Mitigating Climate Change: A Review of Carbon Capture and Separation Technologies

Mitigación del cambio climático: una revisión de las tecnologías de captura y separación de carbono

Mitigando as mudanças climáticas: uma revisão das tecnologias de captura e separação de carbono.

Haider Ali [1] (*), Nomaan Akhtar [2] (*), Saqib Shams [3], Ali Karim [4], Umair Naeem [5]

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Summary. - Carbon capture and separation techniques (CCST) play a pivotal role in addressing the pressing challenge of reducing CO_2 emissions and mitigating climate change impacts. This review paper provides a detailed examination of various CCST methodologies, focusing on their mechanisms, applications, and importance in the broader context of environmental sustainability. The significance of Carbon Capture, Utilization, and Storage (CCUS) strategies is emphasized as an essential pathway for reducing greenhouse gas emissions. Through an in-depth analysis, the paper examines the diverse range of carbon capture technologies, including direct air capture, post-combustion, pre-combustion, and chemical looping. Each technology is scrutinized for its efficiency, scalability, and suitability across different industrial sectors. It also delves into carbon separation technologies, including absorption, adsorption, cryogenic separation, and membrane separation, explaining their mechanisms and applications in CO_2 capture. Additionally, the review addresses the economic, regulatory, and environmental implications of CCST implementation, highlighting challenges and opportunities for scaling up these technologies. This paper contributes to a clearer understanding of CCST as a vital tool for combating climate change and achieving sustainable development goals.

Keywords: *Absorption, Adsorption, Carbon capture and separation; Direct Air Capture; Post-combustion.*

(*) Corresponding author.

[1] Professor, Department of Mechanical Engineering, NED University of Engineering & Technology (Pakistan), haider.ali@neduet.edu.pk, ORCID iD: https://orcid.org/0000-0001-8242-3696

[2] Student, Department of Mechanical Engineering, NED University of Engineering & Technology (Pakistan), nomaan.akhtar2@gmail.com, ORCID iD: https://orcid.org/0009-0007-2969-675X

[3] Student, Department of Mechanical Engineering, NED University of Engineering & Technology (Pakistan), saqibshams200204@gmail.com, ORCID iD: https://orcid.org/0009-0009-3932-6095

[4] Student, Department of Mechanical Engineering, NED University of Engineering & Technology (Pakistan), alikarimptcl@gmail.com, ORCID iD: https://orcid.org/0009-0008-0495-0237

[5] Student, Department of Mechanical Engineering, NED University of Engineering & Technology (Pakistan), umairnaeem139@gmail.com, ORCID iD: https://orcid.org/0009-0003-0763-4081

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Resumen. - *Resumen. - Las técnicas de captura y separación de carbono (CCST) desempeñan un papel fundamental para abordar el desafío urgente de reducir las emisiones de CO2 y mitigar los impactos del cambio climático. Este artículo de revisión ofrece un análisis detallado de diversas metodologías CCST, centrándose en sus mecanismos, aplicaciones e importancia en el contexto más amplio de la sostenibilidad ambiental. Se destaca la importancia de las estrategias de captura, utilización y almacenamiento de carbono (CCUS) como una vía esencial para reducir las emisiones de gases de efecto invernadero. Mediante un análisis exhaustivo, el artículo examina la diversa gama de tecnologías de captura de carbono, incluyendo la captura directa de aire, la postcombustión, la precombustión y el ciclo químico. Cada tecnología se analiza en función de su eficiencia, escalabilidad e idoneidad en diferentes sectores industriales. También profundiza en las tecnologías de separación de carbono, incluyendo la absorción, la adsorción, la separación criogénica y la separación por membranas, explicando sus mecanismos y aplicaciones en la captura de CO2. Además, la revisión aborda las implicaciones económicas, regulatorias y ambientales de la implementación de CCST, resaltando los desafíos y las oportunidades para la ampliación de estas tecnologías. Este artículo contribuye a una mejor comprensión de la captura y separación de carbono como herramienta fundamental para combatir el cambio climático y alcanzar los objetivos de desarrollo sostenible.*

Palabras clave: *Absorción, Adsorción, Captura y separación de carbono, Captura directa de aire, Postcombustión.*

Resumo *. -* *As técnicas de captura e separação de carbono (CCST) desempenham um papel fundamental no enfrentamento do desafio premente de reduzir as emissões de CO2 e mitigar os impactos das mudanças climáticas. Este artigo de revisão fornece um exame detalhado de várias metodologias de CCST, com foco em seus mecanismos, aplicações e importância no contexto mais amplo da sustentabilidade ambiental. A importância das estratégias de Captura, Utilização e Armazenamento de Carbono (CCUS) é enfatizada como um caminho essencial para a redução das emissões de gases de efeito estufa. Por meio de uma análise aprofundada, o artigo examina a diversidade de tecnologias de captura de carbono, incluindo captura direta do ar, pós-combustão, pré-combustão e ciclo químico. Cada tecnologia é analisada quanto à sua eficiência, escalabilidade e adequação a diferentes setores industriais. O artigo também explora as tecnologias de separação de carbono, incluindo absorção, adsorção, separação criogênica e separação por membrana, explicando seus mecanismos e aplicações na captura de CO2. Além disso, a revisão aborda as implicações econômicas, regulatórias e ambientais da implementação de CCST, destacando os desafios e as oportunidades para a ampliação dessas tecnologias. Este artigo contribui para uma compreensão mais clara da CCST como uma ferramenta vital para combater as mudanças climáticas e alcançar os objetivos de desenvolvimento sustentável.*

Palavras-chave: *Absorção, Adsorção, Captura e separação de carbono; Captura direta de ar; Pós-combustão.*

1. Introduction. -

1.1 Importance of Carbon Capture. - The greenhouse effect stands as a central mechanism driving global warming and climate change, as widely reported in climate-change literature. As emphasized by multiple authors, the repercussions of this phenomenon are profound, with current projections indicating serious future risk. Predictions imply that unchecked global warming would cause the melting of polar ice caps, eventually leading to a considerable rise in global sea levels and posing a catastrophic threat to coastal cities globally. Such forecasts are not mere conjecture; they are grounded in scientific data and models that indicate a concerning trajectory. For instance, according to projections cited from the Intergovernmental Panel on Climate Change (IPCC) baseline period of 1961-90, global warming is anticipated to escalate by as much as 4 °C by the year 2050, accompanied by a decrease in rainfall across many regions. These forecasts highlight the importance of addressing climate change and implementing policies to reduce greenhouse gas emissions, notably carbon dioxide (CO_2) emissions. The EU Commission on Climate Change has recognized human activities, mainly the combustion of fossil fuels, as the principal cause of the increase in CO_2 levels. Indeed, by 2020, atmospheric CO_2 levels had risen by an astounding 48% relative to pre-industrial levels [1]. This disturbing trend highlights the critical need for global collaboration to address the main causes of climate change and transition to a low-carbon future.

1.2 Carbon Capture, Utilization and Storage (CCUS). - CCUS techniques are important in the global effort to reduce CO_2 emissions and mitigate climate change. As mentioned in Figure , the process begins with the capture of carbon dioxide from a variety of sources, each with a different concentration. This captured CO_2 passes through a series of essential stages, including separation from contaminants in the mixture. Once purified, the CO_2 can be directed towards two main pathways: storage or utilization. In one scenario, the CO_2 is safely stored in depleted oil and gas fields, preventing its release into the atmosphere and contributing to long-term CO_2 sequestration. Alternatively, captured CO_2 can be utilized for commercial applications, thereby transforming a greenhouse gas into a valuable resource. This multifaceted strategy not only reduces environmental impacts but also promotes innovation and economic growth. Against the backdrop of rising climate concerns, this study examines the most recent breakthroughs in carbon capture and separation technology. By providing insights into these trends, it emphasizes the significance of CCUS methodologies and lays the groundwork for a sustainable future powered by effective carbon management tactics.

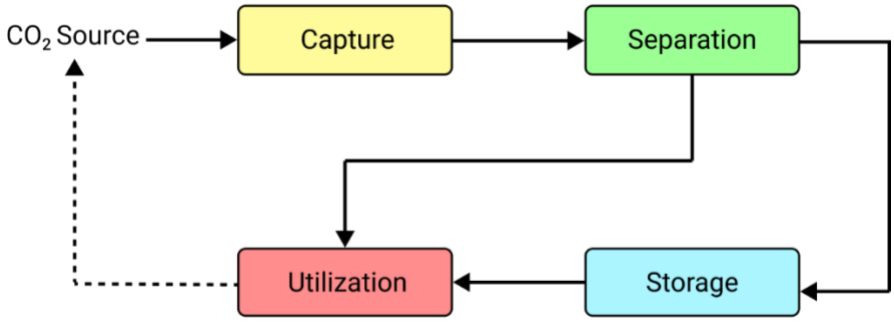

Figure I. Life Cycle of Carbon Dioxide involved in the capture process.

1.3 Review Methodology. - This review was prepared by collecting literature on carbon capture and separation technologies from major scholarly databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Keywords included “carbon capture,” “carbon separation,” “CCUS,” “direct air capture,” “post-combustion capture,” “pre-combustion capture,” “chemical looping,” “absorption,” “adsorption,” “membrane separation,” and “cryogenic separation.” Peer-reviewed journal articles, review papers, and technically relevant studies were prioritized. Non-scholarly sources and duplicate references were excluded where possible. Data extracted from the literature included capture efficiency, Technology Readiness Level, study scale, operating conditions, energy/cost basis, advantages, and limitations. Where conflicting numerical values were reported, ranges were presented and interpreted in relation to study scale, assumptions, and system boundaries.

2. Carbon Capture Technologies. - Technologies aimed at capturing carbon dioxide (CO_2) emissions from a variety of sources, mostly industrial operations and electricity production, are collectively referred to as carbon capture technologies. By limiting the release of CO_2 into the atmosphere, the aim is to lessen the influence of greenhouse gas emissions on climate change. These technologies are illustrated in Figure .

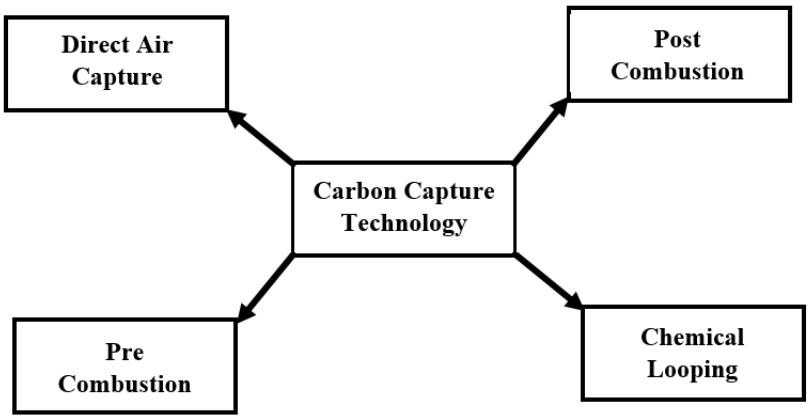

Figure II. Carbon Capture Technologies.

2.1 Direct Air Capture. - Recently, significant research attention has been directed toward greenhouse gas removal (GGR) technologies, which aim to remove CO_2 from the atmosphere. The current level of CO_2 in the atmosphere is over 400 ppm and rising by about 2 ppm per year, mainly as a result of burning fossil fuels [2]. Fossil fuels continue to be a major energy source, so we need technologies to capture and store CO_2 directly from the air, referred to as Direct Air Capture (DAC). Traditional carbon capture methods target specific sources like power plants, but DAC can capture CO_2 from any location, making it more versatile.

Some studies have questioned whether GGR is truly effective as a way to remove CO_2 from the atmosphere. In this situation, Direct Air Capture (DAC) has the potential to support the achievement of net-zero emissions by removing CO_2 directly from ambient air, regardless of the original emission source. DAC is a process that aims to remove CO_2 from the atmosphere and store it permanently or use it for other purposes. DAC is considered one of the negative emission technologies (NET) that are essential for achieving net-zero emissions by 2050 to limit global warming to 1.5°C [3]. Different methods of performing DAC exist, such as sorbent-based systems, membrane-based systems, or biological systems. Previous studies on integrated DAC systems are summarized in Table I, whereas the merits and demerits of DAC Technology are given in Table II.

Author	System Configuration	Major Results
D. Coppitters et al. [4]	Direct Air Capture and Compression with Proton Exchange Membrane (PEM) electrolyzer and methanation unit.	Exergy efficiency varies between 51.3% and 52.6%. Synthetic natural gas production costs range from 130 €/MWh to 744 €/MWh.
T. Daniel et al. [5]	DAC combined with Carbon Dioxide (CO_2) utilization using High-Temperature Steam Electrolysis (HTSE).	The estimated cost is 382 \$/t CO_2.
J. Cui & M. Aziz [6]	Implementation of DAC for ammonia and methanol production.	Among the examined options, the infrastructure for ammonia production demonstrates the most cost-effective energy transmission of US\$10.1/GJ.
P. Cheng et al. [7]	Application of a DAC powered by a natural gas combined cycle (NGCC) plant and post-combustion carbon capture.	Positive net present value is considered to require a CO_2 price of between \$150 and \$225 per tonne (NPV).
G. M. Cole et al. [8]	DAC implementation based on algae-based coating.	The method has a 44% to 51% carbon removal effectiveness, accompanied by sequestration costs per tonne of CO_2 that vary from \$702 to \$1585.
C. Drechsler & D. W. Agar [9]	DAC implementation with heat recovery and electrolyser integration.	Per mole of CO_2 captured, surplus heat output is 475 kJ with an equilibrium cell voltage of 1.5.

Table I. Summary of DAC integrated studies.

The DAC plant consists of various chemical cycles and units designed to capture CO_2 from the air and recycle the solvents used in the process, as illustrated in Figure . Here is a simplified version of the process described by Slavin et al. [10].

1. Air is pulled through a unit called the air contactor. In the contactor, CO_2 reacts with a solution containing KOH to form potassium carbonate (K_2CO_3).
2. The resulting K_2CO_3 solution is sent to the pellet reactor, which holds calcium carbonate ($CaCO_3$) pellets. Calcium hydroxide [$Ca(OH)_2$] is added to the reactor, causing $Ca(OH)_2$ to dissolve and $CaCO_3$ to precipitate.
3. More $CaCO_3$ pellets are added to the top of the reactor. They are removed from the bottom and sent to the calciner.
4. In the calciner, the $CaCO_3$ pellets are heated up to 900 °C, breaking them down into CO_2 and calcium oxide (CaO).
5. CO_2 is finally compressed and cooled for storage or sale.
6. In the slaker unit, the CaO is mixed with water to form $Ca(OH)_2$, which may be reused in the pellet reactor.

Simultaneously, the CO_2 emitted from the calciner is directed into a Solid Oxide Electrolysis Cell (SOEC) reactor, where it mixes with steam. Inside the reactor, three processes take place at once: steam electrolysis, CO_2 electrolysis, and the reverse water-gas shift reaction. The output gases are then divided into two streams: the anode outlet, which contains pure oxygen, part of which is recirculated back to the calciner, and the cathode outlet, which holds the produced syngas along with any unreacted components [5].

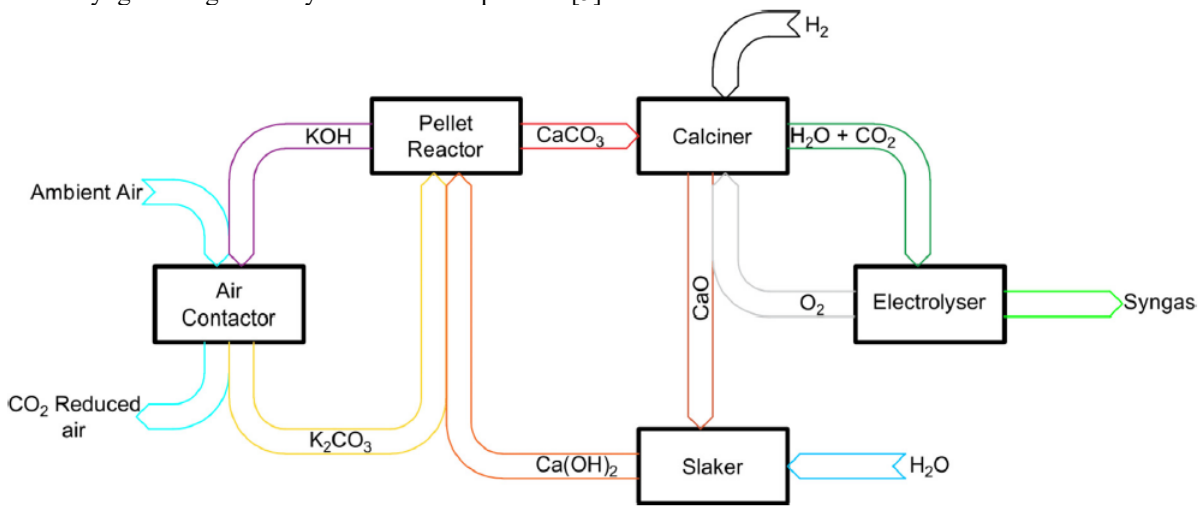

Figure III. DAC Process Diagram [7].

In a typical DAC unit, captured emissions are typically stored in depleted gas and oil fields. However, by incorporating a SOEC, the captured CO_2 can be transformed into a valuable product. This may help offset the plant's operating costs [7].

Over the last twenty years, there has been a notable increase in reports discussing different materials used in DAC to trap carbon dioxide. Recent advancements in DAC adsorbents require further evaluation, including the promising MMO-based amine-functionalized DAC adsorbent. This review examines how well these materials can capture CO_2, how easily they can be regenerated for reuse, and the mechanisms behind their CO_2 capture processes. Such efforts are expected to play a significant role in advancing DAC technology from foundational research to practical, large-scale applications [11]. Over time, there has been rapid progress in developing sorbents for capturing CO_2. Porous solid sorbents, known for their large surface area and adjustable pore structure, offer promising potential for CO_2 capture, addressing issues like equipment corrosion and high costs associated with traditional amine solutions. These sorbents can be categorized into physisorbents and chemisorbents based on their adsorption mechanisms, with the porous structure enhancing adsorption in various ways. Physisorbents benefit from increased interaction with CO_2 molecules in a porous environment, while chemisorbents utilize their porous structure to improve mass transport and adsorption kinetics. Framework materials like MOFs and COFs further refine this control, offering finely tunable pore characteristics [12]. Table contrasts the merits and demerits of direct air carbon capture technology.

Merits	Demerits
It helps reduce atmospheric CO_2 levels.	High initial capital investment is required.
Provides a way to remove CO_2 from hard-to-reach areas.	Energy-intensive process, leading to high operational costs and potential environmental impacts.
Can be deployed in various locations globally.	The efficiency of CO_2 capture may not be as high as desired, leading to limited impact.
Offers potential for carbon utilization and storage.	Challenges with scalability for large-scale deployment.
Contributes to global efforts in climate change mitigation.	Technological uncertainties and risks may hinder widespread adoption.

Table II. Merits and Demerits of DAC [13] [14].

2.2 Post-combustion. - Post-combustion carbon capture focuses on extracting carbon dioxide from the flue gases produced by combustion plants. These gases mainly consist of nitrogen and carbon dioxide at elevated temperatures (120–180°C), along with minor amounts of steam, sulfur dioxide, nitrogen oxides, and particulate fly ash [15]. According to emission standards, flue gas must be cleansed of toxic gases before its release [16]. Due to the lower concentration of carbon dioxide (3–20%) in flue gas compared to the pre-combustion methods, chemical absorption is commonly used to separate CO_2 [17]. Because of the low concentration and partial pressure of carbon dioxide, highly efficient separation methods are necessary. Monoethanolamine (MEA) aqueous solutions are frequently used due to their ability to effectively absorb carbon dioxide and form carbamates [18]. The post-combustion carbon capture process starts by passing the flue gas through a vessel with an absorber, usually MEA. The CO_2 -laden solvent is then moved to a separate vessel, where the CO_2 is extracted, allowing the solvent to be reused in the system [19]. The released CO_2 is subsequently compressed and transported.

Post-combustion carbon capture methods are advantageous over pre-combustion methods due to their flexibility, allowing integration into existing power plants, making them the preferred choice for current facilities [19]. However, these methods significantly increase electricity costs due to the substantial energy required for solvent regeneration and CO_2 compression. For example, coal plants can capture up to 800 tons of CO_2 per day, resulting in a 65% increase in electricity costs [20]. Table compares the advantages and disadvantages of post-combustion carbon capture technology.

Merits	Demerits
It can be installed in existing infrastructure.	The capture and separation of CO_2 require additional energy input, leading to decreased overall plant efficiency.
This technology helps industries and nations meet emission reduction targets and regulatory requirements.	A mismatch between supply and demand could hinder the economic feasibility of carbon utilization pathways and limit their contribution to overall emission reduction efforts.
Captured carbon dioxide can be used for several applications, including enhanced oil recovery (EOR), concrete carbonation, and the synthesis of fuels and chemicals.	Carbon capture processes, particularly those based on solvent absorption, can be resource-intensive, requiring large quantities of water, chemicals, and energy for operation.
Carbon capture and storage (CCS) technologies enable the long-term geological storage of CO_2, reducing its atmospheric concentration.	A risk of CO_2 migration through faults, fractures, or poorly sealed wells. Leakage of stored CO_2 could compromise the integrity of overlying rock layers and contaminate groundwater.

Table III. Merits and Demerits of Post-Combustion Carbon Capture Process [15] [21]

2.3 Pre-Combustion. - The growing concern over climate change and the need to mitigate greenhouse gas emissions have driven considerable research into carbon capture technologies. Among these, pre-combustion carbon capture processes have emerged as a promising avenue for reducing carbon dioxide (CO_2) emissions from industrial sources. As the name suggests, pre-combustion carbon capture involves capturing CO_2 before the combustion of fossil fuels, typically in gasification processes. The gasification of carbonaceous feedstocks, such as coal or natural gas, produces syngas, which is then subjected to carbon capture before combustion.

The process begins with gasification of carbon-rich feedstocks. It is a thermochemical process that converts solid or liquid carbon-containing materials into a gaseous mixture, primarily composed of hydrogen (H_2) and carbon monoxide (CO). This is achieved by reacting the feedstock with a controlled amount of oxygen or steam at elevated temperatures

[22]. The output of the gasification process is syngas, which is a mixture of hydrogen, carbon monoxide, and trace amounts of other gases such as methane. The composition of syngas depends on the type of feedstock and the specific gasification conditions. Before the syngas is combusted, it undergoes a separation process to capture the carbon dioxide. Several methods can be employed for carbon dioxide capture, including absorption, adsorption, and membrane separation, which are discussed in the next section.

In many scenarios, the process is integrated with hydrogen production. The separated CO_2 is often a by-product of hydrogen production through water gas shift reactions or other hydrogen-producing processes. Figure illustrates a pre-combustion carbon capture technology (CCT) system based on pressure-swing separation and stripping. Although pre-combustion CCT can achieve substantial CO_2 emission reduction, its integration generally increases plant complexity, capital cost, and energy requirements, which may affect overall system performance. The two most widely used absorbent types in carbon capture are chemical and physical. Chemical absorbents react with CO_2 to form stable compounds like carbonates, bicarbonates, or hydroxide solutions, but their regeneration requires significant energy, raising the plant's capital expenses. Physical solvents, on the other hand, are more effective at high pressures and low temperatures. Commercially, various physical solvents, such as polypropylene carbonate, methanol (Rectisol), dimethyl ether polyethylene glycol (DMEPEG or Selexol), and N-methyl-2-pyrrolidone (Purisol), have been successfully employed for CCT [16].

Selexol technology physically absorbs CO_2 from syngas using a liquid mixture of dimethyl ethers and polyethylene glycol. The process, which may be configured for variable levels of H_2S / CO_2 selectivity and sulfur removal depth, consists of two absorber units, where Selexol, preloaded with CO_2, removes H_2S first. The rich H_2S solution undergoes regeneration through pressure reduction, and the separated CO_2 is further removed in a second absorber, resulting in a purified gas with minimal uncaptured CO_2 and a rich CO_2 stream for transportation and storage [23].

The Rectisol process uses refrigerated methanol as a solvent to purify syngas produced by heavy oil and coal gasification. The technique, which operates at low temperatures (-40 °C to -60 °C), effectively removes H_2S to ppm levels despite its complexity. A typical Rectisol arrangement incorporates preloading with CO_2 in the first absorption column for H_2S removal, followed by regeneration by flashing and stripping, which can be customized to meet specific process requirements. The rich H_2S solution undergoes partial oxidation to recover elemental sulfur, and the desulfurized gas returns to the CO_2 absorption column, where CO_2 is extracted. The concentrated CO_2 solution is then regenerated in a flash regeneration unit [24].

Purisol process employs N-Methyl-2-pyrrolidone as a solvent to physically absorb H_2S and CO_2 from gas streams. Its flow scheme is similar to that of the Selexol process. This process can be carried out at ambient temperatures or cooled to around -15°C [24].

Physical absorbents use pressure swings and mild heating to remove absorbed gases, resulting in lower energy usage compared to chemical absorbents, which require more energy for bond breakdown. When selecting a physical absorbent, it is important to consider its CO_2 solubility, absorption affinity, density, viscosity, vapor pressure, and other properties.

The cost of a carbon capture (CC)-integrated power plant is influenced by various factors such as location, utilities, and the separation process. Additional costs encompass thermal recovery of absorbents, pumping, and heating or cooling of both liquid and gas streams. The Selexol method is more energy-efficient for CO_2 absorption than the Rectisol and MDEA technologies. In a pre-combustion CCT power plant utilizing Selexol solvent, carbon emissions were reduced by 90.9%, alongside a 5–7% decrease in the lower heating value (LHV), indicating improved thermal efficiency [24]. Table contrasts the merits and demerits of pre-combustion carbon capture technology.

Merits	Demerits
Elevated CO_2 concentrations enhance absorption efficiency.	Significant energy demand for regenerating sorbents.
Well-established process.	Substantial capital and operational expenses for existing sorption systems.

Effectively utilized in various chemical processes, including syngas production.	Temperature challenges related to heat transfer and efficiency concerns are tied to H_2-rich gas turbine fuel.
Possible to retrofit to existing plants.	Complexity and technical challenges.

Table IV. Merits and Demerits of Pre-Combustion Carbon Capture Process [15] [16]

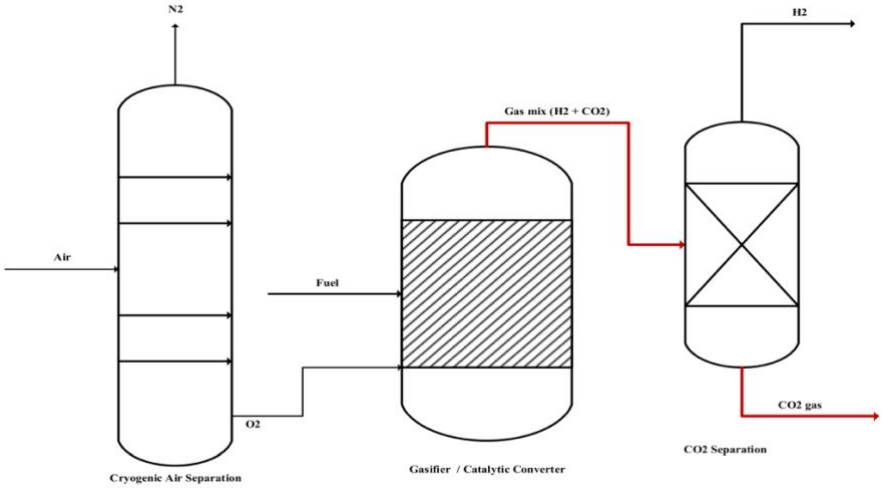

Figure IV. Pre-combustion Carbon Capture Process [22]

Atsonios et al. [24] reported that the recent advancements have focused on integrating pre-combustion carbon capture technologies with Natural Gas Combined Cycle (NGCC) and Integrated Gasification Combined Cycle (IGCC) power plants, showcasing the maturity of these techniques in the chemical industry.

Atsonios [25] proposed detailed optimization of plant design parameters such as column height and packed dimensions to enhance the efficiency of pre-combustion capture processes using various solvents like alkanolamine, polyethylene glycol dimethyl ethers, chilled methanol, and N-Methyl-2-pyrolidone.

Research has explored the use of innovative solvents such as dimethyl ethers of polyethylene glycol for pre-combustion CO_2 capture, showcasing enhanced energy efficiency and reduced specific emissions [26].

Olabi [16] reports that pre-combustion carbon capture technology (CCT) proves effective in mitigating pollution but entails high costs, utilizing both chemical and physical absorbents for carbon capture. Its implementation not only aids in reducing global greenhouse gas emissions but also aligns with UN Sustainable Development Goals, particularly SDG-13 and SDG-7, and brings benefits like cleaner air.

Carbo et al. [27] studied the impact of pre-combustion CO_2 capture on gas turbine operation and reported that gas turbines designed for syngas demonstrate greater efficiencies than modified versions. Gas turbines play a vital role in converting synthesis gas derived from coal gasification into electricity, with redesigned turbines for syngas exhibiting higher efficiencies than those optimized for natural gas, although the lack of nitrogen utilization from air separation units (ASUs) for syngas dilution can result in increased NOx emissions.

Babu et al. [28] investigated the hydrate-based gas separation. In the hydrate-based gas separation process utilizing silica sand and silica gel, silica sand proves more effective for CO_2 separation and exhibits higher water conversion rates compared to silica gel. The significant impact of driving force on gas uptake in the silica sand bed is observed, while employing a combination of depressurization and thermal stimulation results in the complete dissociation of hydrates, showcasing the promising potential for efficient gas separation.

2.4 Chemical Looping. - Chemical looping is a technology used in carbon capture technologies that aims to extract CO_2 from combustion-byproduct flue gas without requiring energy-consuming separation procedures. A chemical looping process breaks down a reaction into two or more smaller reactions. In this process, a cycle of reaction and regeneration is experienced by the chemical intermediates. These chemical intermediates are usually oxides of metals.

A simple example of a redox chemical looping system is shown in Figure V. In order to create desired products, feedstock (fuel) must be fully or partially oxidized using oxygen carriers such as metal oxides. In the event of complete oxidation, the products are H_2O and CO_2 with heat or electricity. When fossil fuels partially oxidize, the most frequent byproduct is syngas, which is a mixture of CO and H_2. It is possible to further convert syngas into finished goods like chemicals, fuels, and hydrogen. When exposed to steam or air, the used oxygen carriers regenerate.

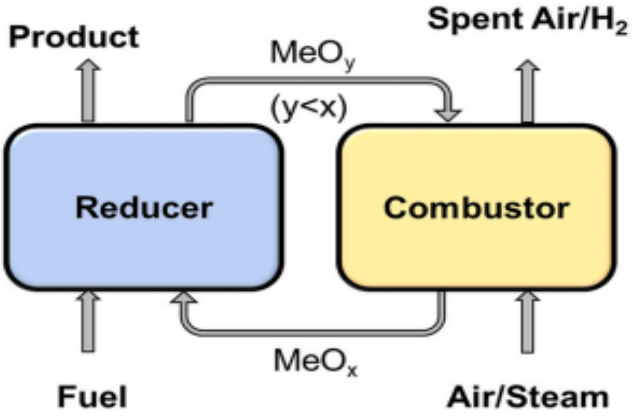

Figure V. Schematic of Redox Reaction [29]

(A) Calcium Looping. - Calcium looping is among the more mature looping-based CO_2 capture approaches. According to Wang [30], for CO_2 capture from industrial gas, carbonation-calcination cycles are used as illustrated in Figure . The process consists of two steps:

1. **Carbon Capture:** Sorbent particles use metal oxide to absorb CO_2 in the carbonator. While other gases pass through unreacted, the metal oxide (MeO) sorbent combines with CO_2 from the flue gas stream to generate metal carbonate (MeCO3). For calcium looping, the reaction is given as,

$$CaO + CO_2 \rightarrow CaCO_3$$

2. **Carbon Release:** Metal Oxide (**MeO**) at high temperature releases a pure stream of CO_2. The carbon regeneration reaction is given as,

$$CaCO_3 \xrightarrow{heat} CaO + CO_2$$

The most common sorbent used is calcium oxide. This is why the process is referred to as calcium **looping**.

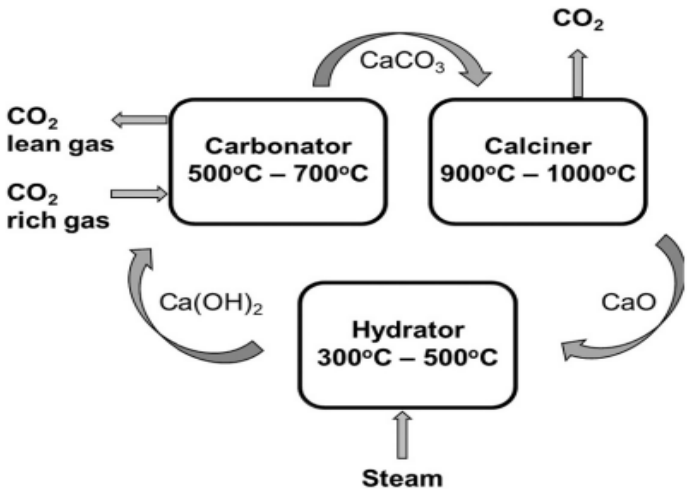

Figure VI. Calcium Looping Cycle [30]

(B) In-situ Methanation. - In-situ Methanation is a process used for converting the captured CO_2 directly into methane using hydrogen as a reducing agent. The chemical reaction is carried out at temperature of 200 – 400 °C in the presence of catalyst (usually Ni, Co, or Fe). The chemical reaction is given as:

$$CO_2 + 4H_2 \xrightarrow[200-400°C]{catalyst} CH_4 + 2H_2O$$

Jin [30] has provided new insights into chemical looping CO_2 capture and in-situ conversion (CL-ICCC) technologies by the use of solid waste as a greener chemical looping alternative. The study discusses the establishment of low-carbon and self-digestion industrial systems.

Zhang [12] integrated CO_2 capture via calcium-looping with in-situ dry reforming of methane through $CaCO_3$, allowing the simultaneous decomposition of $CaCO_3$ to CaO and syngas. Furthermore, the study uses Fischer-Tropsch synthesis for the production of valuable fuels from syngas.

Chirone [31] has found a reactor configuration for catalytic methanation using chemical looping and sorption enhanced methanation, resulting in high methane yield with good temperature control and low operating pressure.

Kim [32] has carried out a thermodynamic analysis to determine viable metal oxides that can serve as oxygen carriers in the chemical looping process.

Chen [33] provides a conceptual design and analysis on the use of Integrated Carbon Capture and Methane (ICCM) to produce methane from flue gas using chemical-looping. Figure provides a simplified illustration of the ICCM process using H_2 from renewable sources.

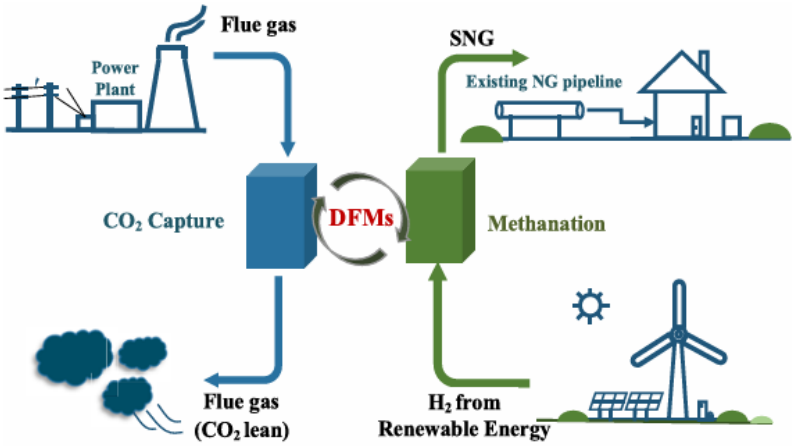

Figure VII. ICCM Process Explained [34]

3. Carbon Separation Technologies. - Carbon separation technologies are used to selectively separate CO_2 from gas mixtures generated in industrial processes and power plants. Some of the technologies are given in Figure .

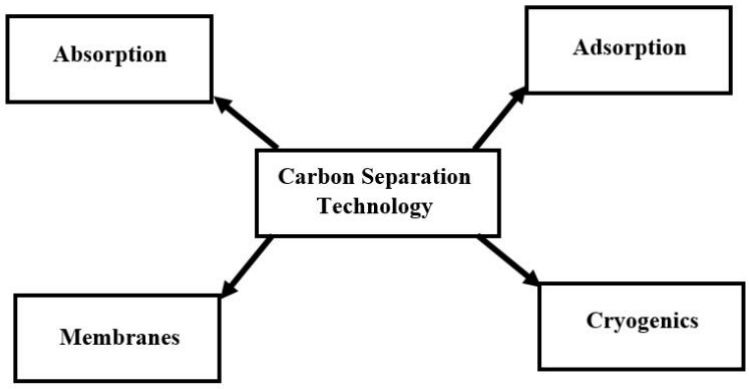

Figure VIII. Carbon Separation Technologies

3.1 Absorption. - The petroleum and chemical industries frequently use absorption, a commercially accessible method of removing carbon dioxide from flue gas. It uses a liquid absorbent that is regenerable by adjustments to pressure and temperature [17]. The technology has two major categories: chemical absorption and physical absorption. Chemical absorption involves chemical reactions, typically acid-base reactions, between CO_2 and the solvent. In contrast, physical absorption is governed by CO_2 solubility in the solvent and depends mainly on temperature and pressure.

MEA is one of the most widely used benchmark solvents for CO_2 absorption due to its high CO_2 recovery (85%-90% vol.), high capacity (4.09 mol CO_2/kg), and CO_2 purity exceeding 99% vol [18]. However, MEA requires a high amount of energy during the regeneration of the solvent. The advantages and disadvantages of the physical absorption processes are compared in Table .

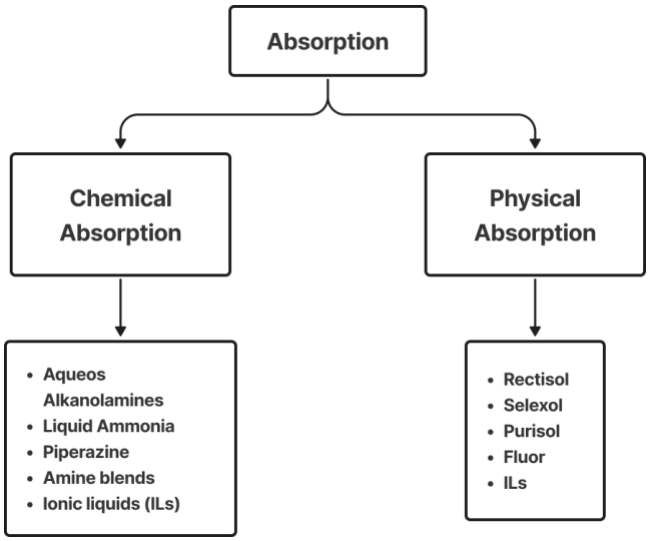

Figure IX. Types of Absorption with some commonly used and emerging materials [15]

Recent developments in absorption techniques have focused on enhancing efficiency and reducing environmental impact. One notable advancement involves the use of novel absorbent materials, such as advanced amines, ionic liquids, phase-change solvents, and membrane contactors, which exhibit higher selectivity and capacity for capturing target gases like carbon dioxide (CO_2) or volatile organic compounds (VOCs).

Additionally, there is increasing interest in process intensification techniques, such as reactive absorption or membrane contactors, which offer improved mass transfer rates and lower energy requirements, thereby making absorption processes more economically viable and sustainable. These developments signify a shift towards greener and more efficient absorption technologies that play a crucial role in various industries, including gas processing, chemical manufacturing, and environmental protection. W. Y. Hong [15] reported that recent studies have highlighted advancements in selecting solvents for CO_2 absorption, with a focus on novel solvents like dimethyl ethers of polyethylene glycol and ionic liquids.

B. Sreenivasulu et al. [34] reported that research has shown improvements in absorption efficiency by using modified activated carbons with MEA-MDEA, enhancing CO_2 adsorption capabilities under pressure swing adsorption conditions.

Advancements in absorption techniques have been integrated with advanced power plant concepts like IGCC, showcasing the potential for efficiency gains and reduced CO_2 emissions through innovative process configurations [35].

Physical Absorption Process	Advantages	Disadvantages
Selexol process	• High selectivity for H_2S • Water wash is not required for solvent recovery. • Chemically and thermally stable. • Flexible, meaning it can be used for both targeted and combination H_2S and CO_2 removal [36]. • Solvent loss is low. • Able to remove moisture, owing to the solvent's hydrophilic nature.	• High viscosity with decreased mass transfer rate and tray efficiency at the low end of the operating temperature range, or 0–175 °C [37]. • Only appropriate for removing CO_2 when CO_2 concentration is higher than H_2S [38].
Rectisol process	• Good CO_2 and H_2S removal efficiency. • Viscosity of the solvent is reasonable. • Low loss of solvent [36]. • Low corrosivity.	• Low-temperature operation (i.e. -30 to -80 °C) [39]. • The potential for amalgam to form at low temperatures as a result of mercury absorption [38].
Purisol process	• High H_2S selectivity. • Flexible, meaning it can be used for both targeted and combination H_2S and CO_2 removal [37].	• Water cleaning is necessary to prevent excessive solvent loss due to the volatile solvent [37].
Fluor process	• Non-corrosive with low-viscosity solvent. • Allows for selective removal of H_2S. • Exhibit high carbon dioxide solubility. • Does not require additional makeup water [38].	• It is not cost-effective to get high product purity. • Need for a gas-liquid contactor with increased efficiency [40]. • Expensive solvent.
Morphysorb process	• Minimal startup and ongoing expenses. • Reduced energy consumption [41]. • Reduced need for recirculation. • Decreased hydrocarbon co-absorption [42].	• A relatively new process that is still in the early phases of pilot testing and laboratory trials. [42].

Table V. Comparison of Merits and Demerits of Physical Absorption Processes

Merits	Demerits
Higher absorption performance is usually greater than 90%.	Energy-intensive and costly solvent recovery.
Heat and/or depressurization can be used to recover sorbents.	Sorbent breakdown caused by repeated heating and cooling cycles.
The most widely established carbon capture method.	Absorption capacity may decrease under unfavorable temperature and pressure conditions.
Suitable for high CO_2 concentrations.	
Low-cost solvent.	

Table VI. Merits and demerits of the absorption technique of CCS [15] [16]

3.2 Adsorption. - Adsorption is a surface-based separation process in which gas molecules adhere to the surface of a solid adsorbent through physical or chemical interactions. The success of CO_2 capture depends on the selection of the adsorbent material. Adsorbents with a high specific affinity for CO_2 and surface area are generally favored. Activated carbon, zeolites, metal-organic frameworks (MOFs), and materials functionalized with amines are examples of commonly used adsorbents. The method of CO_2 collection entails contacting the adsorbent material with flue gas or other streams containing CO_2. This can be carried out in a variety of reactor types, including packed-bed, fluidized-bed, and fixed-bed reactors. Physical or chemical interactions cause the CO_2 molecules to stick to the adsorbent's surface.

3.2.1 Adsorption techniques based on the separation method: TSA (Temperature Swing Adsorption) and VSA (Vacuum Swing Adsorption) are both techniques used in gas separation processes, particularly in the purification of gases. These processes utilize the principles of adsorption to separate different components from a gas mixture.

(A) Temperature Swing Adsorption (TSA): In TSA, the adsorption and desorption of gases occur at different temperatures. Typically, this process involves adsorbing a target gas at a relatively low temperature and then desorbing it at a higher temperature. The adsorbent material selectively adsorbs the target gas at lower temperatures. Then, by increasing the temperature, the adsorbent releases the adsorbed gas, thus regenerating itself. TSA is commonly used for the purification of gases, such as hydrogen, nitrogen, or carbon dioxide, from mixed gas streams in various industries, including petrochemical, chemical, and environmental.

(B) Vacuum Swing Adsorption (VSA): In VSA, adsorption generally occurs at near-atmospheric or moderate pressure, while desorption is promoted by reducing the pressure below atmospheric conditions. VSA is often used for gas separation processes where the target gas can be separated from the feed gas stream by exploiting differences in adsorption capacities under different pressure conditions. This technique is commonly used in applications such as oxygen generation, hydrogen purification, and natural gas processing. Table contrasts the merits and demerits of adsorption-based carbon separation.

Merits	Demerits
Adsorption techniques can selectively separate target components from gas mixtures based on their affinity for the adsorbent material.	Regeneration of the adsorbent material can require additional energy inputs or complex process conditions, which may increase operational costs.
Adsorption processes often require lower energy inputs.	Adsorbent materials can degrade or lose their adsorption capacity due to factors such as fouling.
Adsorption techniques can be applied to a wide range of gas mixtures and can effectively remove impurities.	Adsorption processes can be relatively complex to design, operate, and optimize.
Adsorption processes can be operated continuously, allowing for steady-state operation and continuous production of purified gases.	The initial capital investment for adsorption equipment and systems can be higher.
Adsorption systems can be designed in a modular fashion, allowing for scalability and flexibility.	Adsorption systems may require significant space for installation, especially when considering factors such as adsorbent beds and regeneration equipment.

Table VII. Merits and Demerits of Adsorption [36] [43]

3.2.2 Adsorption using Fixed-Bed Reactor: Figure illustrates the process of adsorption using a fixed-bed reactor. The Ca-looping process, typically carried out in a dual fluidized bed reactor, is regarded as the cornerstone of cutting-edge CO_2 reduction technology. Research on the use of fine activated carbon in sound-assisted fluidization to capture CO_2 from flue gases has shown improved adsorption. Studies on the impact of water on carbon dioxide adsorption with activated carbon in fixed beds have shown that the presence of water decreases the efficiency of the process. In comparison to fluidized beds, the use of fixed beds for CO_2 capture from flue gases has been less extensively researched.

A gas mixture comprising carbon dioxide (CO_2) and nitrogen (N_2) is introduced into the column from gas cylinders. To precisely measure the flow rates of each gas, mass flow controllers (F1 and F2) are installed, with dedicated flow control valves (V1 and V2) regulating the flow rates accordingly. Additionally, a separate mass flow meter (F3) is

utilized to monitor the overall flow entering the infrared (IR) detector. Before commencing experimental runs, the mass flow meters undergo calibration to minimize measurement uncertainties. The pressure within the column is monitored by a pressure gauge (P1), while the concentration of CO_2 at the column outlet is determined using a calibrated IR sensor.

In the experiment, the gas mixture of CO_2 and N_2 undergoes separation, primarily through the adsorption of CO_2 onto the surface of adsorbents. The CO_2-N_2 mixture enters the fixed bed in an ideal plug flow manner, with only CO_2 being adsorbed by the sorbents and subsequently removed from the gas phase. Temperature control is facilitated by a PID temperature controller, which regulates the water temperature. Additionally, a column bypass is incorporated into the system for calibration purposes.

As part of the experimental protocol, a controlled flow of nitrogen (4 L/min) is initially passed through the bed containing sorbents for a duration of 2 hours (7200 seconds). This process ensures the removal of any residual traces of oxygen and CO_2 from the bed. The same experimental approach is replicated to obtain the data under different operating conditions.

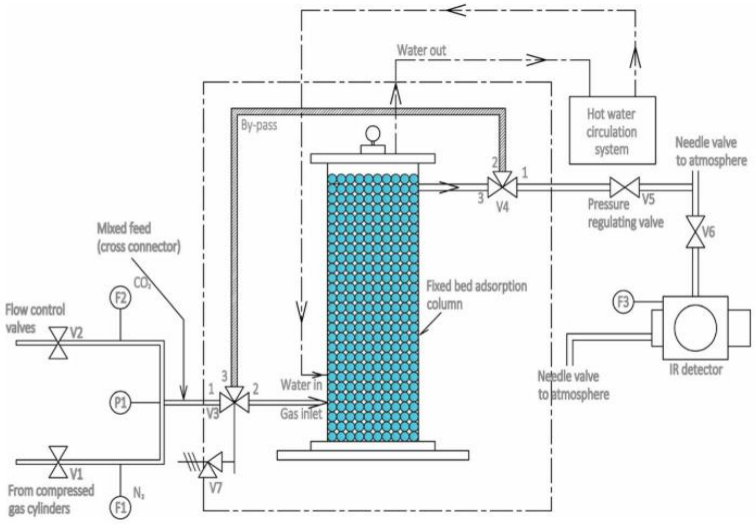

Figure X. Fixed Bed Reactor [44]

3.2.3 Adsorption using Metal Organic Frameworks (MOFs): In the past decade, MOFs (Metal-Organic Frameworks) and MOF-functionalized materials have emerged as novel classes of materials renowned for their exceptional properties, including ultrahigh porosity, large surface area, tunable structures, and thermal stability [45]. Metal-Organic Frameworks (MOFs) are crystalline porous materials made up of metal ions connected to organic ligands via coordinate covalent bonds, often referred to as coordination polymers or metal-organic polymers [46]. They find applications across various fields, such as catalysis [47] [46] [48], adsorption [49] [50], and sensing [51] [52] [53] [54]. Despite their advantages, MOFs face challenges in adsorption, including low capacity at low pressures, sensitivity to moisture and gas mixtures, and high synthetic costs, limiting their widespread use [55].

Researchers have turned to impregnated MOF-based adsorbents for post-combustion carbon capture due to their excellent physisorption and chemisorption characteristics [56]. They [56] investigated the adsorption efficiency of amine-functionalized MOF-177 variants, such as PEI, TEPA, and DETA. They found TEPA-impregnated MOF-177 to exhibit a significant enhancement (4.8 times) in CO_2 capturing compared to unmodified MOF-177 at 298 K. Similarly, Quan et al. [57] developed diamine-appended MOF/polymer composite hollow fiber sorbents, demonstrating higher CO_2 capture (2.5 mmol CO_2 /g-MOF) at relatively low pressures. Additionally, Wu et al. [58] studied a copper-based MOF with distinct pore structures, achieving a CO_2 uptake of 4.63 mmol/g at 100 kPa and 2.92 mmol/g at 15 kPa, outperforming other MOFs due to the presence of strong electrostatic interaction sites.

Addressing limitations of MOFs, Qazvini et al. [59] synthesized MUF-16, a hydrogen-bonded water-stable microporous material coated with PVDF, aiming for large-scale industrial applications with affordable production costs and long-term chemical stability. MUF-16 exhibited promising CO_2 uptake of 47.8 and 61.1 cm3/g of CO_2 at 1 and 20 bar, respectively.

A detailed comparison of these adsorbents, including surface area (m2/g), pore size (nm), regeneration cycles, and adsorption capacity (Qmax), is provided in Table.

3.2.4 Scale of Experimental Validation: Carbon capture technologies are evaluated across multiple levels of experimental maturity, including bench-scale, pilot-scale, and commercial systems. Bench-scale studies are generally performed under controlled laboratory conditions to evaluate material performance, whereas pilot-scale systems operate under more realistic scenarios and provide information regarding system integration, operational challenges, and scalability [60].

3.2.5 Bench-scale experimental studies and boundary conditions: Bench-scale investigations are mainly conducted to validate adsorption performance under controlled environments. These studies are characterized by laboratory-scale setups, well-defined operating conditions, and a strong focus on material-level behavior such as adsorption capacity, selectivity, and stability [60].

Some features of bench-scale studies include:

- Controlled laboratory conditions
- Emphasis on adsorbent performance
- Simplified system boundaries

For example, a representative bench-scale study conducted under conditions simulating a coal-fired power plant employed a flue gas stream with approximately 15% CO_2 by volume and an adsorption temperature range of 50–90 °C. Under these conditions, the presence of impurities such as SO_2 (100 ppm) was found to significantly affect performance, resulting in an approximate 30% reduction in adsorption capacity after 100 adsorption–regeneration cycles. These findings highlight the sensitivity of adsorbent materials to flue gas contaminants, which is often not fully captured under ideal laboratory conditions [60].

3.2.6 Pilot-scale experimental studies: Pilot-scale systems represent an intermediate step between laboratory research and full-scale industrial deployment. These systems are designed to replicate real plant conditions more closely and are essential for evaluating process feasibility, energy requirements, and economic performance.

Key characteristics of pilot-scale studies include:

- Operation under realistic flue gas conditions
- Inclusion of impurities and temperature fluctuations
- Improved estimation of cost and energy performance

A typical pilot-scale study may simulate a coal-fired supercritical power plant (e.g., ~10 MW equivalent capacity) using sorbents such as 35 wt% K_2CO_3. Such systems are significantly larger in scale, with dimensions on the order of tens of meters (e.g., 34 m × 15 m × 59 m), and operate at adsorption temperatures around 80 °C with regeneration temperatures reaching approximately 200 °C.

Compared to bench-scale studies, pilot-scale investigations provide more reliable insights into process integration and operational challenges, although they still involve certain assumptions and simplifications relative to full commercial systems [61].

3.2.7 Future challenges: Despite promising results at laboratory and pilot scales, several challenges remain in scaling adsorption-based carbon capture technologies to commercial deployment. One major limitation is the high cost associated with large-scale production of advanced adsorbent materials.

In addition, process-related challenges such as heat management and temperature control are significant, particularly due to the endothermic nature of adsorption–desorption cycles. Maintaining adsorption capacity over repeated cycles while ensuring efficient thermal management remains a key technical hurdle.

Operational issues such as pressure drop and material handling also pose challenges, especially when dealing with fine adsorbent powders in large-scale systems. These factors collectively highlight the complexity of transitioning from laboratory-scale validation to industrial implementation.

Parameter	Bench-Scale studies	Pilot-Scale studies
Typical objective	Evaluation of performance and screening of material.	Process validation under realistic scenarios.
Efficiency of Capture	Often high under controlled conditions.	Affected by real flue gas conditions; therefore, it varies from moderate to high.
Energy Penalty	Not fully evaluated.	Varies significantly depending upon the process design.
TRL	Low (3-5).	Medium (5-7).
Key limitation	Lack of scalability.	High cost and complex scalability.

Table VIII. Comparison of Bench-Scale and Pilot-Scale Adsorption-Based PCC Systems [61]

Types of Adsor-bent	Adsorbent	Surface Area (m^2/g)	Pore Size (nm)	Operation Parameters	Adsorption Capacity	Author
Chemical adsorbent	70T-MM-550 monolithic adsorbent impregnated with TEPA	10.46	0.02	Pressure (bar): 1, Temp. (°C): 75	151.1 mg g^{-1}	T. Chitsiga et al. [62]
	PAA-100% MA	2.94	30.9	Pressure (bar): 1.1, Temp. (°C): 40	44.2 g kg^{-1}	A. Ra Cho et al. [63]
	2.0PO-PEHA/MPS	472	-	Pressure (bar): 1, Temp. (°C): 50	1.8 mmol g^{-1}	S. Ahmed et al. [64]
	50 wt.% TEPA-functionalized Si-MCM-41	11	1.8	Pressure (bar): 1, Temp. (°C): 75	70.41 mg g^{-1}	E. Atta-Obeng et al. [65]
	Si-MCM-41	993	3.1	Pressure (bar): 1, Temp. (°C): 75	54.65 mg g^{-1}	M. A. O. Lourenço et al. [66]
	L350	2.8	-	Pressure (bar): 0.9, Temp. (°C): 30	1.54 mmol g^{-1}	R. R. Kondakindi et al. [67]
Physical adsorbent	Li-LSX zeolite	662	0.08-0.18	Pressure (bar): 1, Temp. (°C): 25	4.43 mmol g^{-1}	D. Panda et al. [68]

	HZAA-1–3 with urea	126	0.4-5.5	Pressure (bar): 0.2, Temp. (°C): 25	2.86 mmol g^{-1}	K. J. Hwang et al. [69]
	Basalt-based zeolite 4A	726	-	Pressure (bar): 1, Temp. (°C): 50	5.9 mmol g^{-1}	W. Liang et al. [70]
	20% EDHy Zeolite	-	-	Pressure (bar): 1, Temp. (°C): 25	1.76 mmol g^{-1}	D. Panda et al. [71]
	IBA-Z4A	32	3.8	Pressure (bar): 1.2, Temp. (°C): 40	2.56 mmol g^{-1}	S. Y. Lee & S. J. Park [72]
	3D-printed monolith activated carbons	-	-	Pressure (bar): 1, Temp. (°C): 30	3.17 mol kg^{-1}	L. Jiang et al. [73]
	chitosan/MWCNTs	-	-	Pressure (bar): 1, Temp. (°C): 90	3 mg g^{-1}	Krishnamurthy et al. [74]
	3D-printed PEI/(MWCNT)	27	30	Pressure (bar): 1, Temp. (°C): 25	0.064 mol kg^{-1}	Jayakaran et al. [75]
Hybrid adsorbents	20% TEPA-impregnated MOF-177	585	-	Pressure (bar): 1, Temp. (°C): 25	4.6 mmol g^{-1}	W. Quan et al. [58]
	2-ampd-Mg2(dobpdc)	-	-	Pressure (bar): 1, Temp. (°C): 25	2.5 mmol g^{-1}	H. Wu et al. [59]
	Copper-based MOF-11	-	-	Not reported	4.63 mmol g^{-1}	Qazvini & S. G. Telfer [60]

Table IX. Adsorbents for carbon dioxide capture [61]

3.3 Membrane. - Membranes are materials that selectively separate CO_2 from gas mixtures, such as the flue gases from combustion. Membrane separation is based on the difference in permeability of the gases. Membrane separation is driven by partial-pressure differences, and performance is governed by the trade-off between CO_2 permeability and CO_2 selectivity. Some of the common types of membranes include:

3.3.1 Polymeric Membranes. - These membranes are composed of polymers and selectively separate gases based on size, shape, and chemical affinity. Jana [76] has compared the performance of different polymer-based membranes for the separation of a CO_2 and N_2 mixture. These polymers include materials such as PE (Poly Ethylene) and PVC (Poly Vinyl Chloride), with nanofillers. Additionally, membrane performance can be enhanced by the use of grafting. Lai

[77] has shown that by adding ZIF-8 filler to poly (ionic-liquid) membranes, membrane permeance can be enhanced for improved CO_2 and N_2 separation.

3.3.2 Mixed Matrix Membranes. - Combining a polymeric matrix with inorganic fillers or nanoparticles, these membranes enhance selectivity and permeability in gas separation.

3.3.3 Zeolite Membranes. - Utilizing crystalline aluminosilicate structures, zeolite membranes employ molecular sieving properties for effective gas separation. Shi [78] has performed molecular dynamics simulation on MER Zeolite to determine its adsorption behavior in CO_2, CH_4, and N_2. Results show that CO_2 has the least diffusion activation energy (4.38 kJ/mol). This makes MER Zeolite suitable for separation of gas mixtures like CO_2/CH_4 and CO_2/N_2.

3.3.4 Ceramic Membranes. - Made from ceramic materials, these membranes are known for durability and stability at high temperatures, making them suitable for harsh industrial environments.

3.3.5 Metal-Organic Framework (MOF) Membranes. - These porous materials with high surface areas and tunable structures show promise in gas separation due to unique adsorption properties. In Majumdar [79], Mg-MOF-74 crystals were synthesized to create polymer/Mg-MOF-74 mixed matrix membranes (MMM) for CO_2/CH_4 separation.

3.4 Cryogenic Separation. - Cryogenic CO_2 capture builds on the idea of cryogenic distillation, a well-known method for separating different molecules in a mixture based on their boiling points by cooling them. Originally used in industries like oil and gas for liquefied natural gas (LNG) and hydrogen production, this technique has been adapted to remove CO_2 from flue gases. The process involves drying and compressing the gas, then cooling it to separate CO_2 from other components through partial condensation and distillation. Depending on temperature and pressure, CO_2 may be separated either by condensation as a liquid or by desublimation as a solid. Sometimes, an upfront process called PSA is needed to concentrate the CO_2 further [80].

In this approach, various compression techniques are used at normal pressure and temperature to separate gases. This method works well for producing liquid CO_2 and is effective for capturing high concentrations of carbon dioxide. It offers advantages over amine-based scrubbing, such as being more environmentally friendly, resistant to corrosion, using cheaper chemicals, and requiring less water. It supports the production of liquid CO_2 and operates at normal pressure, which helps with the financial aspects of transmitting CO_2. However, there are limitations to cryogenic separation. It has a narrow operating temperature range, leading to high energy consumption and operating expenses. Ice formation in the process can clog pipes, reducing pressure and posing safety risks. Therefore, it is crucial to remove moisture from flue gases before starting the separation process. Implementing a cryogenic CO_2 removal system in a power plant can increase its operating costs by up to 50% [81].

Cryogenics technology is most commonly associated with post-combustion carbon capture, where it can effectively capture carbon dioxide from flue gases emitted by power plants and industrial facilities after the combustion process. However, it can also be utilized in pre-combustion carbon capture processes, particularly in combination with technologies like gasification. Direct air capture (DAC) typically involves different capture methods, not usually cryogenic, as it aims at capturing CO_2 directly from the atmosphere. Direct atmospheric cryogenic carbon capture in cold climates is a novel approach for reducing atmospheric CO_2 emissions. Leveraging the naturally cold temperatures of these regions, this method involves capturing CO_2 directly from the air using cryogenic technology. By utilizing the cold ambient air, the process can potentially be more energy-efficient compared to traditional carbon capture methods. This innovative approach holds promise for mitigating climate change through reduction of greenhouse gas emissions in regions with cold climates.

The method utilizes the high phase-transition temperature of CO_2 compared to other atmospheric gases, except water vapor. By employing desiccant wheels or cooling methods like low ambient temperatures or conventional refrigeration, water vapor can be easily eliminated. Figure depicts the relationship between the desublimation temperature and the mass fraction of CO_2 de-sublimated. Cryogenic distillation is highlighted as the most promising technique for its ability to produce pure CO_2 in solid, liquid, or gas forms, making it economically valuable and easily storable. It does not require new material development and can be quickly scaled up for industrial use [82].

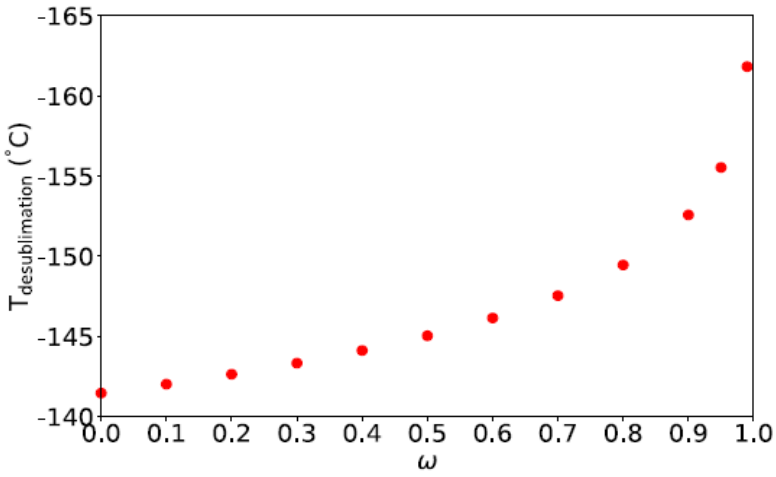

Figure XI. De-sublimation temperature as a function of mass fraction of CO_2 de-sublimated [83]

Cryogenic separation for CO_2 capture is gaining popularity as a technology due to its ability to produce high-purity CO_2 without the need for additional chemicals, reducing pollution in the capture process. This eco-friendly approach holds significant promise and practical value. However, the challenge lies in the demanding cryogenic cooling conditions and capacity required for efficient capture, which have hindered the widespread adoption and advancement of this method [83].

To remove CO_2 from industrial flue gas or the surrounding air, a process known as cryogenic desublimation is employed. This method involves cooling the gas, eliminating water vapor from the mixture, and then freezing the CO_2 into a solid. Studies have shown that significant amounts of CO_2 can be captured using evaporator temperatures ranging from -99 °C to -122 °C. Further research has focused on reducing water content through defrosting and multi-stage condensation. Another proposed method includes cooling, drying, and moderate compression before freezing, achieving a 99% capture rate at -135 °C. Stirling coolers have also been utilized to achieve a 96% capture rate at an energy cost of 1.5 MJ/kg CO_2. Additionally, the minimum energy required for CO_2 separation from air at -20 °C is estimated to be 419 MJ/tonne CO_2 [84].

Inspired by Mars' CO_2 ice cap, a cryogenic direct-air capture (DAC) system proposal suggests locating it in Antarctica, Earth's coldest region, where CO_2 extraction could be economically feasible. This setup would use closed-loop vapor compression refrigeration cycles powered by nearby wind farms to capture atmospheric CO_2 and convert it into solid " CO_2 snow" for storage. Experimental prototypes showed promising reductions in CO_2 concentrations. However, challenges like the remote location, extreme cold, and maintenance issues persist despite advantages like abundant wind energy [84].

In cryogenic direct-air capture (DAC) systems, a thermodynamic model was proposed to analyse a prototype comprising a deposition chamber, cryogenic refrigeration cycle, and precooler heat exchanger. The precooler aims to lower the incoming air temperature, reducing the workload for the cryocooler. Various locations, including Antarctica, were considered for this setup. Subsequent research refined the thermodynamic model, focusing on optimizing CO_2 de-sublimation efficiency through precooling. It was found that achieving higher CO_2 removal rates incurs greater energy penalties due to lower required temperatures. Precoolers with high effectiveness can lead to fouling issues, impacting system performance. Another aspect studied was precompression, which increases the CO_2 partial pressure but incurs energy penalties, particularly in cryogenic DAC systems with low CO_2 partial pressures. Adding turbine recovery to precompression showed limited energy savings under specific conditions. However, these findings are based on idealized scenarios and may differ in practical applications [84].

4. Comparison of Different Carbon Capture and Separation Techniques. - The following section discusses and compares the carbon capture and separation technologies, presenting their efficiency and Technology Readiness Level (TRL), as well as their advantages and disadvantages. Table compares the various carbon capture and separation techniques to provide an overview of their strong and weak points.

CO_2 capture efficiency is a critical metric defining the effectiveness of a carbon capture system in removing CO_2 from a gas stream, such as flue gas from power plants or industrial processes. Expressed as a percentage, it represents the

proportion of CO_2 captured relative to the total CO_2 entering the system. Higher capture efficiency signifies a greater reduction in emissions, highlighting the importance of optimizing capture technologies to mitigate climate change impacts.

Concurrently, the Technology Readiness Level (TRL) framework, originally developed by NASA and now widely used across various industries, provides a systematic approach to evaluating the maturity of CO_2 capture technologies. The TRL scale ranges from 1 to 9, encompassing stages from basic research (TRL 1-3), where new materials and concepts are explored, through lab-scale validation and pilot testing (TRL 4-6), to full-scale demonstration and commercial deployment (TRL 7-9) [84].

4.1 Comparative Assessment. -

	TRL	Study type/Scale	Energy / Cost basis	CO_2 capture efficiency (%)	Advantages	Disadvantages	Reference
Pre-combustion	9	Not specified in the source	Not reported	84–93	- Suitable for large-scale H_2 production. - Low energy penalty (10–15%). - High efficiency. - Lower potential cost. - Applicable to thermal power plants. - Retrofit opportunity for existing plants.	- Still undergoing development. - Requires substantial capital investment. - Novel materials needed for high-temperature CO_2 capture. - Complex process scheme.	[85]
Oxyfuel combustion	7	Not specified in the source	Not reported	92	- Minimal equipment required due to reduced gas volume. - Utilizes mature air separation techniques. - Enhanced absorption efficiency in high CO_2 environments.	- Corrosion issues may arise. - Cryogenic O_2 production is expensive. - Incurs a high energy penalty and efficiency reduction.	[86] [87]
Post-combustion	9	Bench scale	\$75.2/tonne CO_2	55–98	- Retrofitting feasible for existing plants. - Mature technology compared to other methods.	- Efficiency affected by low CO_2 concentrations.	[62] [87]
Absorption	7–9	Not specified in the source	Not reported	80–95	- Effective at various CO_2 pressures. - Minimal hydrocarbon losses. - High selectivity and efficiency. - Standard for coal-fired and natural gas power plants. - Established technology.	- Solvent degradation, corrosion, and emissions. - High energy penalty for solvent regeneration in some cases. - Limited to thermal power plants.	[88] [89] [90]

	TRL	Study type/Scale	Energy / Cost basis	CO_2 capture efficiency (%)	Advantages	Disadvantages	Reference
Membrane technology	5–6	Not specified in the source	Not reported	≤90	- Effective at various CO_2 pressures. - Small footprint. - Chemical-free operation without regeneration. - Suitable for large-scale natural gas processing.	- Unsuitable for low CO_2 concentrations. - Balancing permeability and selectivity. - Hydrocarbon losses. - Requires gas compression.	[91] [92]
Adsorption	3-4	Modeling study	3.23 MJ/kg CO_2	95% purity, ~81% recovery	- High adsorption efficiency (>85%). - Reversible process with recyclable adsorbents.	- High energy requirement for CO_2 desorption. - Specific adsorbents required at high temperatures.	[93]
Chemical looping	6	Not specified in source	Not reported	>90	- Bypasses energy-intensive air separation. - Separates CO_2 from combustion gases.	- Still under development. - Limited large-scale operational experience.	[85]
Direct capture	7	Not specified in source	Not reported	79–91	- Suitable for localized CO_2 capture. - Can be deployed in various locations, including non-arable land. - Significant in climate change mitigation.	- Expensive implementation. - High energy demand. - Technical complexities.	[94] [88]
Cryogenic separation	9	Not specified in source	Not reported	90–99	- Effective at high CO_2 concentrations. - No need for compressors. - Minimal hydrocarbon losses. - High selectivity. - Established technology for natural gas processing.	- Risk of CO_2 freezing. - Energy-intensive refrigeration is required.	[15] [95]

Table X. Carbon Capture Efficiencies & Separation Techniques

Note: Data are compiled from multiple studies with different operating conditions, scales, and system boundaries. Therefore, the reported TRL, capture efficiency, energy, and cost values should be interpreted as indicative rather than directly comparable. Where contextual information was not available in the cited source, it is explicitly marked as "Not specified in source".

5. Conclusion. - The paper provides a comprehensive and insightful overview of the latest advancements in carbon capture and separation technologies, pivotal in the global effort to combat climate change. This review examines the four principal types of carbon capture methods: pre-combustion capture, post-combustion capture, chemical looping, and direct air capture, highlighting their respective efficiencies, technological readiness levels, and the challenges they

face. By evaluating these methods, the literature underscores the critical role each technology plays in reducing CO_2 emissions and the specific hurdles that must be overcome to enhance their viability and efficiency.

The review summarizes current findings and accomplishments, establishing the groundwork for a larger conversation about lowering carbon dioxide emissions. It emphasizes the importance of continued research and innovation in overcoming present technological hurdles and increasing the efficiency and scalability of these solutions. The findings presented in this paper illustrate the potential of existing technology while underlining the importance of future discoveries. These activities are critical to attaining long-term sustainability and tackling the pressing global challenge of climate change.

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Author contribution:
1. Conception and design of the study
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3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
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