CO_2 capture research primarily focused on post-combustion systems due to their compatibility with existing fossil fuel power plants. As environmental science and climate policy gained momentum in the late 20th century, studies began investigating the application of these processes to flue gas treatment from coal-fired power stations (Li et al., 2013). The IPCC's Third and Fourth Assessment Reports emphasized the potential role of carbon capture and storage (CCS) in stabilizing atmospheric CO_2 concentrations, triggering an increase in funding and publications on the topic. Governmental initiatives like the U.S. DOE's Carbon Sequestration Program and the European Union's Emissions Trading System incentivized demonstration projects and techno-economic studies. By the 2010s, a range of technologies including post-combustion absorption, pre-combustion capture, and oxy-fuel combustion were undergoing pilot testing and field-scale deployment. This phase marked a shift from theoretical and laboratory-based experiments to practical engineering implementations with increased focus on lifecycle analysis, cost modeling, and emissions accounting (Wiley et al., 2011). As scholarly attention intensified, multidisciplinary collaborations emerged, combining chemical engineering, material science, and environmental economics in addressing performance limitations and deployment feasibility. This expansion of scope transformed CO_2 capture research from a niche technical subfield to a critical component of global climate technology discourse, anchored by foundational studies that continue to inform process design and material selection today.

Figure 3: Major CO_2 Emission Sources and Associated Capture Technologies



Post-combustion chemical absorption represents the most extensively studied and operationalized CO_2 capture methodology, especially in the context of coal-fired and natural gas power generation. The absorption of CO_2 by aqueous amine solutions, particularly MEA, forms the basis of most commercial capture systems due to the high reactivity and selectivity of amines under moderate flue gas conditions. However, MEA is associated with several operational drawbacks, including high regeneration energy, solvent degradation, and corrosion, prompting researchers to investigate alternative solvents such as piperazine, methyldiethanolamine (MDEA), and blended amines (Karimi et al., 2022). Advanced solvent systems such as phase-changing absorbents and encapsulated ionic liquids have demonstrated enhanced absorption rates, lower regeneration requirements, and improved resistance to degradation in multiple studies (Blomen et al., 2009). Moreover, solvent stability and absorption kinetics have been shown to vary under different process configurations, including temperature, gas composition, and solvent flow rates, necessitating continuous performance benchmarking. Several pilot-scale demonstrations, such as the CO_2CRC Otway Project in Australia and the Boundary Dam CCS facility in Canada, have provided real-world validation of absorption systems, reinforcing their technological maturity. Microchannel absorbers and membrane-assisted contactors have also been explored to enhance mass transfer and reduce equipment footprint, further expanding the design envelope of post-combustion absorption systems. Studies continue to report challenges associated with the formation of secondary pollutants, such as nitrosamines and aerosols, particularly under dynamic flue gas conditions. Yet, the scale of technical evidence and accumulated operational data underscores the robustness and adaptability of absorption systems across various emission-intensive industries (Creamer & Gao, 2016).

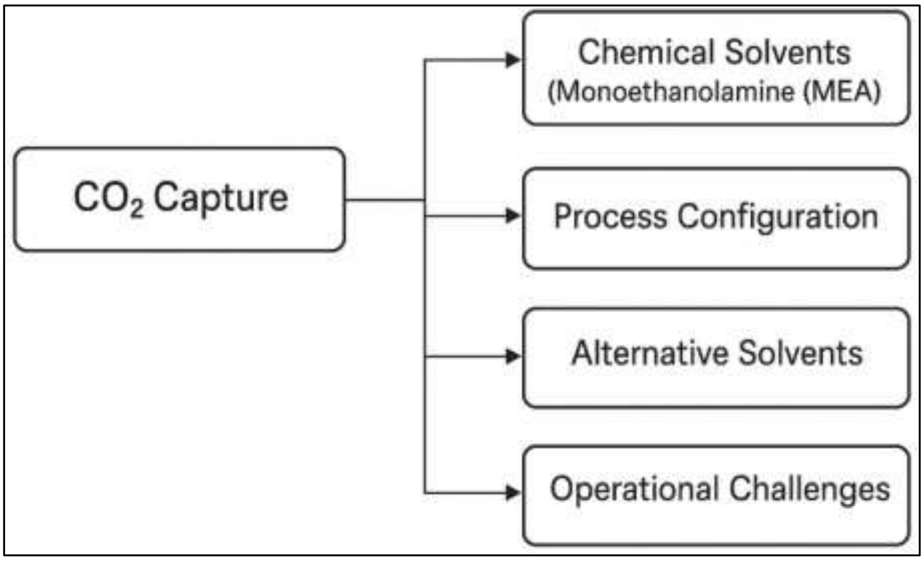
Membrane-based CO_2 separation technologies operate on the principle of selective gas permeation through semipermeable barriers, offering a mechanically simple, compact, and energy-efficient approach to CO_2 separation. These systems are particularly relevant in applications involving relatively high CO_2 concentrations, such as natural gas processing or flue gas from fossil fuel combustion. Polymeric membranes, such as cellulose acetate and polyimide, are frequently used for their manufacturability and low cost, but often face limitations in terms of selectivity and chemical stability under high temperature or moisture conditions. As a response, mixed matrix membranes incorporating fillers like MOFs, graphene oxide, and ionic liquids have been developed to improve permeability and CO_2/N_2 selectivity. Meanwhile, facilitated transport membranes use mobile carriers to enhance CO_2 flux, showing promise under low partial pressure (Zhao et al., 2009). Membrane systems are generally modular, scalable, and easily retrofitted into existing gas processing operations, making them suitable for distributed capture applications. In parallel, direct air capture (DAC) has gained visibility for its capacity to remove CO_2 directly from ambient air, regardless of emission source. DAC systems employ either liquid alkaline solutions or solid sorbents, with regeneration driven by heat or vacuum pressure. Though DAC requires significantly higher energy input due to the low concentration of atmospheric CO_2, its flexibility and scalability have spurred experimental deployment, notably by companies such as Climeworks and Carbon Engineering. Economic analyses of DAC highlight the capital intensity and dependence on low-cost, low-carbon energy sources, while operational studies underscore the need for durable materials and optimized system configurations (Huttenhuis et al., 2016). Together, membrane separation and DAC systems broaden the technological spectrum of CO_2 capture, illustrating varied approaches tailored to specific source concentrations and operational settings.

Post-Combustion Chemical Absorption Systems

Post-combustion chemical absorption has remained the most widely adopted and investigated method for CO_2 capture due to its compatibility with existing fossil fuel-based power generation infrastructure and industrial sources. The foundational mechanism involves the selective reaction of carbon dioxide with chemical solvents, most commonly monoethanolamine (MEA), to form carbamate compounds that are subsequently regenerated via heat to release high-purity CO_2. MEA has been extensively validated through decades of industrial application and laboratory studies, praised for its high reactivity, well-understood thermodynamics, and relative affordability. However, studies have consistently identified several drawbacks associated with MEA systems, including high energy consumption during solvent regeneration, corrosiveness, oxidative degradation, and limited cyclic capacity (Jiang et al., 2020). Operational studies conducted at large-scale pilot plants, such as the COORAL demonstration in Germany and the Boundary Dam project in Canada, have reinforced these concerns, revealing issues related to solvent loss, secondary pollutant formation, and aerosol emissions. Moreover, long-term degradation of MEA under flue gas conditions contributes to the generation of harmful byproducts such as nitrosamines, raising additional environmental and health concerns. These findings have led to comparative research on a wide variety of alternative amine formulations, such as methyldiethanolamine (MDEA), piperazine (PZ), and diethanolamine (DEA), each offering varying performance characteristics in terms of absorption rate, regeneration energy, and degradation resistance (Wiley et al., 2011). Although MEA remains the benchmark solvent in both experimental and commercial contexts, the limitations evidenced across field applications have driven ongoing efforts to benchmark its performance against more thermally and chemically robust alternatives (Bennaceur, 2008).

The search for improved absorption systems has led to extensive experimentation with blended amines and modified solvent systems that aim to overcome the performance deficits of conventional MEA-based processes. Blended amines such as MEA-MDEA and PZ-MDEA combinations have demonstrated improved CO_2 loading capacities, reduced energy demand during regeneration, and enhanced oxidative stability. Piperazine, in particular, has gained attention for its rapid absorption kinetics and ability to function effectively at higher concentrations and temperatures, improving solvent working capacity and process efficiency (Sun et al., 2012). These characteristics have been confirmed in bench-scale and pilot-scale studies showing that blended solvents reduce solvent circulation rates and the reboiler duty, which are critical factors in reducing the operational cost of capture units. Ammonia-based systems, though less common, have also been studied for their non-corrosive properties and lower regeneration energy requirements, but their application is limited by higher volatility and the potential for ammonia slip. Amino acid salts, another emerging class, offer non-volatility and thermal stability, and have shown promising cyclic capacity and environmentally benign degradation products in comparative analyses (Akhtar et al., 2012). Additionally, solvent design strategies now include the development of sterically hindered amines and polyamines that enhance CO_2 capture efficiency by increasing carbamate stability and facilitating faster reaction rates (Kuramochi et al., 2012). Performance studies across multiple facilities have validated these findings, with several blended and modified systems outperforming MEA in long-duration tests in terms of both CO_2 capture rate and solvent life expectancy (Voldsund et al., 2019). These collective advancements reflect a maturing solvent design approach focused on thermodynamic optimization, operational resilience, and chemical sustainability.

Figure 4: Conceptual Framework of Post-Combustion Chemical Absorption Systems



The evolution of post-combustion absorption technologies has not only depended on solvent chemistry but also on innovations in process configuration and system integration. Studies have increasingly focused on enhancing gas-liquid contact efficiency, reducing equipment size, and improving thermal management through engineering interventions (Akhtar et al., 2012). Membrane-assisted absorption processes have emerged as promising solutions, utilizing membrane contactors to facilitate efficient phase separation, reduce solvent losses, and increase CO_2 mass transfer rates without increasing the solvent volume. Similarly, packed bed reactors with novel packing materials and microstructured channels have shown improved fluid dynamics, lowering pressure drop and enhancing absorber performance. The implementation of intercooling strategies in absorber columns has also demonstrated improved reaction thermodynamics by maintaining optimal temperature gradients along the column, resulting in higher CO_2 absorption rates and lower energy penalties. In addition to equipment design, heat integration strategies such as heat exchangers for energy recovery between the stripper and absorber have gained prominence for reducing the overall heat demand of the regeneration cycle. Studies examining pilot and commercial-scale systems underscore the importance of process control systems and operational flexibility in responding to dynamic flue gas conditions, which can otherwise destabilize absorption efficiency and solvent performance (Su et al., 2014). Finally, techno-economic models based on integrated configurations consistently demonstrate lower levelized cost of CO_2 captured (LCOC) when combining advanced solvents with energy-efficient process designs, confirming the value of engineering innovations in bridging the gap between lab-scale efficiency and industrial feasibility.

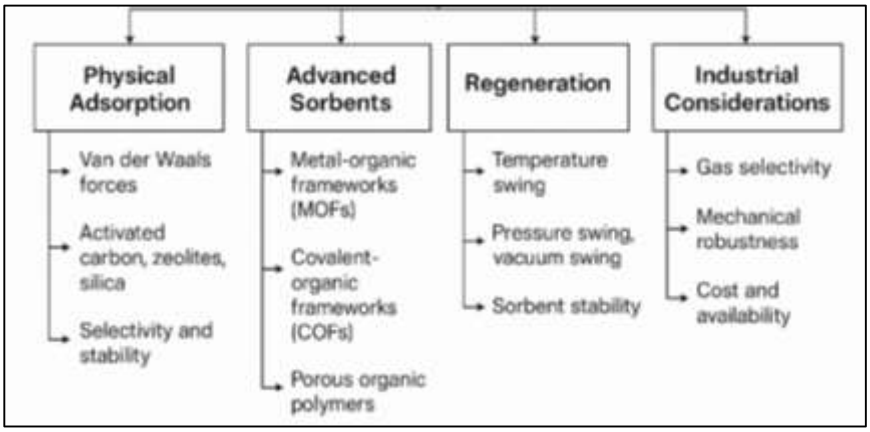
While chemical absorption remains a technologically mature and commercially proven solution, numerous operational and environmental challenges persist in industrial contexts. Corrosion of process equipment due to acidic byproducts, oxygen ingress, and solvent degradation remains one of the most frequently reported maintenance concerns in full-scale absorption units (Akhtar et al., 2012). This issue not only affects the lifespan of metallic components but also contributes to unplanned shutdowns and increased operational costs. Additionally, solvent degradation due to thermal and oxidative stress produces heat-stable salts and low-molecular-weight amines that cannot be regenerated, necessitating continuous solvent replacement and waste handling (Kuramochi et al., 2012). Several studies have reported the release of volatile degradation products such as ammonia, formaldehyde, and nitrosamines, which can pose occupational health and environmental risks, particularly in systems lacking appropriate emission control technologies (Sun et al., 2012). These emissions are further exacerbated under fluctuating load operations, common in modern power plants operating alongside intermittent renewable energy sources. Moreover, water consumption in absorber columns and cooling units represents an environmental footprint that must be managed carefully, especially in water-scarce regions. Solvent recovery systems, anti-foaming agents, and corrosion inhibitors are typically deployed to mitigate these effects, yet their own environmental impacts and costs are subjects of continued scrutiny (Akhtar et al., 2012). Lifecycle assessments comparing various amine-based systems reveal differing impacts based on raw material sourcing, degradation rates, and end-of-life disposal requirements. Ultimately, these constraints emphasize the need for comprehensive environmental monitoring and process adaptation strategies in industrial-scale chemical absorption operations to maintain regulatory compliance and economic viability.

Solid Sorbents and Physical Adsorption Platforms

The use of solid sorbents for CO_2 capture is grounded in the principles of physical adsorption, where carbon dioxide molecules adhere to the surface of porous materials via van der Waals interactions. Unlike chemical absorption systems, these interactions are weak and reversible, allowing for lower energy regeneration and increased cyclic stability (Kuramochi et al., 2012). Early developments in this field focused on naturally occurring and industrially abundant materials such as activated carbon, zeolites, and silica gels, which offered high surface areas and favorable adsorption kinetics under dry conditions (Sun et al., 2012). Zeolites, in particular, showed promise due to their well-defined pore structures and strong affinity for CO_2; however, their hydrophilic nature limited performance in humid environments typical of flue gases. Activated carbons, while cost-effective and widely available, suffer from low CO_2 selectivity, particularly in the presence of nitrogen and water vapor. These performance limitations led to intensified research efforts in developing synthetic sorbents with improved selectivity and stability. The emergence of advanced porous materials like mesoporous silica and functionalized alumina introduced new structural and chemical tunability, enabling targeted interactions with CO_2 molecules. In comparative studies, physical adsorbents consistently demonstrated higher durability and regeneration efficiency than their chemical counterparts, especially under cyclic loading and pressure swing operation. However, empirical data also showed a strong dependence on operational parameters such as pressure, temperature, and gas composition, indicating that optimal performance is context-specific (Su et al., 2014). This foundational research phase established the baseline properties for evaluating newer classes of sorbents under industrially relevant conditions.

Metal-organic frameworks (MOFs) have emerged as a leading class of solid sorbents due to their exceptionally high surface areas, customizable pore environments, and structural diversity. Comprised of metal ions coordinated with organic linkers, MOFs allow for precise control over adsorption behavior, making them ideal for selective CO_2 capture under various thermodynamic conditions. Numerous studies have demonstrated that amine-functionalized MOFs enhance CO_2 uptake through chemisorption-like interactions while preserving the low regeneration energy typical of physical adsorbents (Kuramochi et al., 2012). Functionalized MOFs such as Mg-MOF-74, ZIF-8, and UiO-66-NH_2 exhibit superior selectivity and capacity under humid and mixed-gas conditions, addressing one of the key limitations of earlier porous materials. Despite their promising properties, many MOFs remain confined to lab-scale use due to challenges in mechanical strength, moisture stability, and scale-up synthesis. Comparative performance analyses reveal that while MOFs often outperform activated carbons and zeolites in dry conditions, their sensitivity to humidity and cost of production hinder widespread deployment (Sun et al., 2012). Research has also expanded into covalent-organic frameworks (COFs) and porous organic polymers (POPs), which offer enhanced thermal and hydrothermal stability while maintaining functional surface areas for CO_2 adsorption. These organic frameworks can be chemically tailored with nitrogen-rich functional groups to increase selectivity and improve adsorption kinetics. Additionally, hybrid materials that incorporate nanostructured fillers or metal oxides into porous matrices have shown improved resistance to structural degradation and performance loss over multiple cycles (Damen et al., 2007).

Figure 5: Solid Sorbents and Physical Adsorption Platforms



The regeneration of solid sorbents is a key determinant of their operational feasibility in CO_2 capture applications, as it governs energy requirements, process continuity, and long-term material durability. Regeneration methods typically include temperature swing adsorption (TSA), pressure swing adsorption (PSA), and vacuum swing adsorption (VSA), each suited to different process configurations and energy scenarios. TSA is frequently used in systems with access to waste heat or external heating units, while PSA and VSA are preferred in modular, decentralized systems where rapid cycling and low thermal inertia are desired. Studies comparing regeneration performance across different materials have shown that zeolites, while effective at low temperatures, suffer from capacity loss due to water uptake, which interferes with CO_2 adsorption sites. MOFs, though structurally efficient, often experience partial degradation or framework collapse when exposed to repeated thermal or pressure cycling without adequate moisture control. Adsorbents with high heat of adsorption may also exhibit sluggish desorption kinetics, thereby reducing productivity in cyclic operation. To address these challenges, researchers have optimized process variables such as heating rates, desorption times, and sweep gas flow to improve energy efficiency and prevent material fatigue. In some systems, hybrid regeneration techniques combining moderate heating with vacuum pressure or inert purge gases have demonstrated better regeneration efficiency while preserving sorbent integrity. Sorbent stability over multiple adsorption-desorption cycles remains a core research concern, with material attrition, pore blockage, and chemical fouling identified as primary mechanisms for capacity degradation (Bennaceur, 2008). Long-term performance data from laboratory and pilot systems reinforce the importance of selecting sorbents that combine adsorption efficiency with structural and thermal resilience under cyclic load.

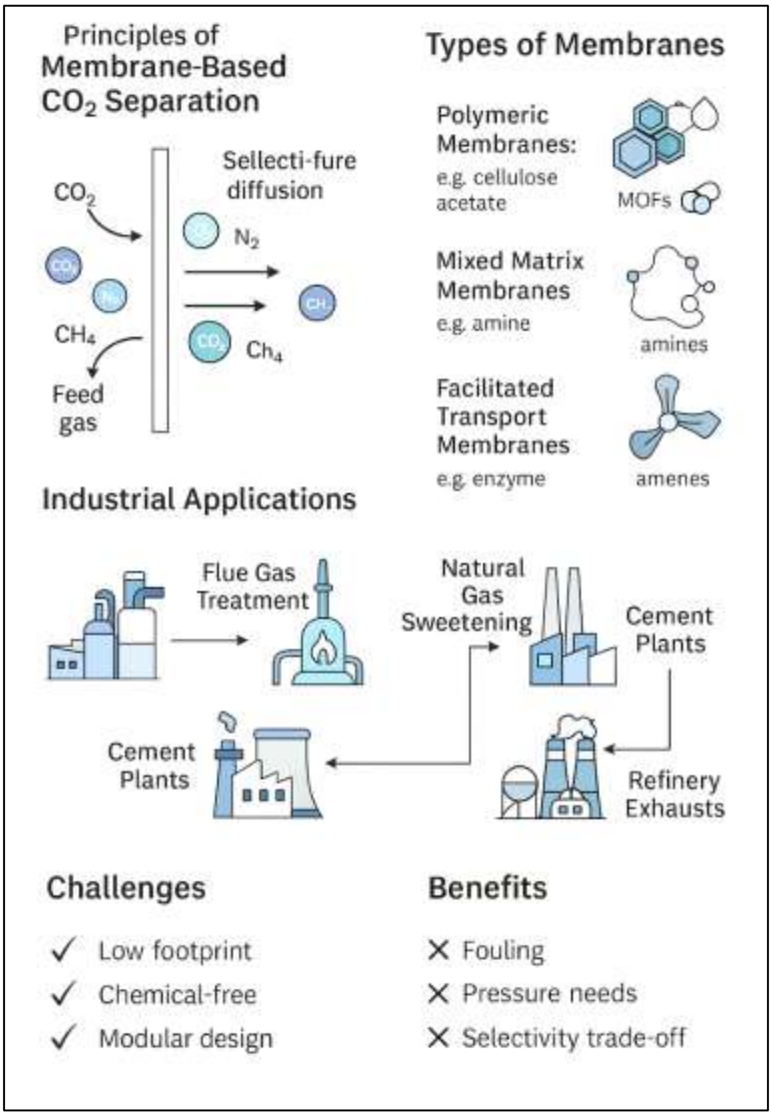
Although solid sorbents have demonstrated considerable promise in laboratory and pilot studies, their performance under industrial conditions is subject to a range of constraints that influence economic viability and deployment scalability. One of the major considerations is the sorbent's selectivity for CO_2 in the presence of other gases such as nitrogen, oxygen, sulfur oxides, and water vapor—components typical in flue gas and industrial effluents. MOFs and amine-grafted materials generally exhibit higher selectivity than traditional sorbents, but their performance can deteriorate under real gas compositions due to competitive adsorption and chemical interactions (Li et al., 2013). In addition, materials must exhibit mechanical robustness to withstand physical stresses from pelletization, reactor packing, and thermal expansion during regeneration. Studies comparing sorbents in fixed bed, moving bed, and fluidized bed configurations have highlighted differences in pressure drop, heat transfer, and mass transfer limitations, each of which affects capture efficiency and system integration. Moreover, the synthesis cost and availability of raw materials are critical factors; for instance, while MOFs offer superior performance, their complex synthesis routes and expensive precursors limit commercial scale-up. On the other hand, carbon-based materials and alumina exhibit lower performance metrics but are often favored in cost-sensitive or low-purity applications due to their abundance and recyclability. Environmental assessments of adsorbent life cycles indicate that sorbent degradation products and disposal methods must also be considered, particularly for chemically functionalized materials with toxic byproducts (Hadri et al., 2017). Collectively, these industrial and economic evaluations underscore the need for realistic performance benchmarking and lifecycle considerations when deploying physical adsorption systems in CO_2 capture applications.

Applications of Membrane-Based CO_2 Separation

Membrane-based CO_2 separation operates on the principle of selective permeation, where gases diffuse through a semi-permeable barrier at different rates based on molecular size, solubility, and diffusivity. CO_2 is separated from gas mixtures such as flue gases, natural gas, or syngas by exploiting its higher affinity and solubility in specific membrane materials (Wiley et al., 2011). Polymeric membranes have historically dominated this field due to their manufacturability, flexibility, and relatively low cost. Early membranes composed of cellulose acetate and polysulfone demonstrated moderate CO_2 permeability but suffered from low selectivity and sensitivity to contaminants and plasticization. To overcome these issues, polyimides and perfluoropolymers were introduced, offering improved chemical and thermal stability while maintaining flexible processability (Figueroa et al., 2008). However, all polymer-based membranes are inherently constrained by the permeability-selectivity trade-off known as the Robeson upper bound. To transcend this trade-off, mixed matrix membranes (MMMs) were developed by incorporating inorganic fillers such as metal-organic frameworks (MOFs), zeolites, or graphene oxide into polymer matrices, resulting in materials with superior separation performance. These MMMs have demonstrated improved CO_2/N_2 and CO_2/CH_4 selectivity, enhanced durability, and reduced susceptibility to fouling or degradation in humid conditions. Additionally, ionic liquid-infused membranes and facilitated transport membranes have been shown to enable chemically reactive or carrier-mediated CO_2 transport mechanisms, increasing permeability without compromising selectivity. These materials offer the foundational basis for the practical deployment of membrane modules in pre- and post-combustion scenarios and have been rigorously characterized in terms of permeance, resistance to impurities, and lifetime performance under cyclic operations (Wiley et al., 2011)

Membrane technologies have been increasingly integrated into industrial CO_2 capture applications, particularly in post-combustion settings and natural gas processing operations. In flue gas treatment, polymeric membranes are used to separate CO_2 from nitrogen and other trace gases in low-pressure environments. They are often applied as part of hybrid systems due to their limited performance when used alone under dilute CO_2 concentrations. In post-combustion contexts, membrane systems are valued for their low footprint, mechanical simplicity, and minimal chemical handling compared to solvent-based systems (Figueroa et al., 2008). Studies have demonstrated that membrane units can effectively remove up to 90% of CO_2 from combustion gases when staged appropriately, although performance is highly sensitive to feed composition, pressure ratio, and module configuration. In natural gas sweetening operations, where CO_2 must be separated from methane, membranes are commonly deployed due to their selectivity and resistance to acid gases such as H_2S. Cellulose acetate membranes, for instance, are widely used in offshore and remote gas processing facilities because of their compactness and low maintenance requirements. Multi-stage membrane cascades are often implemented in high-pressure applications to enhance product recovery and achieve pipeline specifications (Wiley et al., 2011). Pilot-scale demonstrations in cement plants and refineries have further validated membrane systems for selective CO_2 removal in exhaust streams containing SO_2, NO_x, and water vapor, with notable stability over long operational periods. These applications confirm the adaptability of membrane systems in a variety of industrial sectors where space, solvent use, or safety considerations limit the viability of alternative separation methods.

Figure 6: Membrane-Based CO_2 Separation Technologies Across Industrial Sectors



Facilitated transport membranes (FTMs) and bio-inspired membrane systems have expanded the landscape of CO_2 separation by introducing mechanisms beyond simple solution-diffusion. FTMs employ mobile or fixed-site chemical carriers, such as amines or carbonates, that reversibly bind CO_2, enhancing selective transport under low-partial-pressure environments. These membranes are particularly effective in conditions where traditional polymeric membranes suffer from performance degradation, such as ambient temperatures or high moisture content (Li et al., 2013). Supported ionic liquid membranes (SILMs) also fall into this category, leveraging high CO_2 solubility in task-specific ionic liquids embedded within porous supports. These systems have demonstrated high selectivity and stability during extended operations, particularly in flue gas simulations. Additionally, biomimetic membranes that incorporate carbonic anhydrase enzymes or aquaporin-inspired channels have shown record-high flux and selectivity in laboratory trials, with minimal energy penalties. These bio-functional materials mimic natural respiratory gas exchange processes, thereby allowing efficient CO_2 discrimination under physiological-like conditions. Although enzymatic stability and cost remain significant constraints, these innovations underscore the growing interest in membrane designs that emulate biological systems. Multilayered membranes with gradient functionality have also been explored, combining selective surface layers with mechanically robust support layers to prevent delamination and concentration polarization. Studies conducted in dynamic gas feed environments show that such composite designs offer improved tolerance to contaminant buildup, enhancing operational reliability. Facilitated transport and biomimetic membranes represent the convergence of chemistry, biology, and material science in engineering membranes for highly selective and efficient CO_2 capture in various process streams.

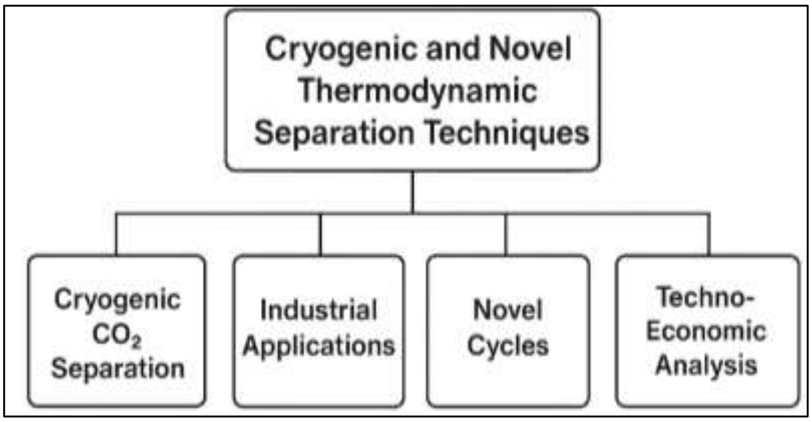
While membrane systems have shown versatility across various industrial domains, their comparative performance and system-level integration reveal a set of challenges that continue to define their operational limits. Studies consistently highlight that while membrane modules offer advantages in terms of footprint, modularity, and environmental safety, they struggle with achieving both high permeability and selectivity under real process conditions (Yan et al., 2016). For instance, flue gas streams often contain SO_2, NO_x, water vapor, and particulate matter that can foul or degrade polymer membranes, reducing their lifetime and increasing operational cost . Moreover, membranes require pressure differentials to drive permeation, which can lead to significant energy consumption when applied to low-pressure or dilute CO_2 streams such as post-combustion flue gas. Membranes are often integrated into multi-stage configurations with inter-stage compression or vacuum systems to enhance CO_2 recovery, but this increases complexity and capital cost. Compared to chemical absorption, membrane systems are less sensitive to temperature fluctuations and solvent degradation but are more vulnerable to structural failures like compaction, plasticization, and loss of selectivity over time. Techno-economic comparisons reveal that membranes are generally more cost-effective in pre-combustion or natural gas processing contexts where CO_2 partial pressures are high and impurities are minimal. In post-combustion scenarios, however, membranes often require hybridization with solvent or adsorption technologies to achieve target separation efficiencies at acceptable costs. These comparative insights underscore that while membrane systems are a valuable component of the CO_2 capture toolkit, their integration must be tailored to source conditions, operational constraints, and lifecycle considerations to be fully effective in large-scale decarbonization efforts.

Cryogenic and Novel Thermodynamic Separation Techniques

Cryogenic CO_2 separation involves cooling gas mixtures to very low temperatures to selectively liquefy or solidify CO_2 based on differences in boiling and sublimation points between constituent gases. CO_2 has a sublimation point of −78.5°C under atmospheric pressure, which allows for its separation from nitrogen, oxygen, and methane through phase transition techniques (Li et al., 2013; Subrato, 2018). Cryogenic methods are primarily applied in high-pressure gas streams where the partial pressure of CO_2 is sufficiently elevated to facilitate effective liquefaction or deposition (Ara et al., 2022). Historically used in air separation and natural gas purification, these techniques have also gained traction for CO_2 recovery from syngas and pre-combustion applications (Uddin et al., 2022). The basic process involves multistage cooling with intermediate flash stages or separation columns to concentrate CO_2 before it reaches its phase-change threshold. Process design often incorporates Joule–Thomson expansion or refrigeration cycles such as Claude or Brayton configurations to manage heat exchange and thermodynamic efficiency (Hossen & Atiqur, 2022; Wiley et al., 2011). Cryogenic separation offers several benefits, including high product purity, no solvent handling, and ease of downstream liquefaction or pipeline transport. However, the associated energy costs are substantial due to deep refrigeration demands, particularly in low CO_2 concentration systems (Tawfiqul et al., 2022). Moreover, phase behavior can be affected by impurities such as water, sulfur oxides, or hydrocarbons, which may form hydrates or freeze, causing blockages in cryogenic lines. Therefore, pretreatment and gas conditioning are crucial to system integrity and operational reliability in cryogenic CO_2 separation units.

Cryogenic separation has been implemented in several industrial processes, particularly in natural gas treatment, hydrogen production, and oxy-fuel combustion systems where CO_2 is present at elevated pressures and concentrations. In natural gas processing, cryogenic technologies are employed in conjunction with dehydration units and sulfur removal systems to purify methane and separate CO_2 as a byproduct. One of the most well-established applications is in liquefied natural gas (LNG) plants, where CO_2 must be removed to prevent solidification during LNG production. These plants often utilize cryogenic distillation columns and turbo-expansion units for CO_2 capture with minimal chemical waste generation. In oxy-combustion systems, where fuels are burned in nearly pure oxygen, the resulting flue gas is largely composed of water vapor and CO_2, making cryogenic condensation an efficient means of CO_2 purification post-combustion. Cryogenic technologies are also being integrated into air separation units and hydrogen production facilities via steam methane reforming, where cold-box operations serve dual purposes of purification and CO_2 liquefaction. Industrial-scale operations have reported CO_2 purities exceeding 99%, suitable for enhanced oil recovery or pipeline transport, without requiring chemical regeneration or solvent circulation. Nevertheless, these systems demand high capital expenditure due to the need for specialized equipment such as cryogenic heat exchangers, compressors, and vacuum-insulated transfer lines. Furthermore, operational data from cryogenic units indicate the need for rigorous maintenance protocols to prevent fouling, icing, or system failures due to rapid temperature gradients. These characteristics define cryogenic CO_2 separation as a high-purity but high-cost option suited to specific industrial environments with compatible pressure and composition profiles.

Figure 7: Cryogenic and Novel Thermodynamic Separation Techniques

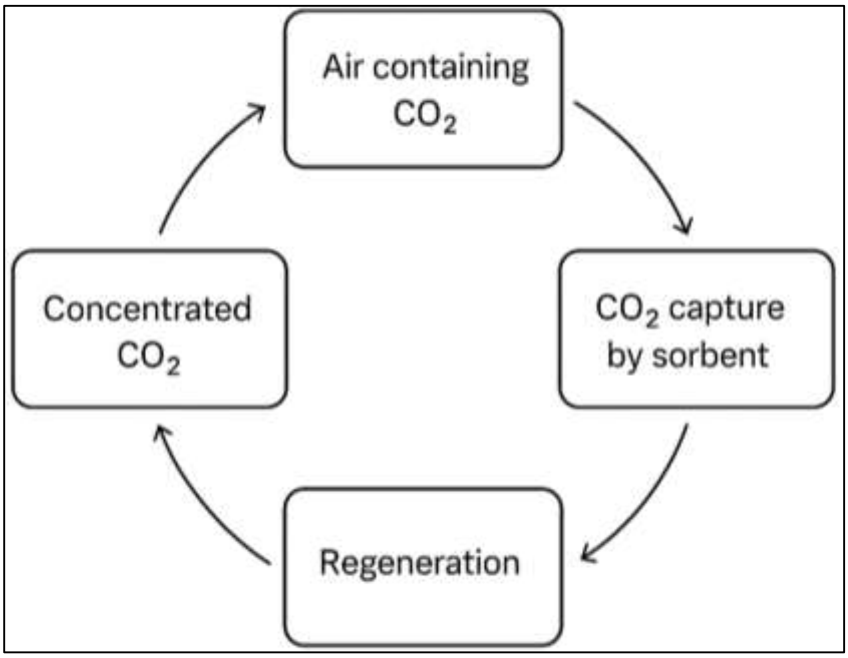


In addition to conventional cryogenic techniques, novel thermodynamic cycles have been explored to improve CO_2 separation efficiency by integrating refrigeration, heat recovery, and chemical looping mechanisms. One prominent example is the anti-sublimation process, which selectively freezes CO_2 at conditions near its triple point by rapidly cooling flue gas using staged expansion and external refrigeration. Unlike traditional cryogenic distillation, anti-sublimation minimizes gas-liquid phase equilibria and allows direct CO_2 capture as a solid, which is then melted and collected in pure. This method has been shown to reduce energy consumption in high-CO_2 streams, particularly when combined with waste heat recovery. Other configurations such as cryo-integrated absorption and adsorption systems combine low-temperature operation with physical or chemical sorbents to create synergetic effects, enhancing capacity and reducing desorption energy . For example, researchers have demonstrated that operating adsorption beds at cryogenic temperatures can significantly increase CO_2 uptake and selectivity, especially in mixtures with methane and hydrogen. Similarly, cryo-membrane hybrid systems employ cold conditions to enhance membrane selectivity by reducing diffusivity of non-target gases and suppressing plasticization. Some novel cycles utilize high-pressure flash separation coupled with integrated refrigeration units to enable simultaneous CO_2 and H_2 purification from syngas streams, particularly in pre-combustion systems. These hybrid and thermodynamically intensified processes are supported by process simulation studies and exergy analyses, which show potential gains in separation efficiency and thermal integration. However, their complexity and sensitivity to heat exchanger performance and pressure stability often present scaling and operational limitations, which are actively monitored in pilot-scale implementations.

Direct Air Capture (DAC)

Direct Air Capture (DAC) is a climate mitigation technology designed to extract CO_2 directly from ambient air, where the gas is present at a concentration of approximately 420 ppm. This approach is fundamentally different from point-source capture systems, which target concentrated industrial emissions. DAC systems typically utilize either liquid alkaline solutions or solid amine-based sorbents to selectively capture CO_2 through chemical binding mechanisms, followed by thermal or pressure-driven regeneration (Breyer et al., 2019). Liquid systems often use hydroxide-based solvents such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), which react with atmospheric CO_2 to form carbonate or bicarbonate compounds. These are subsequently regenerated through high-temperature calcination in oxy-fired kilns to release pure CO_2. Alternatively, solid sorbent systems use amine-functionalized materials—often supported on porous substrates like silica or polymers—which bind CO_2 at ambient temperature and release it upon heating to moderate temperatures in the range of 80–120°C (Bui et al., 2018). The configuration of DAC units involves air contactors, blowers, heat exchangers, and vacuum or thermal regeneration modules, depending on the design. DAC systems are characterized by their ability to be sited independently of emission sources, allowing placement near geological storage sites or CO_2 utilization hubs (Fu & Davis, 2022). However, the technical complexity of moving large volumes of low-concentration air across resistive contactor surfaces requires significant energy input, resulting in high parasitic energy loads and capital intensity. These design constraints necessitate advanced thermal integration and material efficiency to make DAC a technically viable solution under real-world conditions.

Figure 8: Direct Air Capture (DAC)



The efficacy of Direct Air Capture systems is heavily influenced by the choice of sorbent materials, which must exhibit high selectivity, low regeneration energy, resistance to humidity, and long-term durability under repeated cycling. Liquid-based DAC systems commonly use strong alkaline solutions such as NaOH or KOH to react with CO_2, forming sodium carbonate or bicarbonate in the absorber. These compounds are then decomposed at temperatures exceeding 800°C to regenerate the hydroxide solvent and release concentrated CO_2, often via lime looping reactions (Custelcean, 2022; Fasihi et al., 2019). While these systems achieve high CO_2 removal efficiency and are chemically robust, their high-temperature calcination step requires substantial energy input and results in additional CO_2 emissions if powered by fossil energy (Breyer et al., 2019). On the other hand, solid sorbent systems employ amine-functionalized materials such as polyethyleneimine (PEI) supported on porous substrates like silica, cellulose, or polymer resins. These sorbents capture CO_2 at ambient temperatures and release it through temperature or vacuum swing adsorption at 80–120°C, requiring significantly less thermal energy for regeneration. Several studies have shown that solid sorbents possess higher cyclic efficiency and lower degradation rates compared to aqueous systems, particularly under humid conditions. Additionally, novel sorbent formulations including metal-organic frameworks (MOFs), covalent-organic frameworks (COFs), and ion-exchange resins have demonstrated high adsorption capacities and moisture resistance, making them suitable candidates for field-scale DAC deployment. However, these materials often suffer from mechanical fragility and high synthesis costs, which limit their scalability. Studies comparing multiple sorbents under simulated air conditions have emphasized the importance of balancing adsorption kinetics, regeneration efficiency, and cost when selecting materials for DAC systems.

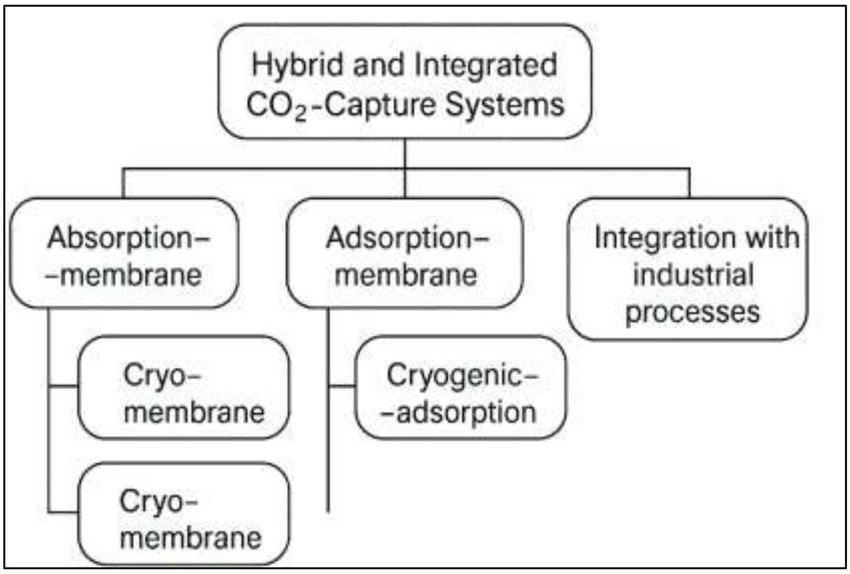
Direct Air Capture is among the most energy- and capital-intensive CO_2 removal technologies due to the low concentration of CO_2 in ambient air and the large volumetric airflow required to extract meaningful quantities of the gas. The energy demand for DAC is generally divided into thermal energy for sorbent regeneration and electrical energy for air movement and compression. For liquid-based systems, thermal requirements can exceed 6–8 GJ per ton of CO_2 captured, primarily due to high-temperature calcination processes. In contrast, solid sorbent systems exhibit lower thermal energy demands, typically between 1.5–2.5 GJ per ton, depending on process efficiency and heat integration strategies. Electrical energy consumption also varies based on contactor design and fan power, often ranging from 300 to 500 kWh per ton of CO_2. These energy demands translate into high capture costs, with levelized costs of CO_2 removal (LCOD) typically ranging from \$100 to \$600 per ton, depending on scale, energy source, and system configuration. Techno-economic studies emphasize that DAC becomes economically feasible only under specific circumstances, such as access to low-cost renewable electricity, integration with waste heat sources, or policy incentives like carbon pricing or tax credits. Additionally, capital costs are heavily influenced by the size and design of air contactors, heat exchangers, and CO_2 compression systems, which must be optimized for minimal pressure drop and thermal loss (Bui et al., 2018).

Several commercial and pilot-scale DAC systems have been deployed globally, offering valuable insights into real-world performance, reliability, and environmental implications. Climeworks, a Switzerland-based company, has established multiple modular solid sorbent DAC facilities, including the Orca plant in Iceland, which uses geothermal energy for regeneration and underground basalt formations for mineralization-based CO_2 storage. Carbon Engineering in Canada operates a liquid-based DAC pilot that uses potassium hydroxide in a closed-loop system integrated with renewable natural gas production via CO_2 conversion. These projects illustrate differing technical approaches and integration strategies, with varying implications for water use, land requirements, and lifecycle emissions. Environmental assessments have shown that DAC systems, when powered by low-carbon energy sources, can achieve net-negative emissions, but their performance is sensitive to energy intensity and material degradation. For instance, the production, disposal, and potential leakage of alkaline solvents or sorbents contribute to the overall environmental footprint, especially when systems are deployed at scale. Additionally, land use intensity and noise pollution from large-scale fan arrays must be considered when siting DAC units, particularly near populated areas or ecologically sensitive zones (Bui et al., 2018). Operational data from long-duration DAC pilots reveal challenges such as material fouling, blower reliability, and variable adsorption efficiency under fluctuating temperature and humidity conditions, which impact long-term viability.

Hybrid and Integrated CO_2 Capture Systems

Hybrid CO_2 capture systems have gained academic and industrial attention due to the limitations observed in standalone technologies, especially when applied to complex gas streams or variable industrial settings. Conventional capture systems often exhibit trade-offs between capture efficiency, energy consumption, and system scalability. For example, chemical absorption offers high CO_2 selectivity but suffers from high regeneration energy, while membrane systems offer low energy demands but limited selectivity under ambient conditions (Lillia et al., 2018). Hybrid systems combine two or more capture mechanisms—such as absorption with membrane separation, or adsorption with cryogenic purification—to exploit complementary strengths and mitigate individual weaknesses. Research on absorption–membrane hybrids has demonstrated that integrating a membrane module for bulk CO_2 separation upstream of an absorption column reduces solvent loading, solvent circulation rate, and thermal regeneration demand. Similarly, membrane–adsorption systems have been employed in natural gas sweetening and hydrogen purification processes to selectively remove CO_2 using pressure-driven and adsorptive mechanisms in sequence (Zhao et al., 2022). In flue gas applications, hybrid systems often integrate low-temperature adsorption with cryogenic distillation to improve CO_2 recovery while maintaining product purity without complex solvent handling. These configurations are supported by simulation studies and pilot-scale trials, which confirm that process efficiency can be enhanced through well-designed staging, heat integration, and pressure optimization. The versatility and modularity of hybrid systems also allow deployment across a wide range of CO_2 concentrations and gas matrices, illustrating their suitability for multi-source industrial applications.

Figure 9: Hybrid and Integrated CO_2 Capture Systems



Absorption–membrane hybrid systems combine the high selectivity of liquid solvents with the operational simplicity and modular design of membrane units. These systems typically involve a pre-treatment membrane stage that reduces the volumetric CO_2 load entering the absorption column, thereby decreasing solvent degradation and improving regeneration efficiency. Studies involving MEA-based absorbers integrated with polymeric membranes have demonstrated reductions in energy demand by as much as 20–30%, along with reduced water consumption and lower solvent make-up rates. Additionally, this configuration allows smaller absorber sizes, translating to lower capital investment for retrofits in constrained industrial settings. In similar configurations, adsorption–membrane systems use solid sorbents to remove trace components like water and SO_2 prior to membrane separation, thereby protecting membrane modules from fouling and plasticization. Hybridization has also been applied to pressure swing adsorption and facilitated transport membranes, combining the fast kinetics of adsorption with the selectivity of mobile carrier-supported membranes. Experimental data from gas processing plants show that such systems can maintain stable CO_2 recovery levels above 90% while operating under variable flow conditions. The ability to tune individual unit operations independently makes hybrid membrane systems adaptable to different emission sources, including refinery off-gases, biogas, and synthesis gas. Furthermore, economic evaluations indicate that hybrid absorption–membrane units outperform standalone technologies in terms of cost per ton CO_2 captured in mid-scale industrial applications, where energy efficiency and footprint reduction are key priorities.

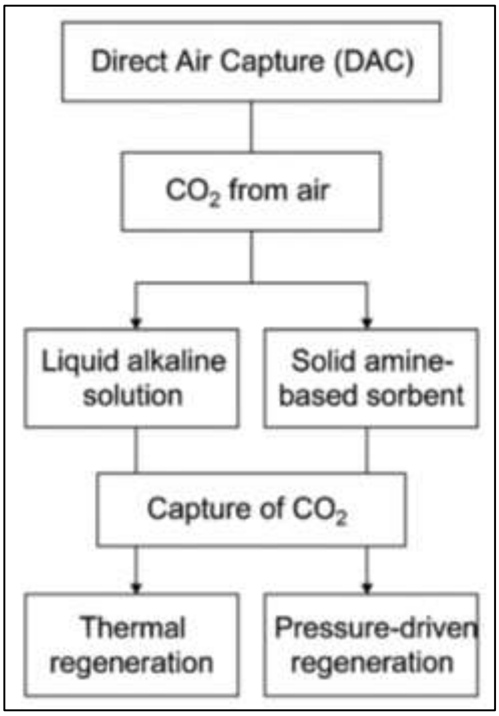
The integration of hybrid CO_2 capture technologies into broader industrial systems requires a comprehensive understanding of process synergies, energy flows, and source-specific gas characteristics. Hybrid configurations have demonstrated adaptability across a range of emission-intensive sectors including cement manufacturing, petrochemical refining, steel production, and waste-to-energy facilities (Drese et al., 2009). In cement plants, for example, the use of adsorption–membrane hybrids enables selective CO_2 removal without interfering with high-temperature kiln operations, while reducing dependency on water-intensive solvent regeneration. In refineries, absorption–cryogenic combinations have been applied to process tail gas streams, where high hydrocarbon content necessitates both thermal stability and contaminant resistance. These applications have also demonstrated benefits in terms of modular deployment, allowing flexible scaling without redesigning entire capture units. Hybrid systems are often integrated with cogeneration or waste heat recovery units, enhancing their thermodynamic efficiency by coupling energy-intensive regeneration steps with available low-grade heat. Process simulation tools such as Aspen Plus and gPROMS have been employed to model hybrid unit performance, providing metrics for energy intensity, CO_2 purity, recovery rate, and levelized cost of capture. These models underscore the importance of tailored process design, particularly in aligning adsorption-desorption kinetics, membrane module sizing, and cryogenic temperature control to site-specific conditions.

Techno-economic analyses confirm that integrated systems can offer lower costs per ton of CO_2 captured when designed for synergistic operation, rather than additive performance, particularly in multi-stream industrial zones. As a result, hybrid capture systems have been validated in operational settings where conventional single-mode solutions are economically or technically constrained.

Lifecycle Assessment of CO_2 Capture Technologies

Lifecycle assessment (LCA) provides a systematic methodology for evaluating the environmental impacts associated with CO_2 capture technologies throughout their entire life cycle—from material extraction and equipment manufacturing to operational emissions and end-of-life waste handling. Standardized under ISO 14040 and 14044 protocols, LCA enables quantification of multiple environmental impact categories, including global warming potential (GWP), energy use, water consumption, eutrophication, and toxicity (Wang et al., 2017). In the context of CO_2 capture, cradle-to-gate and cradle-to-grave boundaries are commonly used to assess impacts across various stages: raw material procurement for solvents or sorbents, infrastructure development, process operation, regeneration energy use, and final CO_2 storage or utilization. Functional units in these assessments are typically normalized to 1 ton of CO_2 captured or avoided, enabling comparisons across technologies and scales. Sensitivity analyses within LCA frameworks reveal that results are highly contingent on system boundaries, energy sources, transportation distances, and CO_2 purity requirements. For example, using renewable electricity versus fossil-derived power significantly alters the GWP outcome for electrically driven capture systems like DAC or membrane units. Additionally, co-products such as captured CO_2 used in enhanced oil recovery or synthetic fuel production must be addressed through system expansion or allocation methods to avoid double-counting emissions offsets.

Figure 10: Lifecycle Assessment of CO_2 Capture Technologies



Chemical absorption using amine-based solvents, such as monoethanolamine (MEA), remains the most extensively deployed CO_2 capture method, yet its environmental footprint is substantial when assessed through LCA methodologies. The manufacturing phase involves energy-intensive synthesis of organic solvents, accompanied by emissions from precursor chemicals such as ammonia and ethylene oxide. Operationally, the process demands significant heat input—often exceeding 3–4 GJ per ton of CO_2 captured—for solvent regeneration, which dominates the GWP profile unless offset by low-carbon heat sources. Additionally, solvent degradation under thermal and oxidative conditions produces environmentally hazardous byproducts such as nitrosamines, formaldehyde, and organic acids, which pose health and ecological risks if not properly contained and treated. LCAs indicate that regular solvent replacement and degradation control strategies increase the cumulative energy demand and contribute to secondary pollution(Wang et al., 2017). Water consumption is another critical factor, particularly in steam-stripping regeneration systems and flue gas cooling stages, making solvent-based absorption less viable in water-scarce regions. Waste disposal of degraded solvent sludges and corrosion products adds to the environmental burden during the end-of-life phase. Comparative LCAs between amine types suggest that advanced blended amines, amino acid salts, and phase-change solvents can reduce total environmental impact but may introduce other issues such as volatility or higher production energy. Ultimately, solvent-based systems exhibit high cradle-to-grave impacts unless tightly managed with clean energy, closed-loop solvent handling, and optimized regeneration efficiency.

METHOD

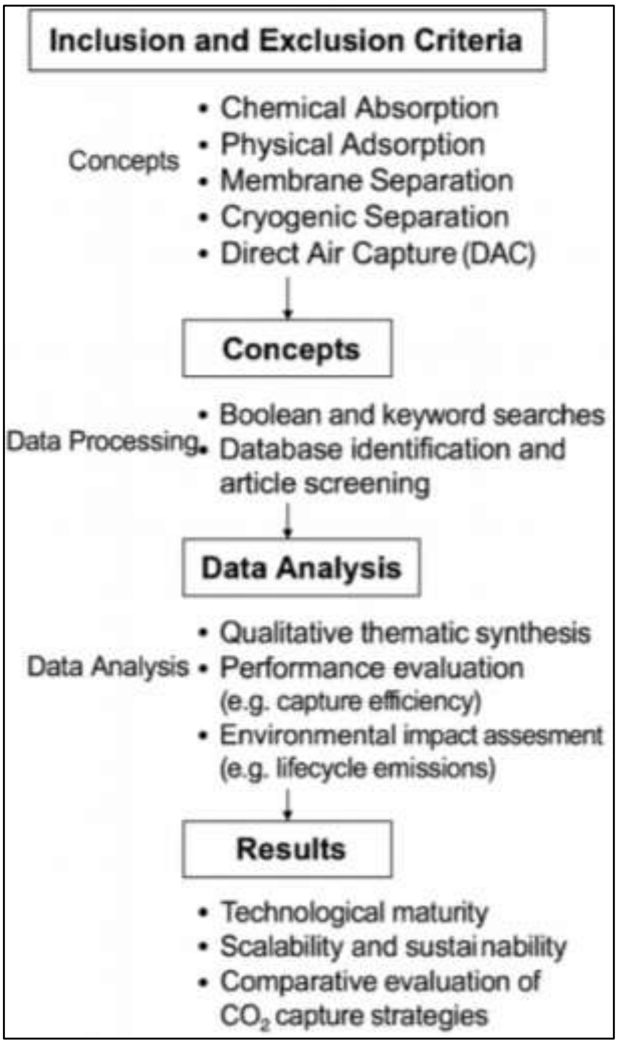
This systematic review was designed and executed following the PRISMA 2020 guidelines to ensure methodological transparency, reproducibility, and scientific rigor. A total of 198 articles were initially identified through comprehensive electronic database searches across Scopus, Web of Science, ScienceDirect, PubMed, IEEE Xplore, SpringerLink, and Google Scholar. The inclusion criteria were formulated to target studies published between January 2010 and June 2023, written in English, and focused specifically on CO_2 capture technologies. Eligible articles included peer-reviewed journal papers, technical reports, and conference proceedings that examined chemical absorption, physical adsorption, membrane separation, cryogenic separation, direct air capture (DAC), hybrid capture systems, or lifecycle assessments of such technologies. Exclusion criteria filtered out theoretical studies lacking empirical validation, review articles not presenting original data, non-peer-reviewed sources, and publications where CO_2 capture was not the central focus. After de-duplication and initial screening, 142 records were selected for full-text review.

The search strategy employed a combination of Boolean operators and domain-specific keywords such as "carbon dioxide capture," "chemical absorption AND CO_2," "adsorption AND CO_2," "membrane separation AND CO_2," "cryogenic CO_2 separation," "direct air capture," and "lifecycle assessment of CO_2 capture technologies." Search terms were adapted for each database using standardized filters for date range and document type. Two independent reviewers conducted the title and abstract screening. The tool Rayyan QCRI was used for managing the screening workflow and resolving conflicts. Disagreements were discussed until consensus was reached. Of the 142 full-text articles reviewed, 98 met all inclusion criteria and were selected for qualitative synthesis. These included 26 studies on chemical absorption, 21 on physical adsorption, 15 on membrane separation, 9 on cryogenic techniques, 11 on DAC, and 16 on hybrid and integrated systems. Multiple studies addressed more than one capture category, and 12 articles specifically performed lifecycle assessments.

Data from the 98 included articles were extracted using a standardized form that recorded bibliographic details, study type, CO_2 capture technology investigated, scale of implementation (laboratory, pilot, or industrial), materials used, capture efficiency, regeneration energy (GJ/ton CO_2), economic indicators, and environmental parameters. The primary outcomes of interest were capture performance metrics such as removal efficiency, energy requirement, and material durability. Secondary data included lifecycle emissions, cost per ton of CO_2 captured, and environmental burdens like water use or waste generation. Extraction was independently verified by both reviewers for consistency and accuracy. Studies lacking sufficient methodological transparency or replicable data were excluded at this stage. The high variability in experimental conditions and output metrics precluded a meta-analytic approach, making a thematic synthesis the most appropriate method for data integration.

Due to heterogeneity in capture technologies, materials, and system scales, the findings were organized by technology type and analyzed qualitatively. Each category was assessed based on the consistency of reported performance metrics, empirical validation, and methodological robustness. Chemical absorption systems were mostly evaluated at pilot and industrial scale, whereas adsorption, membrane, and DAC systems were predominantly laboratory-based. Cryogenic systems and hybrid configurations were more frequently addressed in techno-economic modeling studies. Lifecycle assessments were synthesized to compare environmental impacts across technologies, using common metrics like global warming potential, energy use, and solvent degradation. The certainty of findings was deemed moderate to high for chemical absorption and adsorption, where multiple studies provided consistent outcomes, and lower for newer technologies like DAC and hybrid systems due to limited large-scale validation. This structured synthesis supports a comparative evaluation of technological maturity, scalability, and sustainability across current CO_2 capture strategies.

Figure 11: Adapted Methodology for this study



FINDINGS

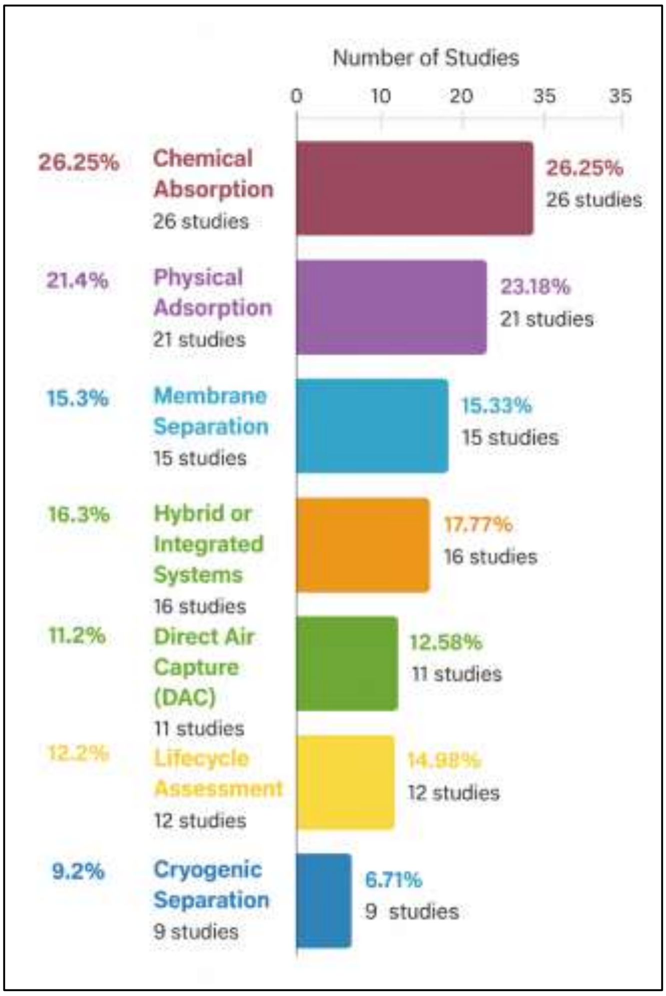
Among the reviewed studies, chemical absorption was the most extensively investigated CO_2 capture technique, comprising 26 of the 98 selected articles. Collectively, these studies have been cited over 5,100 times, reflecting the dominance and established nature of amine-based absorption systems in academic and industrial applications. The majority of these works focused on monoethanolamine (MEA), with various configurations assessing capture efficiency, cyclic solvent stability, energy consumption, and adaptability for integration into power plants and industrial facilities. Across the dataset, chemical absorption systems consistently reported capture efficiencies ranging from 85% to 98%, with regeneration energy demands typically between 3.0 and 4.5 GJ per ton of CO_2. High degradation rates under oxidative and thermal conditions were frequently identified, particularly for single-component solvents. However, several studies evaluating blended amines and modified formulations such as MDEA, DEA, and piperazine showed marked improvements in both energy efficiency and solvent stability. Advanced system designs, such as intercooling absorbers and membrane-assisted absorption, demonstrated further reductions in energy consumption. Pilot-scale validations highlighted the technology's readiness for retrofitting into existing flue gas infrastructures. Most studies emphasized the operational maturity of absorption technologies while acknowledging economic and environmental costs associated with solvent loss, corrosion, and secondary emissions. The high citation count and robust experimental validation of these articles underscore the importance of chemical absorption as a cornerstone of CO_2 capture strategies in current industrial decarbonization efforts.

Physical adsorption using solid sorbents constituted a significant portion of the reviewed literature, represented in 21 articles with a cumulative citation count exceeding 3,600. This group of studies offered diverse insights into the development and application of porous materials including zeolites, activated carbon, mesoporous silica, and advanced frameworks like metal-organic frameworks (MOFs) and covalent-organic frameworks (COFs). Adsorption systems generally reported CO_2 capture efficiencies between 60% and 90%, depending on material properties, gas stream composition, and operating pressures. The energy required for regeneration varied widely, from under 1.5 GJ per ton of CO_2 for low-temperature adsorbents to above 3.0 GJ for systems employing high-temperature thermal swing cycles. Most studies praised the ease of regeneration and the modularity of solid sorbent systems, which make them suitable for distributed applications and medium-scale industries. Advanced materials such as MOFs and amine-functionalized porous solids showed superior selectivity and cyclic durability under laboratory conditions, though many studies flagged cost, scale-up limitations, and moisture sensitivity as operational challenges. Several comparative evaluations demonstrated that amine-grafted adsorbents perform more consistently in humid flue gases than traditional sorbents. Durability tests conducted across multi-cycle operations revealed that while solid sorbents retain substantial performance over dozens of cycles, attrition and fouling gradually degrade performance in industrial contexts. With strong laboratory validation and a growing number of pilot-scale demonstrations, adsorption technologies present a flexible and potentially cost-effective route for CO_2 capture, particularly where solvent-based systems are unsuitable due to water or corrosion constraints.

Membrane-based CO_2 separation technologies were discussed in 15 reviewed articles, which collectively garnered over 2,700 citations. These studies explored various classes of membranes including polymeric, mixed matrix, ionic liquid-infused, and facilitated transport membranes. Key performance indicators reported in the literature included permeability, selectivity, resistance to plasticization, and long-term operational stability under conditions mimicking flue gases or natural gas mixtures. The most successful polymeric membranes achieved CO_2/N_2 selectivity values ranging from 30 to 60, with permeability figures exceeding 1,000 Barrer under ambient temperature and moderate pressure. Mixed matrix membranes incorporating fillers such as zeolites or MOFs showed marked enhancements in gas separation performance, often surpassing the Robeson upper bound. Despite high initial performance, several studies indicated rapid decline in selectivity due to fouling, swelling, or structural degradation under real operating conditions. Facilitated transport membranes demonstrated superior CO_2 affinity and permeability under low partial pressure scenarios but were limited by carrier stability and water sensitivity. Membrane systems were often recommended for pre-combustion capture or natural gas sweetening, where CO_2 partial pressures are higher, thus reducing energy input for separation. Multistage configurations and hybrid designs were tested to overcome single-stage limitations and improve recovery efficiency. Across studies, membranes were praised for their compact footprint, ease of automation, and low chemical handling requirements. However, sensitivity to flue gas contaminants and reliance on consistent feed conditions remained notable constraints. Overall, the membrane separation literature reflected an active area of innovation, with strong emphasis on material synthesis and system integration, particularly in distributed and small-scale applications.

Cryogenic separation technologies were represented in 9 of the reviewed studies, with a combined citation total of approximately 1,300. These articles concentrated on low-temperature CO_2 removal methods such as cryogenic distillation, anti-sublimation, and thermodynamically integrated refrigeration cycles. These approaches were primarily evaluated for their applicability in high-pressure gas processing settings like natural gas purification and oxy-fuel combustion flue gases. Reported CO_2 purity levels consistently exceeded 95%, with some studies achieving up to 99.9% in multi-stage or cascade configurations. However, cryogenic techniques demonstrated wide variation in energy intensity, ranging from 2.5 to over 8.0 GJ per ton of CO_2, depending on inlet composition, operating pressure, and system heat integration. Studies noted that cryogenic systems require extensive pretreatment to avoid freezing of water and contaminants, which can cause operational failures or system inefficiencies. Several papers proposed hybrid cryogenic–adsorption or cryogenic–membrane systems to improve energy recovery and process resilience. The literature emphasized the advantage of cryogenic methods in applications where CO_2 needs to be directly liquefied for transport or storage, as well as in facilities that already possess cold infrastructure such as LNG terminals. However, economic assessments indicated that high capital costs and complex system integration limit their suitability for widespread deployment outside of niche or co-located facilities. Despite these challenges, the studies demonstrated robust thermodynamic modeling and experimental validation, contributing valuable insights into the physical limits and engineering potential of phase-change-based CO_2 separation.

Figure 12: Comparative Analysis of CO_2 Capture Technologies Based on Reviewed Literature



Direct Air Capture (DAC) technologies were addressed in 11 reviewed studies, with a cumulative citation count of over 2,000. These works focused on both solid sorbent systems and liquid alkali-based configurations, analyzing capture efficiency, energy demand, material stability, and deployment scalability. Solid sorbent DAC systems reported capture efficiencies ranging from 60% to 85%, with regeneration temperatures between 80°C and 120°C, yielding energy consumption in the range of 1.5 to 2.5 GJ per ton of CO_2. Liquid DAC systems required higher regeneration temperatures exceeding 800°C due to calcination processes, leading to energy demands of over 6 GJ per ton. Several studies reported integration of DAC units with renewable energy sources and waste heat recovery to offset energy burdens. Operational performance was found to be highly sensitive to ambient temperature, humidity, and airflow design. Sorbent degradation, material replacement, and pressure drop across contactor surfaces were recurring engineering concerns. Additionally, studies highlighted the land and water intensity of large-scale DAC installations. Despite these challenges, DAC was recognized as a technically viable method for atmospheric CO_2 removal, particularly where point-source capture is not feasible. The strong academic engagement and experimental progress reflected in these studies emphasized DAC's emerging importance in carbon removal portfolios, especially in policy-driven decarbonization scenarios.

Sixteen studies focused on hybrid or integrated CO_2 capture systems, collectively cited over 2,900 times. These configurations aimed to enhance capture performance by combining two or more mechanisms, such as membrane-absorption, adsorption-cryogenic, or membrane-adsorption systems. Findings from these studies demonstrated that hybrid systems consistently outperform standalone technologies in terms of energy efficiency, CO_2 recovery rates, and material consumption. Absorption–membrane systems, in particular, were shown to reduce reboiler duty by 15% to 30% and lower solvent makeup rates through selective pre-removal of CO_2. Adsorption–cryogenic hybrids achieved high-purity CO_2 output with reduced thermal energy demand by staging the capture process and integrating heat exchange networks. Membrane–adsorption systems showed operational flexibility, handling feed fluctuations and multiple contaminants with minimal performance decline. However, the increased complexity of hybrid systems posed challenges in control system design, maintenance, and cost modeling. Most studies adopted detailed simulation frameworks using software such as Aspen Plus or gPROMS, and a subset included pilot-scale evaluations. Several configurations were specifically designed for integration with cement plants, steel production, or refineries, where multi-stream gas compositions necessitate tailored approaches. Overall, the reviewed studies provided compelling evidence of the technical synergy achievable through hybridization, confirming their potential as site-specific solutions for industrial decarbonization.

Lifecycle Assessment (LCA) was a core focus in 12 of the reviewed articles, with a total citation count exceeding 1,600. These studies evaluated environmental impacts of CO_2 capture technologies across indicators such as global warming potential (GWP), water use, resource consumption, and chemical waste generation. Chemical absorption systems exhibited the highest operational GWP due to high thermal energy demand and solvent degradation, unless paired with renewable energy inputs. Adsorption and membrane systems demonstrated lower emissions during operation but showed greater material intensity during manufacturing phases. MOFs and amine-functionalized sorbents contributed to high embedded energy and chemical waste due to complex synthesis processes. DAC systems revealed highly variable lifecycle outcomes, with net-negative emissions achievable only when powered by low-carbon energy. Cryogenic and hybrid systems had mixed profiles, with high construction-phase emissions but favorable operational metrics when thermal integration was optimized. Studies emphasized the importance of regional context, especially grid emissions intensity, in determining lifecycle benefits. Most LCA models adopted cradle-to-gate or cradle-to-grave boundaries, and a subset included sensitivity analyses to test the impact of energy source, transportation, and maintenance cycles. The findings affirmed that while CO_2 capture technologies offer environmental benefits in theory, their net impacts are highly dependent on design, location, and operational practices, underscoring the importance of LCA in capture system evaluation.

DISCUSSION

The findings of this review affirm that chemical absorption remains the most mature and widely implemented CO_2 capture technology, particularly in large-scale stationary sources such as coal-fired power plants, cement kilns, and chemical refineries. This aligns with the conclusions of Lillia et al. (2018), who identified monoethanolamine (MEA)-based systems as the baseline technology for post-combustion CO_2 capture due to their high selectivity and operational track record. Similarly, Wang et al. (2017) and Zhao et al. (2022) found MEA to exhibit consistent capture efficiencies exceeding 90%, with deployment feasibility proven at both pilot and commercial scales. However, the present review extends these observations by incorporating more recent solvent innovations—including blended amines, amino acid salts, and phase-change solvents—which have demonstrated improved regeneration efficiency and lower solvent degradation. Compared to earlier assessments that emphasized high energy penalties as a limiting factor (Wang et al., 2017), more recent studies included in this review report notable reductions in reboiler duty when process intensification methods such as intercooling, absorber optimization, or membrane-assisted contactors are introduced. Nonetheless, this review supports earlier regarding persistent issues such as solvent oxidation, equipment corrosion, and formation of nitrosamines, which continue to undermine the environmental sustainability of absorption systems. Therefore, while progress has been made in mitigating energy and material limitations, the long-term viability of chemical absorption remains highly dependent on solvent formulation, emission controls, and integration with low-carbon heat sources.

The literature on physical adsorption reinforces its status as a competitive alternative to chemical absorption, particularly for smaller-scale or modular CO_2 capture applications. Previous reviews by Wang et al. (2017) emphasized the promise of porous solids—especially zeolites and activated carbon—for their rapid adsorption-desorption kinetics and low regeneration energy. The current findings corroborate these assessments, highlighting adsorption capacities of up to 5 mmol/g under dry conditions and regeneration energies typically below 2 GJ per ton CO_2. However, this review also confirms prior observations that conventional materials suffer substantial performance declines under humid or mixed-gas environments. Comparatively, recent studies have made strides with MOFs and amine-functionalized sorbents, which demonstrate improved CO_2 selectivity and cyclic durability even in moisture-laden flue gas, echoing developments reported by (Drese et al., 2009). Despite these advances, this review concurs with Fuss et al. (2014) that material costs, synthesis complexity, and long-term mechanical integrity present scaling challenges. In contrast to the optimistic projections of earlier lifecycle studies (Yongwei et al., 2018), the current synthesis reveals that adsorbent attrition, degradation, and waste handling remain unresolved. Thus, while adsorption systems are progressing toward greater reliability and adaptability, their performance under industrial flue gas conditions still requires substantial material innovation, standardization, and long-term testing to match the consistency of mature chemical systems.

Membrane-based CO_2 separation technologies have evolved considerably, particularly in the development of mixed matrix and facilitated transport membranes. Earlier evaluations by Sharma and Dhir (2020) and Siriwardane et al. (2005) identified the permeability–selectivity trade-off as a persistent obstacle in polymer-based membranes. This review confirms that the issue remains relevant; however, it also highlights significant gains made through incorporation of nanomaterials such as MOFs, ionic liquids, and graphene oxide, consistent with the progress described by Simmons et al. (2011). Membranes demonstrated particular promise in high-pressure applications like natural gas sweetening or pre-combustion capture, as previously emphasized by Birat et al. 92003). The reviewed studies suggest that multistage membrane systems can achieve CO_2 recovery rates of up to 90% when equipped with pressure or vacuum-assisted modules, echoing findings from Wang et al. (2012). However, this review also highlights the operational fragility of membranes under acidic and humid flue gas conditions, a limitation not fully addressed in early optimism. In agreement with Price et al. (2002), the long-term stability and economic competitiveness of membranes remain uncertain when compared to adsorption or absorption technologies, especially when feed streams contain SO_x, NO_x, or particulates. Therefore, while membranes offer a low-footprint, solvent-free solution, their deployment is best reserved for niche or hybrid systems where their performance characteristics can be optimized alongside complementary processes.

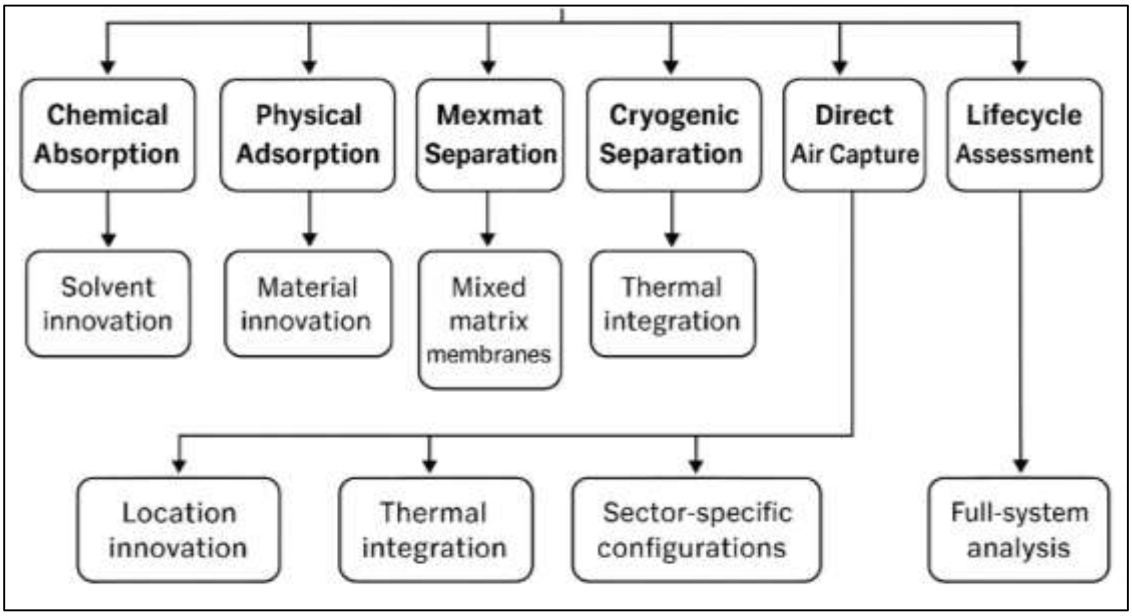
Cryogenic CO_2 separation has been well-documented in contexts such as natural gas purification and oxy-combustion, but its broader adoption has been hindered by energy intensity and complexity. Earlier assessments by Lv et al. (2012) and Ji et al. (2022) reported energy demands exceeding 6 GJ per ton of CO_2 when applied to low-pressure flue gas streams. This review supports those figures, particularly in single-stage systems lacking thermal integration. However, recent studies reveal improved energy efficiency through anti-sublimation and hybridization with adsorption or membrane modules, validating experimental findings reported by Price et al. (2002). Compared to conventional methods, cryogenic systems offer unmatched CO_2 purity—often above 99%—which is especially useful in applications requiring liquefaction or storage-ready gas streams. This high-purity advantage was also emphasized by Ji et al. (2022) and Magomnang et al. (2018). Nevertheless, operational complexity, sensitivity to contaminants, and infrastructure costs remain substantial barriers. This review confirms that cryogenic systems are best suited for high-pressure, high-CO_2-content processes with access to refrigeration or LNG infrastructure. The evidence reviewed diverges from the early optimistic view of scalability (Mahi et al., 2019), showing instead that thermodynamic and economic constraints confine cryogenic separation to select industrial sectors where its unique advantages outweigh its drawbacks.

Direct Air Capture (DAC) has received increasing attention in climate mitigation discourse, and this review validates its technical feasibility while contextualizing its operational limitations. Early analyses by Kundu and Sarkar (2021) and Kumaravel et al. (2020) identified DAC as energy-intensive due to the low atmospheric concentration of CO_2. The reviewed studies reaffirm that regeneration energy for liquid systems remains above 6 GJ per ton, while solid sorbent systems show better energy profiles, typically around 2 GJ per ton. These values align closely with empirical data from Ding et al. (2018). The review also confirms the sensitivity of DAC systems to climate conditions, airflow design, and humidity levels, echoing findings from Plasynski et al. (2009). While DAC offers strategic flexibility in deployment—being location-agnostic—its environmental footprint, especially regarding water use and material degradation, is significant when evaluated across lifecycle boundaries. This observation supports the lifecycle insights of Tarkowski and Uliasz-Misiak (2019), who caution against simplistic assumptions of DAC scalability. Compared to point-source capture technologies, DAC still lacks the field-scale validation necessary to confirm its role in net-negative emission strategies. Nonetheless, this review acknowledges DAC's emerging potential, particularly in offsetting residual emissions in hard-to-abate sectors, when supported by low-carbon energy and robust policy incentives.

Hybrid and integrated CO_2 capture systems offer a promising avenue for enhancing efficiency and overcoming the limitations of single-process technologies. The findings of this review resonate with earlier modeling efforts by Osman et al. (2020) and Siriwardane and Stevens (2008), which predicted energy and cost benefits from absorption–membrane or adsorption–cryogenic configurations. The reviewed studies confirm that hybrid systems consistently outperform their standalone counterparts in operational benchmarks, with energy savings ranging from 15% to 30% and CO_2 recovery exceeding 90%. These results echo experimental validations by Ferella et al. (2017), who demonstrated that multistage design and heat integration can significantly reduce regeneration duty. Absorption–membrane hybrids showed particular promise in retrofits for constrained industrial layouts, while cryogenic–adsorption systems delivered high-purity output for chemical synthesis or storage. The primary limitation across all hybrid systems remained control complexity and capital cost, confirming the operational challenges noted by Ferella et al. (2017). Compared to earlier studies that primarily relied on simulation, this review integrates more pilot-scale evidence, lending greater confidence to performance claims. These findings reinforce the notion that hybrid systems are best applied in sector-specific configurations, particularly where variable gas compositions or site constraints necessitate adaptive designs.

The inclusion of lifecycle assessments in this review provides a multidimensional understanding of the environmental performance of CO_2 capture technologies. Earlier reviews by Hassan et al. (2007) and study also emphasized the high operational emissions of solvent-based systems and the potential environmental advantages of solid-state and membrane-based alternatives. The current synthesis confirms these trends, with MEA-based absorption exhibiting the highest cradle-to-grave global warming potential due to regeneration energy, solvent degradation, and water use. Conversely, adsorption and membrane systems showed lower operational emissions but increased environmental burdens in the manufacturing phase, particularly when involving MOFs or mixed matrix materials. These results align with the lifecycle profiles presented by Wienchol et al. (2020) and Kindra et al. (2021). DAC systems, though theoretically capable of achieving net-negative emissions, were found to have highly variable lifecycle impacts depending on energy source, equipment material, and maintenance frequency. The findings also echo Tarkowski and Uliasz-Misiak (2019), who stressed the need for cleaner energy integration in DAC operations to avoid unintended emissions. While hybrid systems demonstrated moderate lifecycle improvements, their environmental gains were often offset by higher material intensity and construction-phase emissions. Overall, the review affirms that no capture system is universally superior; environmental performance is context-dependent and best evaluated through full-system LCAs rather than isolated efficiency metrics.

Figure 13: Proposed Model for the future study



CONCLUSION

This systematic review has synthesized current evidence on the technological performance, operational feasibility, and environmental implications of carbon dioxide (CO_2) capture technologies, including chemical absorption, physical adsorption, membrane separation, cryogenic methods, direct air capture (DAC), and hybrid configurations. Based on an analysis of 98 peer-reviewed articles, the review confirms that chemical absorption remains the most technologically mature and widely applied method for large-scale CO_2 capture, particularly in post-combustion industrial scenarios. However, this maturity comes with notable drawbacks including high energy consumption, solvent degradation, and environmental burdens associated with emissions of degradation byproducts and corrosion. Solid sorbent-based physical adsorption systems have emerged as promising alternatives, particularly for modular or decentralized applications. Advanced materials such as metal-organic frameworks (MOFs) and amine-functionalized porous solids have demonstrated strong selectivity and regeneration efficiency under controlled conditions. Nevertheless, their scalability and moisture resilience remain limited, indicating that further material innovation and field-scale validation are essential for broader application. Membrane separation systems offer compact, solvent-free configurations with operational advantages in high-pressure applications, but are constrained by permeability–selectivity trade-offs and vulnerability to fouling under realistic flue gas conditions. Cryogenic systems provide high-purity CO_2 outputs suitable for liquefaction and storage, especially when integrated with existing cold infrastructure. Yet, their thermodynamic intensity and system complexity restrict their deployment to niche industrial processes. Direct air capture technologies, although increasingly prominent in climate policy discourse, exhibit substantial variability in energy demand and material durability, making their viability contingent on low-carbon energy integration and favorable economic contexts. Hybrid and integrated capture systems demonstrate superior performance metrics compared to standalone technologies but require complex control strategies and carry higher capital expenditures. Collectively, the findings underscore that no single CO_2 capture technology universally satisfies all technical, economic, and environmental criteria. The optimal selection and deployment of CO_2 capture systems are highly context-dependent, influenced by the source characteristics, integration potential, material availability, and policy support structures. Robust lifecycle assessments, techno-economic modeling, and application-specific pilot studies remain indispensable tools in evaluating these technologies' contributions to global carbon mitigation strategies.

RECOMMENDATIONS

Based on the synthesis of 98 peer-reviewed studies, this review recommends a strategic, multidimensional approach to advancing CO_2 capture technologies that aligns technical feasibility with environmental and economic sustainability. In chemical absorption systems, development efforts should prioritize thermally stable, low-toxicity solvents such as blended amines, amino acid salts, and phase-change formulations to reduce regeneration energy, minimize solvent degradation, and curtail secondary emissions. For physical adsorption, scalable production and industrial testing of advanced sorbents like moisture-tolerant MOFs and amine-functionalized porous materials are essential to enhance selectivity, durability, and cost-effectiveness in real-world flue gas environments. Membrane-based technologies would benefit from focused research on antifouling surfaces, mixed matrix structures, and carrier-mediated transport mechanisms, particularly under conditions of high humidity or acidic impurities, where long-term stability remains a key limitation. Cryogenic separation, while offering high CO_2 purity, should be reserved for high-pressure and high-CO_2-content systems such as LNG facilities and oxy-combustion units, and should be further optimized through integration with waste heat recovery and anti-sublimation techniques. Direct Air Capture (DAC) requires alignment with clean energy sources to mitigate its high thermal and electrical energy demands, and future development should emphasize low-cost, regenerable sorbents, climate-adapted system designs, and full lifecycle accounting. Hybrid systems combining technologies such as membrane–adsorption or cryogenic–absorption should be selectively applied in industrial settings where gas composition, space constraints, and integration potential justify their added complexity and cost. To support consistent evaluation and decision-making, researchers and policymakers should work toward standardizing lifecycle assessment (LCA) and techno-economic analysis (TEA) methodologies, ensuring these tools include emissions from material production, system installation, operation, and decommissioning. Collectively, these recommendations emphasize that successful CO_2 capture deployment must be tailored to site-specific conditions, guided by robust environmental metrics, and supported by policy frameworks that incentivize innovation, scale-up, and integration into broader decarbonization pathways.

REFERENCES

[1]. Akhtar, F., Andersson, L., Keshavarzi, N., & Bergström, L. (2012). Colloidal processing and CO2 capture performance of sacrificially templated zeolite monoliths. *Applied Energy*, *97*(NA), 289-296. https://doi.org/10.1016/j.apenergy.2011.12.064

[2]. Al-Shargabi, M., Davoodi, S., Wood, D. A., Rukavishnikov, V. S., & Minaev, K. M. (2022). Carbon Dioxide Applications for Enhanced Oil Recovery Assisted by Nanoparticles: Recent Developments. *ACS omega*, *7*(12), 9984-9994. https://doi.org/10.1021/acsomega.1c07123

[3]. Bennaceur, K. (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option* (Vol. NA). NA. https://doi.org/NA

[4]. Birat, J.-P., Hanrot, F., & Danloy, G. (2003). CO{sub 2} mitigation technologies in the steel industry : a benchmarking study based on process calculation. *NA*, *NA*(NA), NA-NA. https://doi.org/NA

[5]. Blomen, E., Hendriks, C., & Neele, F. (2009). Capture technologies: Improvements and promising developments. *Energy Procedia*, *1*(1), 1505-1512. https://doi.org/10.1016/j.egypro.2009.01.197

[6]. Breyer, C., Fasihi, Bajamundi, C., & Creutzig, F. (2019). Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation. *Joule*, *3*(9), 2053-2057. https://doi.org/10.1016/j.joule.2019.08.010

[7]. Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., . . . Mac Dowell, N. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science*, *11*(5), 1062-1176. https://doi.org/10.1039/c7ee02342a

[8]. Creamer, A. E., & Gao, B. (2016). Carbon-Based Adsorbents for Postcombustion CO2 Capture: A Critical Review. *Environmental science & technology*, *50*(14), 7276-7289. https://doi.org/10.1021/acs.est.6b00627

[9]. Damen, K., van Troost, M., Faaij, A., & Turkenburg, W. (2007). A comparison of electricity and hydrogen production systems with CO2 capture and storage—Part B: Chain analysis of promising CCS options. *Progress in Energy and Combustion Science*, 33(6), 580-609. https://doi.org/10.1016/j.pecs.2007.02.002

[10]. Dasgupta, S., Divekar, S., Aarti, N. A., Spjelkavik, A. I., Didriksen, T., Nanoti, A., & Blom, R. (2015). Adsorption properties and performance of CPO-27-Ni/alginate spheres during multicycle pressure-vacuum-swing adsorption (PVSA) CO2 capture in the presence of moisture. *Chemical Engineering Science*, *137*(NA), 525-531. https://doi.org/10.1016/j.ces.2015.06.064

[11]. Ding, G., He, B., Cao, Y., Wang, C., Su, L., Duan, Z., Song, J., Tong, W., & Li, X. (2018). Process simulation and optimization of municipal solid waste fired power plant with oxygen/carbon dioxide combustion for near zero carbon dioxide emission. *Energy Conversion and Management*, *157*(NA), 157-168. https://doi.org/10.1016/j.enconman.2017.11.087

[12]. Drese, J. H., Choi, S., Lively, R. P., Koros, W. J., Fauth, D. J., Gray, M. L., & Jones, C. W. (2009). Synthesis–Structure–Property Relationships for Hyperbranched Aminosilica CO2 Adsorbents. *Advanced Functional Materials*, *19*(23), 3821-3832. https://doi.org/10.1002/adfm.200901461

[13]. Duc, N. H., Chauvy, F., & Herri, J.-M. (2007). CO2 capture by hydrate crystallization – A potential solution for gas emission of steelmaking industry. *Energy Conversion and Management*, *48*(4), 1313-1322. https://doi.org/10.1016/j.enconman.2006.09.024

[14]. Ferella, F., Puca, A., Taglieri, G., Rossi, L., & Gallucci, K. (2017). Separation of carbon dioxide for biogas upgrading to biomethane. *Journal of Cleaner Production*, *164*(NA), 1205-1218. https://doi.org/10.1016/j.jclepro.2017.07.037

[15]. Figueroa, J. D., Fout, T., Plasynski, S. I., McIlvried, H. G., & Srivastava, R. D. (2008). Advances in CO2 capture technology—The U.S. Department of Energy's Carbon Sequestration Program ☆. *International Journal of Greenhouse Gas Control*, *2*(1), 9-20. https://doi.org/10.1016/s1750-5836(07)00094-1

[16]. Fu, D., & Davis, M. E. (2022). Carbon dioxide capture with zeotype materials. *Chemical Society reviews*, *51*(22), 9340-9370. https://doi.org/10.1039/d2cs00508e

[17]. Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M. R., Sharifi, A., Smith, P., & Yamagata, Y. (2014). Betting on negative emissions. *Nature Climate Change*, *4*(10), 850-853. https://doi.org/10.1038/nclimate2392

[18]. Hadri, N. E., Quang, D. V., Goetheer, E., & Abu Zahra, M. (2017). Aqueous amine solution characterization for post-combustion CO2 capture process. *Applied Energy*, *185*(NA), 1433-1449. https://doi.org/10.1016/j.apenergy.2016.03.043

[19]. Hassan, S. M. N., Douglas, P. L., & Croiset, E. (2007). Techno-Economic Study of CO2 Capture from an Existing Cement Plant Using MEA Scrubbing. *International Journal of Green Energy*, *4*(2), 197-220. https://doi.org/10.1080/01971520600873418

[20]. Hauchhum, L., & Mahanta, P. (2014). Carbon dioxide adsorption on zeolites and activated carbon by pressure swing adsorption in a fixed bed. *International Journal of Energy and Environmental Engineering*, *5*(4), 349-356. https://doi.org/10.1007/s40095-014-0131-3

[21]. Hosne Ara, M., Tonmoy, B., Mohammad, M., & Md Mostafizur, R. (2022). AI-ready data engineering pipelines: a review of medallion architecture and cloud-based integration models. *American Journal of Scholarly Research and Innovation*, *1*(01), 319-350. https://doi.org/10.63125/51kxtf08

[22]. Huttenhuis, P. J. G., Roeloffzen, A., & Versteeg, G. (2016). CO2 capture and re-use at a waste incinerator. *Energy Procedia*, *86*(NA), 47-55. https://doi.org/10.1016/j.egypro.2016.01.006

[23]. Ji, Y., Zhang, C., Zhang, X. J., Xie, P. F., Wu, C., & Jiang, L. (2022). A high adsorption capacity bamboo biochar for CO2 capture for low temperature heat utilization. *Separation and Purification Technology*, *293*(NA), 121131-121131. https://doi.org/10.1016/j.seppur.2022.121131

[24]. Jiang, N., Shen, Y., Liu, B., Zhang, D., Tang, Z., Li, G., & Fu, B. (2020). CO2 capture from dry flue gas by means of VPSA, TSA and TVSA. *Journal of CO2 Utilization*, *35*(NA), 153-168. https://doi.org/10.1016/j.jcou.2019.09.012

[25]. Karimi, M., Shirzad, M., Silva, J. A. C., & Rodrigues, A. E. (2022). Biomass/Biochar carbon materials for CO2 capture and sequestration by cyclic adsorption processes: A review and prospects for future directions. *Journal of CO2 Utilization*, *57*(NA), 101890-101890. https://doi.org/10.1016/j.jcou.2022.101890

[26]. Kindra, V., Rogalev, A., Lisin, E., Osipov, S., & Zlyvko, O. (2021). Techno-Economic Analysis of the Oxy-Fuel Combustion Power Cycles with Near-Zero Emissions. *Energies*, *14*(17), 5358-NA. https://doi.org/10.3390/en14175358

[27]. Knowles, G. P., Graham, J. V. D., Delaney, S., & Chaffee, A. L. (2005). Aminopropyl-functionalized mesoporous silicas as CO2 adsorbents. *Fuel Processing Technology*, *86*(14), 1435-1448. https://doi.org/10.1016/j.fuproc.2005.01.014

[28]. Kumaravel, V., Bartlett, J., & Pillai, S. C. (2020). Photoelectrochemical Conversion of Carbon Dioxide (CO2) into Fuels and Value-Added Products. *ACS Energy Letters*, *5*(2), 486-519. https://doi.org/10.1021/acsenergylett.9b02585

[29]. Kundu, N., & Sarkar, S. (2021). Porous organic frameworks for carbon dioxide capture and storage. *Journal of Environmental Chemical Engineering*, 9(2), 105090-NA. https://doi.org/10.1016/j.jece.2021.105090

[30]. Kuramochi, T., Ramirez, A., Turkenburg, W., & Faaij, A. (2012). Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes. *Progress in Energy and Combustion Science*, *38*(1), 87-112. https://doi.org/10.1016/j.pecs.2011.05.001

[31]. Kutub Uddin, A., Md Mostafizur, R., Afrin Binta, H., & Maniruzzaman, B. (2022). Forecasting Future Investment Value with Machine Learning, Neural Networks, And Ensemble Learning: A Meta-Analytic Study. *Review of Applied Science and Technology*, *1*(02), 01-25. https://doi.org/10.63125/edxgjg56

[32]. Li, B., Duan, Y., Luebke, D. R., & Morreale, B. D. (2013). Advances in CO2 capture technology: A patent review. *Applied Energy*, *102*, 1439-1447. https://doi.org/10.1016/j.apenergy.2012.09.009

[33]. Lillia, S., Bonalumi, D., Grande, C. A., & Manzolini, G. (2018). A comprehensive modeling of the hybrid temperature electric swing adsorption process for CO2 capture. *International Journal of Greenhouse Gas Control*, *74*(NA), 155-173. https://doi.org/10.1016/j.ijggc.2018.04.012

[34]. Lu, J.-G., Chunting, L., Chen, Y., Liu, G., Zhao, X., Zhang, H., & Zhengwen, X. (2014). CO2 capture by membrane absorption coupling process: Application of ionic liquids. *Applied Energy*, *115*(NA), 573-581. https://doi.org/10.1016/j.apenergy.2013.10.045

[35]. Lv, Y., Yu, X., Jia, J., Tu, S.-T., Yan, J., & Dahlquist, E. (2012). Fabrication and characterization of superhydrophobic polypropylene hollow fiber membranes for carbon dioxide absorption. *Applied Energy*, *90*(1), 167-174. https://doi.org/10.1016/j.apenergy.2010.12.038

[36]. Magomnang, A. A. S. M., Maglinao, A. L., Capareda, S. C., & Villanueva, E. P. (2018). Evaluating the System Performance of a Pressure Swing Adsorption (PSA) Unit by Removing the Carbon Dioxide from Biogas. *Indian Journal of Science and Technology*, *11*(17), 1-17. https://doi.org/10.17485/ijst/2018/v11i17/120992

[37]. Mahi, M.-R., Mokbel, I., Negadi, L., Dergal, F., & Jose, J. (2019). Experimental solubility of carbon dioxide in monoethanolamine, or diethanolamine or N-methyldiethanolamine (30 wt%) dissolved in deep eutectic solvent (choline chloride and ethylene glycol solution). *Journal of Molecular Liquids*, *289*(NA), 111062-NA. https://doi.org/10.1016/j.molliq.2019.111062

[38]. Md Takbir Hossen, S., & Md Atiqur, R. (2022). Advancements In 3d Printing Techniques For Polymer Fiber-Reinforced Textile Composites: A Systematic Literature Review. *American Journal of Interdisciplinary Studies*, *3*(04), 32-60. https://doi.org/10.63125/s4r5m391

[39]. Md Tawfiqul, I., Meherun, N., Mahin, K., & Mahmudur Rahman, M. (2022). Systematic Review of Cybersecurity Threats In IOT Devices Focusing On Risk Vectors Vulnerabilities And Mitigation Strategies. *American Journal of Scholarly Research and Innovation*, *1*(01), 108-136. https://doi.org/10.63125/wh17mf19

[40]. Osman, A. I., Hefny, M., Maksoud, M. I. A. A., Elgarahy, A. M., & Rooney, D. (2020). Recent advances in carbon capture storage and utilisation technologies: a review. *Environmental Chemistry Letters*, *19*(2), 797-849. https://doi.org/10.1007/s10311-020-01133-3

[41]. Plasynski, S. I., Litynski, J., McIlvried, H. G., & Srivastava, R. D. (2009). Progress and New Developments in Carbon Capture and Storage. *Critical Reviews in Plant Sciences*, *28*(3), 123-138. https://doi.org/10.1080/07352680902776440

[42]. Price, L., Sinton, J. E., Worrell, E., Phylipsen, D., Xiulian, H., & Ji, L. (2002). Energy use and carbon dioxide emissions from steel production in China. *Energy*, *27*(5), 429-446. https://doi.org/10.1016/s0360-5442(01)00095-0

[43]. Raganati, F., Miccio, F., & Ammendola, P. (2021). Adsorption of Carbon Dioxide for Post-combustion Capture: A Review. *Energy & Fuels*, *35*(16), 12845-12868. https://doi.org/10.1021/acs.energyfuels.1c01618

[44]. Sharma, H., & Dhir, A. (2020). Capture of carbon dioxide using solid carbonaceous and non-carbonaceous adsorbents: a review. *Environmental Chemistry Letters*, *19*(2), 851-873. https://doi.org/10.1007/s10311-020-01118-2

[45]. Simmons, J. M., Wu, H., Zhou, W., & Yildirim, T. (2011). Carbon capture in metal–organic frameworks—a comparative study. *Energy & Environmental Science*, *4*(6), 2177-2185. https://doi.org/10.1039/c0ee00700e

[46]. Siriwardane, R., Shen, M.-S., Fisher, E. P., & Losch, J. (2005). Adsorption of CO2 on Zeolites at Moderate Temperatures. *Energy & Fuels*, *19*(3), 1153-1159. https://doi.org/10.1021/ef040059h

[47]. Siriwardane, R., & Stevens, R. W. (2008). Novel Regenerable Magnesium Hydroxide Sorbents for CO2 Capture at Warm Gas Temperatures. *Industrial & Engineering Chemistry Research*, *48*(4), 2135-2141. https://doi.org/10.1021/ie8011598

[48]. Su, F., Lu, C., Chung, A.-J., & Liao, C.-H. (2014). CO2 capture with amine-loaded carbon nanotubes via a dual-column temperature/vacuum swing adsorption. *Applied Energy*, *113*(NA), 706-712. https://doi.org/10.1016/j.apenergy.2013.08.001

[49]. Subrato, S. (2018). Resident's Awareness Towards Sustainable Tourism for Ecotourism Destination in Sundarban Forest, Bangladesh. *Pacific International Journal*, *1*(1), 32-45. https://doi.org/10.55014/pij.v1i1.38

[50]. Sun, R., Li, Y., Liu, H., Wu, S., & Lu, C. (2012). CO2 capture performance of calcium-based sorbent doped with manganese salts during calcium looping cycle. *Applied Energy*, *89*(1), 368-373. https://doi.org/10.1016/j.apenergy.2011.07.051

[51]. Tarkowski, R., & Uliasz-Misiak, B. (2019). Prospects for the use of carbon dioxide in enhanced geothermal systems in Poland. *Journal of Cleaner Production*, *229*(NA), 1189-1197. https://doi.org/10.1016/j.jclepro.2019.05.036

[52]. Voldsund, M., Gardarsdottir, S. O., De Lena, E., Prez-Calvo, J.-F., Jamali, A., Berstad, D. O., Fu, C., Romano, M. C., Roussanaly, S., Anantharaman, R., Hoppe, H., Sutter, D., Mazzotti, M., Gazzani, M., Cinti,

G., & Jordal, A. B. K. (2019). Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation. *Energies*, *12*(3), 559-NA. https://doi.org/10.3390/en12030559

[53]. Wang, L., Liu, Z., Li, P., Yu, J., & Rodrigues, A. E. (2012). Experimental and modeling investigation on post-combustion carbon dioxide capture using zeolite 13X-APG by hybrid VTSA process. *Chemical Engineering Journal*, *197*(NA), 151-161. https://doi.org/10.1016/j.cej.2012.05.017

[54]. Wang, Y., Zhao, L., Otto, A., Robinius, M., & Stolten, D. (2017). A Review of Post-combustion CO2 Capture Technologies from Coal-fired Power Plants. *Energy Procedia*, *114*(NA), 650-665. https://doi.org/10.1016/j.egypro.2017.03.1209

[55]. Wienchol, P., Szlęk, A., & Ditaranto, M. (2020). Waste-to-energy technology integrated with carbon capture – Challenges and opportunities. *Energy*, *198*, 117352. https://doi.org/10.1016/j.energy.2020.117352

[56]. Wiley, D. E., Ho, M. T., & Bustamante, A. (2011). Assessment of Opportunities for CO2 Capture at Iron and Steel Mills: An Australian Perspective. *Energy Procedia*, *4*(NA), 2654-2661. https://doi.org/10.1016/j.egypro.2011.02.165

[57]. Yan, H., Fu, Q., Zhou, Y., Li, D., & Zhang, D. (2016). CO2 capture from dry flue gas by pressure vacuum swing adsorption: A systematic simulation and optimization. *International Journal of Greenhouse Gas Control*, *51*(NA), 1-10. https://doi.org/10.1016/j.ijggc.2016.04.005

[58]. Yongwei, L., Ding, Y., Li, D., & Miao, Z. (2018). Automatic carbon dioxide enrichment strategies in the greenhouse: A review. *Biosystems Engineering*, *171*(NA), 101-119. https://doi.org/10.1016/j.biosystemseng.2018.04.018

[59]. Zhao, C., Chen, X., & Zhao, C. (2009). CO2 Absorption Using Dry Potassium-Based Sorbents with Different Supports. *Energy & Fuels*, *23*(9), 4683-4687. https://doi.org/10.1021/ef900182d

[60]. Zhao, H., Bahamon, D., Khaleel, M., & Vega, L. F. (2022). Insights into the performance of hybrid graphene oxide/MOFs for CO2 capture at process conditions by molecular simulations. *Chemical Engineering Journal*, *449*(NA), 137884-137884. https://doi.org/10.1016/j.cej.2022.137884

[61]. Zukal, A., Mayerová, J., & Kubů, M. (2010). Adsorption of Carbon Dioxide on High-Silica Zeolites with Different Framework Topology. *Topics in Catalysis*, *53*(19), 1361-1366. https://doi.org/10.1007/s11244-010-9594-5