Pathways to Carbon Neutrality: A Review of CO_2 Reduction Strategies

Nure Jannat Zubly

Department of Mechanical Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

Email: jannatzubly@gmail.com

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Abstract

The global climate crisis, driven largely by the escalating levels of carbon dioxide (CO_2) emissions, has prompted an urgent need for effective mitigation strategies. CO_2, the predominant greenhouse gas, is primarily released through fossil fuel combustion, industrial processes, and deforestation. Its continuous accumulation in the atmosphere has led to severe climate disruptions, including rising global temperatures, extreme weather events, and ocean acidification. In response, the scientific community and policymakers worldwide have turned their focus toward the development of comprehensive CO_2 reduction technologies. However, despite considerable progress, the challenge remains to identify, optimize, and implement these methods on a global scale. This review paper provides a holistic analysis of the current CO_2 reduction technologies, assessing their mechanisms, efficiencies, and scalability. The paper aims to categorize and evaluate a broad spectrum of techniques, including CO_2 capture, storage, and utilization. By integrating both well-established and emerging technologies, this review presents a complete picture of the existing landscape of CO_2 mitigation efforts. The results of this review indicate that while CO_2 capture and storage technologies offer immediate potential to curb emissions, their high costs and energy demands pose significant challenges to widespread adoption. On the other hand, utilization methods, particularly the conversion of CO_2 into fuels and chemicals, demonstrate promising economic prospects but are still limited by technological barriers. Ultimately, this paper highlights the need for a multifaceted approach that combines technological innovation, policy support, and international collaboration to achieve long-term carbon neutrality. The review concludes with recommendations for future research, targeting the scalability, cost reduction, and integration of CO_2 reduction technologies into existing energy and industrial systems.

Keywords: CO_2 mitigation, global warming, carbon capture, carbon storage, carbon utilization.

1. Introduction

Carbon dioxide (CO_2) emissions have emerged as one of the leading contributors to global warming, with concentrations in the atmosphere continuing to rise at alarming rates. The world has witnessed a significant increase in CO_2 emissions from anthropogenic sources, particularly from fossil fuel combustion, deforestation, and industrial activities (Friedlingstein et al., [1]). According to the Global Carbon Project (2019), global CO_2 emissions from fossil fuels surpassed 40 billion tons annually, driving the increase in atmospheric CO_2 levels. This increase has directly contributed to the intensification of climate change, as CO_2 is a major greenhouse gas responsible for trapping heat in the Earth's atmosphere. Without effective strategies for reducing CO_2 emissions, the trajectory of global temperature rise will continue unchecked, with catastrophic consequences for ecosystems, human health, and infrastructure (Le Quéré et al., [2]).

The CO_2 reduction crisis represents an urgent challenge that requires global collaboration and technological advancements to mitigate the effects of climate change. While several strategies have been proposed, achieving substantial reductions in CO_2 emissions remains difficult, largely due to the continued reliance on fossil fuels in many industries. In response, a wide range of CO_2 reduction technologies, including carbon capture and storage (CCS), renewable energy integration, and direct air capture (DAC), are being explored to address this crisis. These technologies aim to capture CO_2 at the source, prevent its release into the atmosphere, or remove it directly from the air (Rogelj et al., [3]). However, the scale of deployment required to stabilize atmospheric CO_2 levels demands innovative solutions and significant investment, while also addressing concerns related to cost, efficiency, and environmental safety. The rapid adoption of these technologies is essential for achieving climate targets set by international frameworks like the Paris Agreement, which aims to limit global temperature rise to well below 2°C by the end of the century (IPCC- 2018, [4]).

CO_2 reduction technologies have the potential to mitigate the impacts of climate change and provide substantial environmental and economic benefits. By capturing and reusing CO_2, these technologies not only reduce the concentration of greenhouse gases in the atmosphere but also enable the production of valuable byproducts such as biofuels, chemicals, and synthetic fuels. Recent advancements in CO_2 capture and utilization (CCU) technologies have shown promise in various industries, from power generation to transportation, making significant strides toward decarbonizing these sectors (Bui et al., [5]). Additionally, renewable energy systems, when combined with CO_2 reduction methods, can further reduce the dependence on fossil fuels, accelerating the transition to a carbon-neutral economy. As research and development in this field continue, it is expected that these technologies will play a crucial role in preventing global warming from exceeding the critical threshold of 1.5°C, thus safeguarding the planet for future generations (Gasser et al., [6]).

Despite extensive research on CO_2 reduction technologies, few studies have explored the integration of methods like carbon capture and storage (CCS) and CO_2 utilization to achieve carbon neutrality. Existing research often focuses on isolated approaches, overlooking the efficiency, cost-effectiveness, and scalability of combining these technologies. Additionally, there is limited analysis of implementation challenges and alignment with global climate targets. This work evaluates the collective impact of CO2 reduction strategies by assessing their technological advancements, economic feasibility, and scalability. It examines CCS and CO_2 utilization for creating value-added products. By addressing efficiency, cost, and environmental safety, the study identifies gaps and proposes pathways for rapid adoption. This forward-looking analysis contributes to the global pursuit of a sustainable, carbon-neutral future.

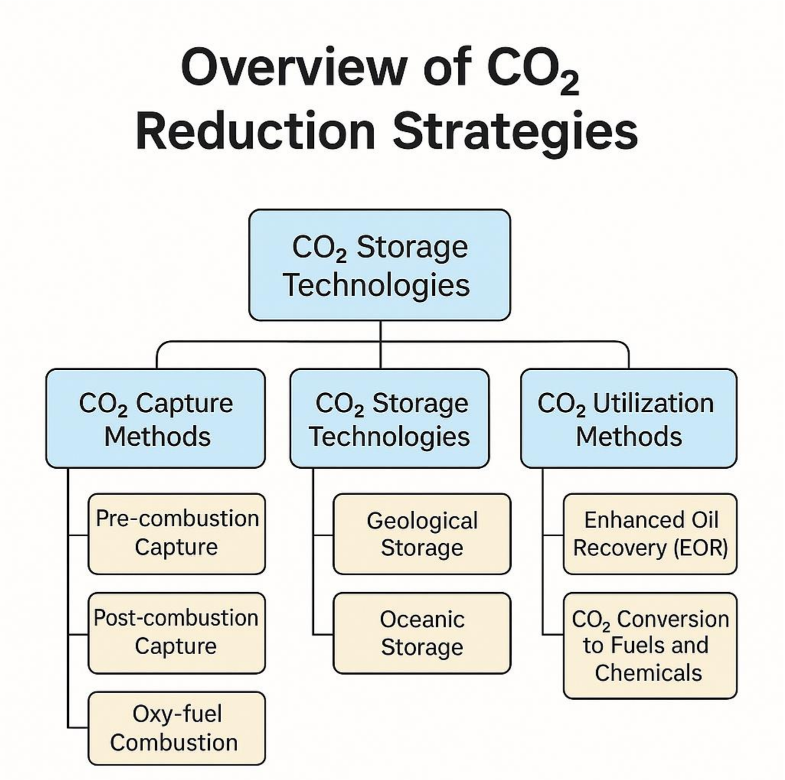

Fig 1. Overview of CO2 Reduction Technologies: Mechanisms, Efficiency, and Scalability.

2. Capture Technologies

CO_2 capture is the process of trapping carbon dioxide emissions from industrial activities or power generation before they can enter the atmosphere. This can be achieved through methods such as pre-combustion, post-combustion, or oxy-fuel combustion. The captured CO_2 is then compressed for transport to a storage site or reused in various industrial processes. The goal of CO_2 capture is to significantly reduce the amount of greenhouse gases released, playing a key role in efforts to combat climate change.

2.1 Pre-combustion Carbon Capture

In the study by Hyun Ju Lee et al. [7], carbon capture during the pre-combustion process involves forming gas hydrates from a CO_2/H_2 gas mixture. The mixture, which typically contains around 40% CO_2 and 60% H_2, mimics the composition of synthesis gas from IGCC power plants. The addition of tetrahydrofuran (THF) to the mixture significantly enhances the hydrate formation process by lowering the pressure and temperature conditions required. The gas hydrate formation was carried out in a high-pressure reactor, where CO_2 and H_2 gases were supplied continuously while the temperature was maintained constant. As the gases were consumed to form hydrates, the composition of the gas phase was monitored using gas chromatography. The experiments showed that the addition of 1.0 mol% THF provided the most favorable conditions for efficient CO_2 capture, allowing for separation without significant gas compression. The method proves effective for separating CO_2 from the gas mixture, with potential applications in industrial-scale carbon capture processes. Again, in the study by Xiao-Sen Li et al. [8], carbon dioxide capture in the pre-combustion process is achieved through hydrate formation using a combination of tetra-n-butyl ammonium bromide (TBAB) and cyclopentane (CP). A CO_2/H_2 gas mixture is injected into a high-pressure reactor containing the TBAB solution. The TBAB helps create a hydrate structure that traps CO_2

molecules while releasing hydrogen. The addition of CP further enhances CO_2 separation by increasing gas uptake and speeding up the hydrate nucleation process. Under optimal conditions of 274.65 K and 4.0 MPa, the gas uptake was doubled, and the CO_2 concentration in the decomposed hydrate gas phase reached approximately 93 mol%. This method effectively captures CO_2 by stabilizing it within hydrate crystals, which can then be separated from the hydrogen. In the study by Padurean et al. [9], pre-combustion CO_2 capture is integrated into an Integrated Gasification Combined Cycle (IGCC) power plant using gas–liquid absorption with different solvents. The Selexol® process, a physical solvent method, is highlighted as the most energy-efficient for CO_2 capture. It works by absorbing CO_2 and H_2S from syngas, followed by regenerating the solvent through pressure reduction rather than heating. The CO_2 is captured by lowering the pressure of the solvent-rich CO_2, which is then dried, compressed, and prepared for storage. Simulation results show that for the 425–450 MW IGCC power plant, implementing Selexol® with 70% CO_2 capture increases capital costs by 19.55%, while 90% capture increases costs by 22.55%. Selexol® is more energy-efficient compared to other solvents due to lower regeneration energy requirements.

In the paper by Mantripragada and Rubin [10], two CO_2 capture technologies—chemical looping combustion (CLC) and calcium looping (CaL)—are compared for their application in coal-based IGCC power plants. The CLC process captures CO_2 by using a solid oxygen carrier (NiO) to combust syngas, producing streams of CO_2 and water, from which the water is condensed, leaving high-purity CO_2 for sequestration. In contrast, the CaL process captures CO_2 by reacting it with CaO to form CaCO3, which is later decomposed to release CO_2. The study concludes that both systems are more efficient than conventional solvent-based methods, with CLC offering higher efficiency and lower costs than CaL, due to the significant heat required for CaL's calcination step. In the study by Oreggioni et al. [11], a techno-economic evaluation of carbon capture processes was conducted for a 10 MWth biomass combined heat and power (CHP) plant utilizing a Fast Internally Circulating Fluidized Bed (FICFB) gasifier. The researchers focused on comparing a two-stage, two-bed Pressure Vacuum Swing Adsorption (PVSA) system with a conventional amine process for CO_2 capture from syngas. The PVSA process effectively increased the CO_2 mole fraction from around 31.9% to over 95% while achieving approximately 90% CO_2 recovery. The authors found that the specific energy consumption for the adsorption process was about half that of the amine process, making it more economical for small-to-medium scale applications. The study concludes that adsorptive carbon capture is a promising alternative due to its lower capital costs and efficiency in capturing CO_2 in biomass-fueled systems, where achieving over 90% carbon capture is not necessary due to the carbon-neutral nature of biomass.

In the study by Nannan Sun et al. [12], a novel method for enhancing carbon dioxide (CO_2) capture from activated carbon beads was developed through surface modification techniques. Initially, activated carbon beads were produced from phenolic resins via a hydrothermal process. The beads underwent nitric acid (HNO3) oxidation followed by amination at various elevated temperatures (300, 600, and 800 °C). Characterization of these modified samples revealed that their porosity and surface chemistry were significantly improved, enhancing their adsorption performance. CO_2 capture primarily occurred through a combination of physisorption and chemisorption, with the latter facilitated by the introduction of amine groups during the surface modification process. The capture was evaluated using both thermogravimetric analysis and high-pressure volumetric analysis, showing that the highest CO_2 adsorption capacity reached approximately 8.64 mmol g^{-1} at 20 bar and 30 °C for the oxAC-800NH3 sample. The results indicated that low-temperature amination effectively increased CO_2 uptake at low pressures, while high-temperature treatment enhanced adsorption at high pressures. Thus, the modified spherical carbon beads exhibit significant potential for pre-combustion CO_2 capture, particularly in pressure swing adsorption systems. In their study, Zhai and Rubin [13] developed a comprehensive modeling framework to evaluate the use of ionic liquids (ILs), specifically 1-hexyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide, for pre-combustion carbon capture in integrated gasification combined cycle (IGCC) power plants. The process involves using the IL as a physical solvent to absorb CO_2 from syngas, relying on phase equilibrium and mass balance models to simulate the absorption and stripping processes. The capture primarily occurs through physical absorption mechanisms, where CO_2 dissolves in the IL, facilitated by its unique properties. Results indicate that the estimated cost of CO_2 avoided by this IL-based system is around $63 per tonne, showing comparable performance and cost effectiveness to traditional Selexol-based systems. The study highlights the need for enhancements in CO_2 solubility and novel compression technologies to improve the viability of ILs for large-scale carbon capture applications.

In the study by Azpiri Solares et al.[14], Carbon dioxide (CO_2) is captured using a pressure swing adsorption (PSA) process involving amine-modified activated carbons. The process begins with a mixture of nitrogen and CO_2 being fed into a fixed-bed reactor containing the modified adsorbents, such as the novel blend of monoethanolamine-monodiethanolamine (MEA-MDEA). As the gas mixture passes through the adsorbent bed at elevated pressures (25 bar), the CO_2 selectively adsorbs onto the activated carbon due to its enhanced adsorption capacity from the chemical modification, while the nitrogen remains in the gas phase. The breakthrough curve, which plots the concentration of CO_2 in the outlet over time, indicates the time until saturation, revealing a delayed break-point of approximately 200 seconds for the MEA-MDEA modified carbon compared to unmodified carbons. The PSA process then proceeds through a cycle of pressurization, adsorption, and depressurization steps, which allows for the efficient separation and purification of CO_2. Ultimately, this method results in a highly purified CO_2 product stream, with the study reporting purity levels over 90% under optimized conditions. In the carbon capture procedure outlined by Zhou et al. [15], the process begins with the introduction of flue gas containing CO_2 into an absorption column where it interacts with ionic liquids (ILs). The CO_2 molecules are selectively absorbed into the IL phase, while hydrogen (H_2) remains in the gas phase due to the non-volatility of the ILs. The absorption of CO_2 into the ionic liquid is driven by the favorable thermodynamic interactions, enhancing solubility. The captured CO_2 can then be separated from the IL through a desorption process, typically involving temperature or pressure changes, allowing for the recovery of the IL for reuse in subsequent cycles. This method effectively reduces CO_2 emissions, demonstrating the potential of ILs as a promising alternative to conventional solvents in pre-combustion carbon capture systems.

2.2 Post-combustion Capture

In the study by Bounaceur et al. [16], a systematic analysis of membrane processes for post-combustion carbon dioxide (CO_2) capture is conducted, focusing on the energy efficiency and separation performance of a single-stage membrane module. The process involves introducing a CO_2/N2 mixture into the membrane system, where CO_2 selectively permeates through the membrane, resulting in a CO_2-enriched permeate stream while nitrogen remains in the retentate. The research identifies key operational parameters, such as membrane selectivity, pressure ratios, and stage cuts, and highlights the relationship between CO_2 recovery ratio and permeate composition. The findings indicate that while current membranes can achieve significant energy savings, reducing energy costs to approximately 0.5–1 GJ/tonne CO_2 recovered, their effectiveness diminishes when the CO_2 concentration in the flue gas is below 20%. Consequently, the study underscores the need for advanced membrane materials to enhance selectivity and efficiency in carbon capture applications. The CO_2 removal process described by Merkel et al. [17] involves using a membrane-based system with a two-step vacuum and counter-flow design. Initially, flue gas containing CO_2 is passed through the first membrane, where a vacuum pump helps separate CO_2 from the other gases. The CO_2-enriched gas is then compressed and cooled, which removes water and increases CO_2 concentration. The gas undergoes further compression to produce supercritical CO_2 ready for sequestration. In the second step, a portion of the flue gas is passed through another membrane with air used as a sweep gas, enhancing the removal of CO_2 by creating a stronger driving force for separation. The remaining gases are vented or recycled, while the captured CO_2 is prepared for transport and storage.

In the study by Notz et al. [18], a shortcut method is presented for post-combustion CO_2 capture using an absorption-desorption process. The process involves passing flue gas through an absorber column, where CO_2 is absorbed into a liquid solvent, such as monoethanolamine (MEA). The absorbed CO_2-rich solvent is then sent to a desorber, where heat regenerates the solvent and releases the CO_2 gas. A modified Kremser equation, incorporating discretized equilibrium isotherms, is used to estimate the number of equilibrium stages in the absorber and desorber, as well as to predict the minimum reboiler energy required for solvent regeneration. The CO_2 is captured through cyclic absorption and desorption processes, where different solvent properties influence the energy efficiency. The results showed that solvent CASTOR2 had a lower energy requirement compared to MEA, indicating its higher efficiency for CO_2 capture. The CO_2 removal process described by Padurean et al. [19] involves the use of aqueous solutions of alkanolamines, such as MEA, DEA, MDEA, and AMP, to chemically absorb CO_2 from flue gases. In this post-combustion carbon capture method, the flue gas is passed through an absorber column where the alkanolamine solution reacts with CO_2 to form a carbamate or bicarbonate compound. Once the CO_2 is captured by the solvent, the rich solution is then sent to a stripper or regeneration column, where heat is applied to reverse the chemical reaction, releasing pure CO_2. The regenerated solvent is cooled and recycled back to the absorber for further CO_2 removal, while the captured CO_2 is compressed and stored or utilized. This cyclical process allows for continuous capture and separation of CO_2 from the flue gas stream. The removal of carbon dioxide (CO_2) using the solvents SOLVENT1 (2-Amino-2-methyl-1-propanol), SOLVENT2 (Diethanolamine), SOLVENT3 (N-Methyl-2-pyrrolidone), and SOLVENT4 (Methyldiethanolamine) involves a chemical absorption process, as discussed by Ghorbani et al. [20]. When flue gas containing CO_2 comes into contact with the amine-based solvents, the CO_2 molecules chemically react with the amine groups in the solvents, forming stable carbamate compounds. This reaction allows the solvents to effectively capture and hold CO_2 from the gas stream. Once the solvents become saturated with CO_2, they are heated in a regeneration process, where the heat breaks the carbamate bonds, releasing CO_2 for storage or utilization while regenerating the solvents for reuse. The efficiency of CO_2 removal varies among the solvents, with each exhibiting different reaction kinetics and thermal regeneration characteristics that impact overall capture performance.

In the study by Moussaa et al. [21], the process of CO_2 capture was examined through the adsorption capabilities of activated carbons derived from olive stones, specifically those activated with KOH and K2CO3. The authors demonstrated that under post-combustion conditions (10% CO_2 at atmospheric pressure and 50°C), both types of activated carbon exhibited rapid adsorption and desorption kinetics, highlighting the significance of ultramicropores ($L0 \leq 0.5$ nm) for effective CO_2 removal. The activated carbon AC_KOH showcased a notable CO_2 capture capacity of 5.6 mmol g^-1 at 1 bar, while AC_K2CO3 displayed an exceptional uptake of about 1.67 wt% at 50°C. This emphasizes the necessity of tailoring pore structures in carbon materials to enhance CO_2 adsorption efficiency. The study concludes that optimizing the porosity of adsorbents is crucial for improving their performance in carbon dioxide capture applications. In the study, Zhao et al. [22] explored the process of post-combustion carbon dioxide (CO_2) capture using piperazine-activated blended absorbents, including methyldiethanolamine (MDEA), potassium carbonate (K2CO3), and aqueous ammonia (NH3·H_2O). The CO_2 capture process involves the absorption of CO_2 from exhaust flue gas in an absorber unit, followed by the regeneration of the absorbent in a stripper unit. Key factors such as absorbent concentration, CO_2 loading, and temperatures of the lean and rich liquids were optimized to achieve an 85% CO_2 capture efficiency. The study highlights the trade-offs between absorbent flow rates, reboiler heat duties, and cooling water consumption, recommending PZ-activated MDEA in their study.

The study by Ghorbani et al. [23] presents a novel hybrid system for simultaneously producing liquefied natural gas (LNG), capturing carbon dioxide (CO_2), and desalinating water using solar energy. This integrated approach consists of four main subsystems: an Organic Rankine Cycle (ORC) for power generation with parabolic trough collectors, a refrigeration cycle utilizing a mixture of ammonia and water to produce LNG and liquid CO_2, a CO_2 capture process using chemical absorption with amine-based solvents, and a multi-effect distillation (MED) desalination unit. The amine scrubbing process, which is central to the CO_2 capture mechanism, involves two key sections: absorption and desorption. In this continuous scrubbing system, flue gas enters the absorber where it is contacted with a CO_2-rich amine solvent, effectively removing CO_2 from the gas stream. The concentrated CO_2 is then stripped from the solvent in a stripper column, regenerated by steam provided from a reboiler, and subsequently compressed for storage or utilization. This hybrid system demonstrates impressive performance metrics, with a total exergy efficiency of 88.97%, capable of generating 14.5 tons/hour of LNG, 1.693 tons/hour of desalinated water, and 2.611 tons/hour of liquid CO_2. The economic analysis reveals a payback period of six years and a prime cost of 24.2 cents/kg for LNG, highlighting its potential for both environmental and economic benefits in addressing the rising global energy demand and associated CO_2 emissions.

2.3 Oxy-fuel Combustion

The CO_2 removal process in the Staged, Pressurized Oxy-Combustion (SPOC) power plant, as outlined by Gopan et al. [24], involves a series of integrated steps designed to enhance efficiency and maximize carbon capture. Initially, coal is combusted in a staged manner using nearly pure oxygen, which facilitates better temperature control and minimizes flue gas recycling needs. The combustion gases pass through a series of heat exchangers where heat is recovered and utilized for steam regeneration. After combustion, the flue gas undergoes cooling and moisture condensation in a Direct Contact Cooler (DCC), where pollutants such as SOx and NOx are also removed through chemical reactions. The cleaned flue gas is then compressed to 35 bar, with a small fraction recycled to transport coal. Finally, the CO_2 is purified using cryogenic distillation to meet specifications for enhanced oil recovery (EOR). In the paper by Gładysz and ZięBik [25], the authors analyze CO_2 capture processes within an integrated oxy-fuel combustion (OFC) power plant that incorporates biomass co-firing and dedicated biomass boilers. The CO_2 capture is achieved through oxy-fuel combustion, where oxygen is used instead of air, resulting in a flue gas that is primarily composed of CO_2 and water vapor. This gas can be easily condensed to remove water, leaving a high concentration of CO_2 that can be subsequently captured. The chemical reaction involved in the combustion of biomass can be represented as:

$$CxHy+O_2 \rightarrow CO_2+H_2O+\text{energy}$$

Here, the biomass (composed of carbon and hydrogen) reacts with oxygen to produce CO_2 and water. The integration of carbon capture and storage (CCS) technology allows for a significant reduction in cumulative CO_2 emissions, making the overall process more sustainable, particularly when biomass is included, as it can lead to “negative” CO_2 emissions by offsetting emissions from other sectors. In the study by Serrano et al. [26], CO_2 is removed primarily through the use of oxy-fuel combustion, which involves burning fuel with pure oxygen instead of air. This process generates a flue gas that is primarily composed of CO_2 and water vapor, making it easier to capture CO_2 for storage or utilization. The exhaust gases are cooled, causing the water vapor to condense and separate, leaving almost pure CO_2, which can then be compressed and stored in carbon capture and storage (CCS) systems. Additionally, the use of exhaust gas recirculation (EGR) in the combustion process further dilutes the oxidizer and manages the thermal conditions, enhancing the overall efficiency of CO_2 capture.

3. CO_2 Storage Technologies

CO_2 storage involves capturing carbon dioxide emissions and safely storing them to prevent their release into the atmosphere. The captured CO_2 is compressed and stored in secure locations where it can remain for long periods without leaking. The process ensures that the carbon does not contribute to atmospheric greenhouse gas levels, helping mitigate climate change. Effective storage methods focus on keeping the CO_2 stable and isolated, ensuring it doesn't interact with the environment or escape back into the air. This method is crucial for balancing carbon emissions and supporting sustainability efforts.

3.1 Geological Storage

Geological storage of CO_2 is a process where carbon dioxide is injected into deep underground formations like depleted oil fields, saline aquifers, or coal beds that cannot be mined. The CO_2 is securely trapped beneath layers of impermeable rock, preventing it from leaking into the atmosphere. This method provides a stable and long-term solution for managing carbon emissions. Gunter et al. [27] explored the potential of aquifer disposal as a long-term solution for CO_2 storage by injecting CO_2 into deep sedimentary basins. Their research indicated that water-rock reactions could mineralize CO_2, trapping it as solid carbonates like siderite and calcite over hundreds of years. Experiments conducted at high temperatures and pressures demonstrated slow reaction kinetics, but geochemical models predicted that significant CO_2 trapping would occur over geological timescales. This method of CO_2 storage offers a promising solution to reduce greenhouse gas emissions, although challenges such as long reaction times and potential impacts on aquifer permeability must be considered. Baines et al. [28] discuss several methods for CO_2 storage, highlighting geological storage as a key solution. CO_2 can be injected into subsurface formations like saline aquifers, depleted oil and gas fields, and unmineable coal seams. Saline aquifers offer significant storage capacity, while depleted hydrocarbon reservoirs benefit from extensive geological data and existing infrastructure. Enhanced oil recovery (EOR) also utilizes CO_2, boosting oil production while storing CO_2. These storage methods ensure that CO_2 remains trapped, either as a supercritical fluid, dissolved in formation waters, or through mineralization, which offers long-term sequestration. However, the safety, economic viability, and environmental implications need careful consideration, especially to ensure secure storage and public acceptance of this technology.

Izgec et al. [29] explore CO_2 storage in saline carbonate aquifer formations through laboratory experiments, focusing on the changes in permeability and porosity during CO_2 injection. CO_2 is stored primarily through mineral trapping, where the gas reacts with carbonate minerals, leading to calcite deposition and preferential flow paths like wormholes in the rock matrix. The study indicates that CO_2 can be stored efficiently, though its injectivity and rock-fluid interactions vary with conditions like salinity, flow orientation, and temperature. These variations affect the efficiency of CO_2 storage and the long-term stability of the storage sites. Implications include the potential for CO_2 sequestration in carbonate formations, though changes in rock properties may pose challenges to predictability and sustainability of storage systems. Vishal et al. [30] conducted a numerical simulation to investigate CO_2 storage in coal seams through CO_2-enhanced coal-bed methane (ECBM) recovery. CO_2 is injected into coal seams, where it adsorbs onto the coal matrix, replacing methane (CH4) that is then desorbed and produced. This adsorption process primarily occurs in micropores, and coals with higher sorption times demonstrate a greater capacity for CO_2 storage due to their ability to absorb more gas over time. Implications of this method include its potential for both enhanced methane production and long-term greenhouse gas sequestration in deep, unmineable coal seams. This approach offers dual benefits: reducing atmospheric CO_2 and improving energy production from coal reservoirs. Buscheck et al. [31] describe a CO_2 storage system that utilizes a tandem reservoir approach to manage geologic CO_2 storage efficiently. CO_2 is injected into a high-seal CO_2-storage reservoir after a pre-injection phase where brine is extracted to reduce pressure buildup, increasing storage capacity and minimizing risks such as induced seismicity and caprock fracture. Brine is then reinjected into an adjacent brine-storage reservoir or used for beneficial purposes like water generation. This method helps ensure safe long-term CO_2 sequestration by reducing reservoir pressure and overpressure-related hazards, while also optimizing reservoir management. The approach also supports integration with renewable energy systems through cyclic brine production, enhancing the sustainability of CO_2 storage operations.

Hannis et al. [32] discuss CO_2 storage in depleted or depleting oil and gas fields, emphasizing the use of existing infrastructure and the management of wellbore integrity risks. CO_2 is injected into these fields, where it occupies the pore spaces previously filled by hydrocarbons, allowing for effective storage. The process involves monitoring reservoir pressure and ensuring that the caprock remains intact to prevent leakage. Implications of this storage method include the potential for quick climate abatement returns, cost savings from utilizing existing facilities, and the enhancement of hydrocarbon recovery through CO_2-enhanced oil recovery (EOR). This approach offers a viable solution to address short-term CO_2 storage needs while larger saline aquifer projects are developed. Fawad and Mondol [33] outline the process of CO_2 storage as follows: Carbon dioxide is injected into subsurface geological formations, such as depleted oil and gas reservoirs, deep saline aquifers, or coal beds, where it is stored in its supercritical phase. The injection occurs at depths between 1 and 3 km, ensuring that the CO_2 remains in a stable state under pressure and temperature conditions conducive to effective containment. Monitoring techniques, including seismic and controlled-source electromagnetic surveys, are employed to track the migration of the CO_2 plume and to verify that it remains contained within the storage site. This monitoring is critical for ensuring safety and compliance throughout the storage period. In the study by Song et al. [34], CO_2 is stored in geological formations through a series of water-rock-gas reactions that result in mineral transformations. The process begins with the injection of CO_2, which triggers the dissolution of feldspar. This dissolution provides conditions favorable for the precipitation of solid carbonate minerals. As CO_2 interacts with the formation water, feldspar primarily dissolves to form montmorillonite and quartz. Under high-temperature and high-pressure conditions, montmorillonite undergoes hydrolysis, transforming into illite, while chlorite dissolution leads to the precipitation of ankerite. The resulting secondary clay minerals and carbonate precipitates adhere to mineral surfaces, potentially causing pore blockage. The rate of montmorillonite transformation to illite correlates positively with the abundance of K-feldspar, which releases metal cations that promote carbonate mineral precipitation. Consequently, this mineralization process contributes to the stable storage of CO_2 as carbonate minerals within the geological formation, enhancing its long-term storage potential.

3.2 Ocean Storage

Ocean CO_2 storage is a process where carbon dioxide is injected into the deep ocean, where the intense pressure and cold temperatures cause it to dissolve and form stable layers or hydrate compounds. This method capitalizes on the ocean's natural ability to retain CO_2, offering potential for long-term containment without atmospheric release. Aya et al. [35] investigate a method for CO_2 storage in deep ocean basins by dissolving CO_2 in seawater, where it forms a stable, stratified layer due to high pressure and low temperature. The CO_2, injected into a cubic beaker under 30 MPa pressure, gradually dissolves in seawater and forms clathrate hydrates, which help trap the CO_2. The stratified layer remains stable if the current velocity at the ocean floor is below 0.66 m/s, ensuring minimal CO_2 dissolution into the ambient flow. This method offers potential for long-term CO_2 storage, but further studies are required to understand the impact of heat from dissolution and hydrate formation on the layer's stability. Thomas et al. [36] describe an enhanced CO_2 storage system in coastal and marginal seas, specifically the North Sea, where atmospheric carbon dioxide is absorbed and stored in subsurface waters through the continental shelf pump. The system works by separating production and respiration processes, leading to the accumulation of dissolved inorganic carbon (DIC) in deeper layers, which are then exported to the North Atlantic Ocean. This CO_2 storage method contributes to the global carbon cycle by reducing atmospheric carbon levels. The implication of this process is a significant enhancement in open ocean CO_2 storage, accounting for around 20% of the global ocean's uptake of anthropogenic CO_2, underscoring the importance of coastal seas in mitigating climate change.

House et al. [37] propose a method for permanent CO_2 storage in deep-sea sediments at depths greater than 3,000 meters, where CO_2 can be injected in liquid form beneath several hundred meters of sediment. At these depths, the high pressure and low temperature conditions make CO_2 denser than the surrounding pore fluids, ensuring gravitational stability and preventing its upward migration. Additionally, CO_2 hydrate formation acts as a secondary cap, further inhibiting CO_2 flow. The process involves injecting CO_2 into calcareous sediments, where dissolution with the host rock slightly increases porosity and enhances permeability. The injected CO_2 transitions through phases, eventually dissolving into the surrounding pore fluids, with buoyancy-driven advection accelerating its mixing and stabilizing it over time. This system provides a potentially massive storage capacity along the U.S. coastline, capable of storing thousands of years' worth of current CO_2 emissions. Adams and Caldeira [38] outline several methods for CO_2 storage in the ocean to mitigate climate change, primarily involving the capture of CO_2 from power plants and its injection into the deep ocean. Various injection techniques have been proposed, including introducing CO_2 as a buoyant liquid to form rising plumes, creating lakes on the seafloor, and dissolving CO_2 directly into seawater. The ocean's immense capacity suggests that injected CO_2 could remain sequestered for several hundred years. However, the viability of these methods depends on further field experiments to assess their environmental impact and effectiveness.

4. CO_2 Utilization Methods

Carbon dioxide (CO_2) utilization methods represent transformative pathways for addressing climate change by converting waste emissions into valuable products. Advanced approaches include electrochemical reduction, where CO_2 is converted into fuels and chemicals using renewable electricity, and mineral carbonation, which sequesters CO_2 into stable mineral forms, such as carbonates. Emerging innovations like biological assimilation leverage photosynthetic organisms or engineered microbes to produce biofuels and bioplastics. Thermochemical processes, such as dry reforming and photocatalysis, enable the synthesis of syngas and methanol, offering a dual benefit of CO_2 reduction and energy generation. Novel methods like supercritical CO_2 extraction are gaining traction for their efficiency in producing high-value compounds while simultaneously sequestering carbon. Additionally, integration with circular economy frameworks, such as closed-loop systems for polymers and fuels, transforms CO_2 from a pollutant into a resource, driving sustainability. Cutting-edge research focuses on hybrid methods, like electro-biocatalysis, that combine the strengths of multiple technologies for enhanced efficiency and scalability.

4.1 Enhanced Oil Recovery (EOR)

The reviewed paper by Jia et al. [39] examines the recent progress, challenges, and advancements in gas injection techniques for enhanced oil recovery (EOR) in shale reservoirs, focusing on injection schemes, reservoir characteristics, numerical simulations, oil recovery mechanisms, laboratory experiments, and pilot tests. Cyclic gas injection (huff-n-puff) is preferred in ultra-low permeability reservoirs due to injectivity limitations, while continuous flooding is more effective in reservoirs with higher permeability. Advanced simulation techniques, such as the EDFM method and molecular modeling, have enhanced fracture characterization and understanding of phase behavior in nanopores, although more work is needed to address confinement effects and adsorption phenomena. Recovery mechanisms differ based on the gas type, with CO_2 promoting oil swelling and dissolution, while N2 utilizes capillary pressure gradients for oil extraction. Diffusion plays a critical role in low-permeability reservoirs, necessitating improved measurement methods and models for accuracy. Laboratory studies show promise but require better realism, such as including natural fractures and optimizing soaking periods, to ensure field-scale applicability and economic feasibility. The paper emphasizes the importance of integrating reservoir characterization, gas selection, and operational strategies to maximize oil recovery in shale reservoirs.

4.2 CO_2 Conversion to Fuels and Chemicals

CO_2 conversion to fuels and chemicals, particularly methanol and synthetic fuels, offers a promising pathway to reduce greenhouse gas emissions while producing valuable, carbon-neutral energy. Methanol, one of the most prominent products derived from CO_2, is synthesized through hydrogenation, where CO_2 reacts with hydrogen in the presence of a catalyst. Recent advancements in catalyst development, particularly those based on copper (Cu), have improved the efficiency and stability of methanol production. Ren et al. [40] discuss various catalysts, including those integrated with renewable hydrogen, which are crucial in developing sustainable methanol synthesis processes. By utilizing captured CO_2 and renewable energy, this process could play a significant role in achieving carbon neutrality in the chemical industry.

Regarding CO_2 reduction processes, Xu et al. [41] showed that various methods have been developed to transform CO_2 into valuable fuels and chemicals. The process generally involves breaking the strong C=O bonds in CO_2, which requires significant energy input. This can be achieved through different strategies, such as thermal catalysis, where high temperatures facilitate the reaction, or through electrochemical methods, which use electricity to reduce CO_2. Photocatalysis, which harnesses light to activate CO_2, has also gained attention due to its potential for renewable energy integration. In addition, biocatalytic approaches inspired by photosynthesis offer more sustainable and efficient conversion, combining light-driven reactions with enzymatic assistance to selectively reduce CO_2. These efforts aim to recycle carbon emissions into useful products, contributing to both environmental protection and energy production.

Together, these technologies present a viable strategy for utilizing CO_2 emissions as a resource, turning a waste product into a valuable commodity while helping to mitigate the impacts of climate change. Both methanol and synthetic fuel production from CO_2 show great promise, though further research is needed to optimize processes and address economic and technological barriers for large-scale adoption.

5. Comparative Analysis of CO_2 Reduction and Storage Techniques

A comparative analysis of various CO_2 reduction and storage techniques reveals that each method offers distinct advantages and limitations. Pre-combustion and oxy-fuel combustion technologies demonstrate high capture efficiency and CO_2 purity, respectively, though they require complex system integration and incur high operational costs. Post-combustion capture, particularly using amine-based adsorbents, remains attractive for retrofitting existing plants, albeit with significant energy penalties. Geological storage in depleted fields stands out as a proven and stable solution, despite requiring extensive monitoring to mitigate leakage risks. Emerging oceanic storage methods, such as clathrate hydrate formation and ocean alkalinity enhancement, present promising large-scale potential but face environmental and stability concerns that must be carefully managed. Meanwhile, advancements in material science, such as amine-functionalized mesoporous adsorbents, have improved capture selectivity, although long-term performance and cost remain challenges. Additionally, natural geochemical processes like clay mineral transformation offer enhanced sealing capacity for storage sites, contributing positively to long-term CO_2 containment. Thus, the selection of an appropriate strategy necessitates a careful balance between technical feasibility, economic cost, and environmental sustainability.

Table 1. Summary of different CO2 reduction techniques and their implications.

Method	**Main Advantage**	**Key Limitation**	**Economic Feasibility**	**Stability / Long-Term Security**	**Example Studies**
Pre-combustion Capture	High capture efficiency	Complex integration with existing plants	Moderate	High	General combustion studies
Post-combustion Capture	Retrofit existing plants	Energy-intensive regeneration	Moderate to low	Medium	Studies on amine-based adsorbents
Oxy-fuel Combustion	High CO_2 purity	High oxygen production cost	Low to moderate	High	Combustion optimization research
Geological Storage (Depleted Fields)	Proven technology	Risk of leakage, long-term monitoring	High initially, lowers over time	High	General studies on geological CO_2 storage.
Oceanic Storage (Clathrate Hydrates)	Natural trapping mechanism	Environmental and stability concerns	Low	Medium to High (with heterogeneity)	Studies on oceanic CO_2 storage techniques
Ocean Alkalinity Enhancement	Large-scale potential	Unknown ecological impacts	Low to moderate	High (if controlled)	General research on ocean alkalinity
Amine-functionalized Adsorbents	High selectivity	Deactivation over time, cost	Moderate	Medium	Studies on amine-based CO_2 capture
Clay Mineral Transformation	Enhances sealing properties	Complex geochemistry	N/A (natural process)	High (over long periods)	General research on clay mineral transformation in CO_2 storage

6. Conclusion

In this review, a wide spectrum of CO_2 emission reduction strategies has been analyzed, showcasing the technological advancements and potential pathways toward carbon neutrality. From innovative capture techniques to advanced utilization and storage methods, the field has made significant progress in mitigating the impact of anthropogenic CO_2 emissions. Each method carries unique benefits and challenges, requiring a tailored approach depending on regional, economic, and environmental considerations. By exploring technologies like pre-combustion and post-combustion capture, geological and oceanic storage, and CO_2 utilization methods, this paper provides a comprehensive perspective on the multifaceted efforts needed to address climate change effectively. Integrating these strategies with global policies and energy systems will be critical to achieving sustainability. Below are the main conclusions derived from the study:

- Pre-combustion, post-combustion, and oxy-fuel combustion capture methods are effective yet require optimization for scalability.
- Geological storage in depleted reservoirs and saline aquifers is promising but demands stringent monitoring for safety.
- Ocean storage offers large potential but necessitates further research into environmental impacts and stability.
- CO_2 utilization methods, like enhanced oil recovery and methanol synthesis, demonstrate value creation but face cost barriers.
- Policy frameworks and economic incentives are essential for large-scale adoption and sustainability.

The path to achieving carbon neutrality lies in combining robust technological innovation with strategic policy frameworks. This review highlights that while significant advancements have been made, further interdisciplinary research is necessary to address the economic and technical challenges inherent in these methods. Collaboration between academia, industry, and governments will be essential to accelerate deployment and ensure equitable access to these technologies. The integration of CO_2 capture, storage, and utilization within a circular economy framework presents an opportunity to transition from a carbon-intensive system to a sustainable, low-carbon future.

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