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Carbon Capture, Utilization, and Storage (CCUS) Hybrid CO_2 Sequestration and Enhanced Oil Recovery: A Sustainable Approach Assessment of CO_2 injection strategies that maximize hydrocarbon recovery while ensuring long-term geological storage stability.

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ABSTRACT: Carbon Capture, Utilization, and Storage (CCUS) technologies are pivotal in mitigating climate change by reducing CO_2 emissions from industrial sources. Among the most promising CCUS approaches is the integration of CO_2 sequestration with Enhanced Oil Recovery (EOR), which not only aids in reducing atmospheric CO_2 but also enhances hydrocarbon recovery from mature oil reservoirs. This evaluates hybrid CO_2 sequestration and EOR strategies, focusing on the optimization of CO_2 injection methods that maximize oil recovery while ensuring the long-term geological stability of the stored CO_2. CO_2 injection into oil reservoirs enhances oil recovery through mechanisms such as miscible displacement, oil viscosity reduction, and swelling effects. The study examines various CO_2 injection strategies, including continuous, cyclic, and water-alternating-gas (WAG) injection, and their effectiveness in improving oil recovery efficiency. Additionally, advanced methods like foam-assisted CO_2 injection are explored for their potential in increasing sweep efficiency and reducing CO_2 mobility, thus enhancing both hydrocarbon recovery and storage security. Ensuring the long-term stability of stored CO_2 is critical to the success of CCUS projects. The study assesses the factors influencing CO_2 retention, including capillary trapping, mineralization, and solubility trapping, and highlights the role of advanced monitoring techniques, such as 4D seismic imaging and pressure monitoring, to detect potential leakage and ensure the integrity of storage sites. This emphasizes the environmental and economic benefits of hybrid CCUS-EOR systems, which offer a dual advantage of climate change mitigation and extended hydrocarbon production. The review concludes with an analysis of the challenges and future directions for large-scale deployment, including technological advancements, cost barriers, and regulatory considerations, ultimately advocating for policy support and investment in CCUS technologies for sustainable energy production.

KEYWORDS: Carbon capture utilization storage (CCUS), Enhanced oil recovery (EOR), CO_2 Injection, Hydrocarbon recovery, Geological storage stability, Sequestration strategies, Climate change mitigation.

1 INTRODUCTION

As the global community faces the growing threat of climate change, effective strategies to mitigate greenhouse gas (GHG) emissions have become increasingly critical (Egbumokei *et al.*, 2024). Among the diverse range of technologies aimed at reducing atmospheric carbon concentrations, Carbon Capture, Utilization, and Storage (CCUS) has emerged as a key solution. CCUS encompasses a suite of techniques designed to capture carbon dioxide (CO_2) from industrial processes or directly from the atmosphere, with the goal of either repurposing it for beneficial uses or storing it safely underground (Onukwulu *et al.*, 2024). The integration of CCUS into climate policies is widely recognized as a pivotal measure to achieve net-zero emissions and limit global warming.

One of the primary functions of CCUS is CO_2 sequestration, which involves the capture and storage of CO_2 in deep geological formations such as saline aquifers, depleted oil and gas fields, and unmineable coal seams (Onukwulu *et al.*, 2024; Egbumokei *et al.*, 2024). By sequestering CO_2 in stable, underground reservoirs, it is prevented from entering the atmosphere, where it contributes to the greenhouse effect. CO_2 sequestration plays a vital role in reducing the atmospheric concentration of this potent greenhouse gas, which is a major driver of global warming. As part of a broader climate strategy, the successful implementation of

CO_2 sequestration can significantly reduce the cumulative carbon emissions associated with industrial processes, energy production, and fossil fuel use (Egbumokei *et al*., 2024).

In parallel with its environmental benefits, the use of CO_2 for Enhanced oil recovery (EOR) provides a unique synergy within the CCUS framework (Johnson *et al*., 2024). EOR refers to the injection of CO_2 into depleted oil reservoirs to improve oil extraction rates. This process not only extends the life of existing oil fields but also allows for the safe and effective storage of CO_2 underground. The dual benefits of EOR economic enhancement of oil production and environmental mitigation of CO_2 emissions present a compelling case for the integration of CO_2 storage into commercial oil operations. By injecting CO_2 into these reservoirs, oil companies can simultaneously boost production and contribute to climate goals, fostering both economic and environmental sustainability (Onukwulu *et al*., 2021).

The objective of this review is to explore the optimization of CO_2 injection strategies for dual benefits enhancing oil recovery while ensuring the safe, long-term sequestration of CO_2. As CO_2 injection into geological formations can have significant implications for both oil production and carbon storage, it is essential to evaluate and improve injection techniques to maximize efficiency and reduce risks. Furthermore, assessing the long-term geological stability of stored CO_2 is crucial to prevent leakage and ensure that CO_2 remains securely contained for centuries or longer. This review will critically examine current methods, challenges, and emerging trends in the optimization of CO_2 injection, with a focus on balancing the economic and environmental benefits of this technology.

2.0 METHODOLOGY

The PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was employed to systematically assess the various CO_2 injection strategies used in the context of hybrid CO_2 sequestration and Enhanced Oil Recovery (EOR). The objective was to evaluate approaches that maximize hydrocarbon recovery while ensuring long-term geological storage stability. A comprehensive literature search was conducted across multiple databases, including Web of Science, Scopus, and Google Scholar, using a combination of keywords such as "CCUS," "CO_2 sequestration," "enhanced oil recovery," "CO_2 injection strategies," and "geological storage stability." Studies published from the year 2000 to the present were considered for inclusion.

The inclusion criteria focused on peer-reviewed articles that addressed the optimization of CO_2 injection strategies in EOR operations, with a particular emphasis on those that incorporated a dual approach of CO_2 sequestration and enhanced hydrocarbon recovery. Both laboratory-based and field studies were included to provide a broad understanding of the applicability and real-world implementation of CO_2 injection technologies. Studies examining the long-term stability of CO_2 storage, specifically regarding leakage risks and geological integrity, were also prioritized. Exclusion criteria involved articles that did not focus on the technical, environmental, or economic aspects of CO_2 injection or those that did not meet the established quality standards for inclusion.

A data extraction process was developed to collect key information from each selected study, including the type of CO_2 injection method, the geological formations used for storage, the amount of CO_2 injected, the techniques employed for EOR, and the impact of these strategies on hydrocarbon recovery rates and CO_2 containment. Additionally, the stability and monitoring techniques used to assess the long-term safety of CO_2 storage were noted, along with any reported risks related to geological leakage or seismic activity. Quality assessment was carried out using standardized appraisal tools to assess the methodological rigor of each study, considering factors such as sample size, study design, and the robustness of results.

The synthesis of findings was carried out through a thematic analysis, with a focus on identifying common themes and differences across studies regarding the effectiveness of various CO_2 injection strategies. The results were categorized into key areas: optimization of injection parameters for enhanced oil recovery, approaches to ensure the long-term stability of CO_2 storage, and the integration of hybrid sequestration-EOR systems. The review also highlighted technological innovations, such as the use of monitoring systems and modeling techniques, that enhance the safety and efficiency of CO_2 injection processes.

This methodology provides a structured approach to understanding the complex interplay between CO_2 sequestration, enhanced oil recovery, and long-term geological stability. The findings contribute valuable insights into the optimization of CO_2 injection strategies, highlighting their potential to support both hydrocarbon recovery and climate change mitigation goals.

2.1 Fundamentals of CO_2 Sequestration and Enhanced Oil Recovery (EOR)

The integration of Carbon Capture, Utilization, and Storage (CCUS) technologies into Enhanced oil recovery (EOR) practices has become a promising solution for both addressing climate change through CO_2 sequestration and improving hydrocarbon recovery from depleted oil reservoirs (Egbumokei *et al*., 2021; Digitemie and Ekemezie, 2024). EOR with CO_2 involves the injection of CO_2 into oil reservoirs to enhance the extraction of oil while simultaneously sequestering CO_2 underground to prevent its release into the atmosphere. This process is of particular importance as it supports the dual goals of reducing greenhouse gas emissions and maximizing resource extraction (Iriogbe *et al*., 2024).

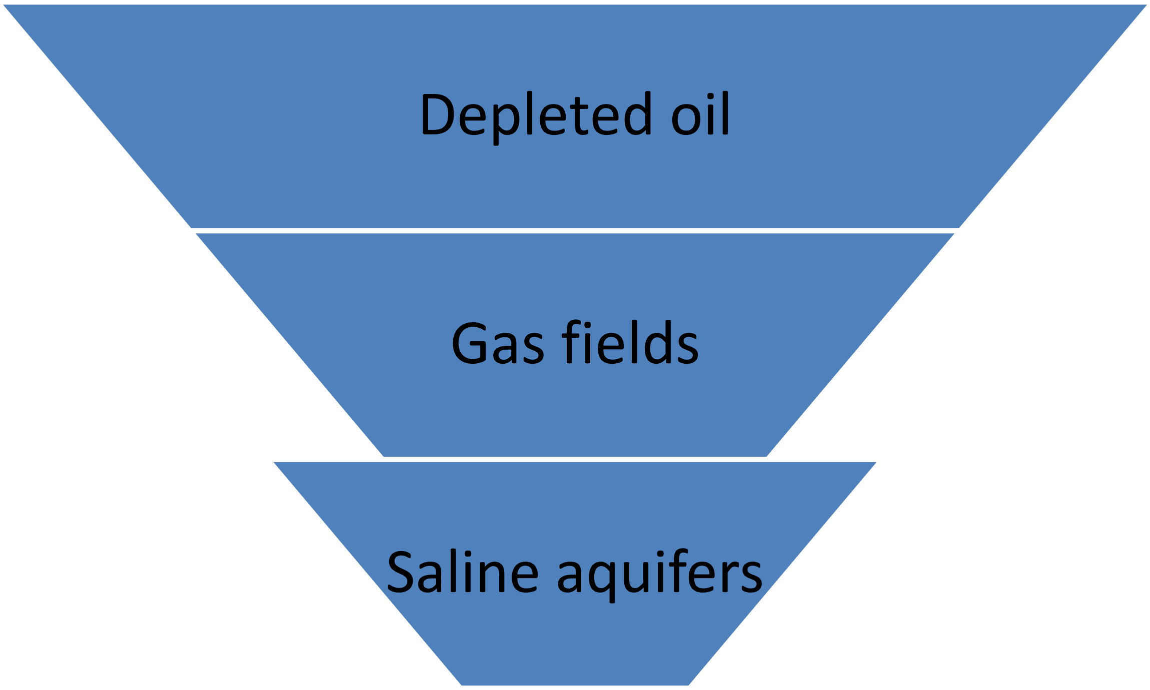

Figure 1: Reservoir types for CO_2 sequestration

The mechanisms of CO_2-EOR are critical to understanding how CO_2 can effectively improve oil recovery rates. The process can be broadly categorized into miscible and immiscible displacement mechanisms. In miscible CO_2-EOR, the injected CO_2 dissolves into the oil, forming a single-phase mixture that reduces the oil's viscosity and increases its mobility. This allows for more efficient displacement of oil from the reservoir. In contrast, immiscible CO_2-EOR occurs when the injected CO_2 does not mix with the oil but instead displaces it through pressure and density differences (Uchendu *et al*., 2024). While miscible displacement tends to offer higher recovery efficiencies, immiscible CO_2 injection can still improve oil recovery under certain conditions.

CO_2 injection also induces significant physical and chemical changes in the oil that further contribute to enhanced recovery (Onukwulu *et al*., 2022). One of the key effects is the reduction of oil viscosity, which improves its flow characteristics and allows for easier extraction. CO_2 can also cause oil swelling, which increases the overall volume of the oil and, in turn, enhances its recovery from the reservoir. These effects are particularly valuable in the case of heavy and viscous oils, which are difficult to extract using traditional methods. By reducing the oil's viscosity and causing it to swell, CO_2 injection enables the extraction of oil that would otherwise remain trapped in the reservoir. Geological considerations play a crucial role in the success of CO_2 sequestration, as the injected CO_2 must remain securely stored in the underground formations for extended periods. Reservoir types such as sandstone, carbonate, and unconventional formations (e.g., shale) each present unique challenges and opportunities for CO_2 storage. Sandstone reservoirs, which are often highly porous and permeable, are particularly suited for CO_2 injection due to their ability to host large volumes of gas. Carbonate reservoirs, though less porous, can also serve as effective storage sites with the proper sealing mechanisms. Unconventional formations, such as shale, offer lower permeability but can be targeted with advanced injection techniques to achieve CO_2 sequestration and enhanced recovery.

Seal integrity and caprock behavior are also vital considerations when assessing the suitability of a reservoir for CO_2 storage (Onukwulu *et al*., 2023). The caprock, which is a layer of impermeable rock above the reservoir, acts as a seal to prevent the upward migration of CO_2. The effectiveness of this seal depends on the geological properties of the caprock, including its thickness, integrity, and the presence of fractures. Any weaknesses or fractures in the caprock can lead to CO_2 leakage, undermining the long-term effectiveness of CO_2 sequestration (Johnson *et al*., 2024). Therefore, thorough geological assessments are necessary to ensure the stability of the storage site.

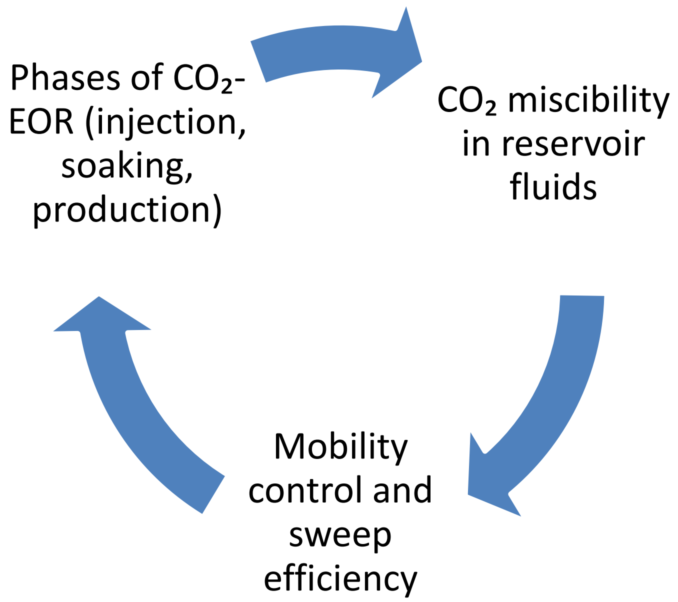

Figure 2: CO_2 enhanced oil recovery (CO_2-EOR) mechanisms

Hybrid CCUS-EOR approaches, which combine CO_2 sequestration with enhanced oil recovery, offer significant advantages over traditional methods. Traditional oil recovery methods often fail to extract oil from deeper or more challenging reservoirs, leaving a substantial amount of hydrocarbons behind. By incorporating CO_2 injection, these hybrid systems not only enhance oil recovery but also provide a mechanism for large-scale CO_2 sequestration. This dual-benefit approach helps reduce carbon emissions while improving the economic feasibility of oil extraction. Moreover, the ability to use CO_2 that would otherwise be emitted into the atmosphere further aligns the energy industry with sustainability goals. The synergy between CO_2 storage and oil recovery thus offers a more sustainable and economically viable solution compared to traditional extraction techniques, presenting an essential strategy in the transition toward cleaner energy systems. CO_2 sequestration combined with enhanced oil recovery offers significant potential for both climate mitigation and resource optimization (Digitemie and Ekemezie, 2024). By understanding the mechanisms of CO_2-EOR, geological considerations, and the benefits of hybrid approaches, the industry can harness the full potential of CO_2 injection technologies for sustainable oil production and environmental protection.

2.2 CO_2 Injection Strategies for Optimized EOR and Sequestration

The integration of Carbon Capture, Utilization, and Storage (CCUS) technologies with Enhanced oil recovery (EOR) presents an advanced method to optimize both hydrocarbon extraction and CO_2 sequestration (Anaba *et al.*, 2023). The effectiveness of CO_2 injection in these applications relies heavily on selecting the appropriate injection strategies, which are designed to maximize oil recovery, enhance the sweep efficiency of injected CO_2, and ensure the secure and long-term storage of CO_2 in geological formations. Different injection techniques have been developed to address the specific characteristics of oil reservoirs, improve recovery rates, and minimize the risks of CO_2 leakage, contributing to the successful implementation of hybrid CCUS-EOR systems.

One of the primary injection strategies used in CO_2-EOR is the continuous CO_2 injection technique. In this approach, CO_2 is injected into the reservoir at a constant rate over a prolonged period, maintaining reservoir pressure and promoting continuous oil displacement (Onukwulu *et al.*, 2021). Continuous injection is particularly effective in reservoirs where the CO_2 is miscible with the oil, enabling more efficient oil extraction. This method is advantageous in scenarios where there is a need to sustain pressure in the reservoir, ensuring steady CO_2 injection into the formation. However, while continuous injection is efficient in increasing oil recovery, it does not always achieve the most uniform sweep across the reservoir, potentially leaving pockets of oil behind.

In contrast, cyclic CO_2 injection—also known as "huff and puff" injection—alternates periods of injection with production cycles. During the injection phase, CO_2 is injected into the reservoir to increase pressure and displace oil, followed by a production phase where the extracted oil is brought to the surface. This alternating approach allows for the gradual accumulation of CO_2 in the reservoir, improving the efficiency of oil recovery, particularly in reservoirs with heterogeneous permeability. Cyclic injection can increase the contact between CO_2 and oil, allowing for improved oil recovery from lower-permeability zones that might be bypassed in continuous injection (Basiru *et al*., 2023). This technique also helps in optimizing the timing of CO_2 injection to match production dynamics, allowing for a more controlled and flexible EOR process.

Another important injection strategy is the water-alternating-gas (WAG) method, which combines the injection of water and CO_2 in alternating cycles. WAG injection helps to improve the overall sweep efficiency by using water to push the CO_2 deeper into the reservoir, preventing the CO_2 from bypassing oil pockets and enhancing the displacement of trapped oil. The water phase serves to reduce the mobility of CO_2, allowing it to better interact with the oil and improving the overall efficiency of the CO_2 injection. This technique has been shown to significantly reduce the gas-to-oil ratio and improve the ultimate oil recovery factor by providing a more uniform sweep across the reservoir (Eyo-Udo *et al*., 2024). The WAG method is particularly useful in reservoirs where CO_2 has high mobility or in cases where CO_2 injectivity is a limiting factor.

Foam-assisted CO_2 injection is an emerging strategy that aims to reduce the mobility of CO_2 in the reservoir, further enhancing both the oil recovery and CO_2 storage capacity. In foam-assisted injection, CO_2 is mixed with surfactants to create a foam, which reduces the mobility of the injected CO_2 and allows it to be more evenly distributed throughout the reservoir (Johnson *et al*., 2024). The foam acts as a mobility control agent, creating a viscous barrier that slows the movement of CO_2 and prevents the gas from flowing too quickly through the formation, ensuring that CO_2 can access more oil-rich regions. This strategy also improves the CO_2 retention time in the reservoir, which enhances the storage capacity of the geological formation. Foam-assisted CO_2 injection can be particularly effective in heterogeneous reservoirs, where CO_2 may otherwise be channelized through high-permeability zones, bypassing large areas of oil.

Reservoir simulation models are crucial tools for optimizing CO_2 injection strategies, as they allow for the modeling of reservoir behavior under different injection scenarios. These models simulate the complex interactions between injected CO_2, water, oil, and rock formations, providing valuable insights into the best injection rates, pressures, and injection cycles. Through advanced numerical simulations, engineers can predict the movement and distribution of CO_2 within the reservoir, enabling the optimization of injection parameters to maximize oil recovery and minimize CO_2 leakage. Reservoir simulation models also allow for the assessment of the long-term stability of CO_2 storage, evaluating the risks of CO_2 migration and potential leakage pathways, which is essential for ensuring the effectiveness of CO_2 sequestration. These models can incorporate data from reservoir monitoring, such as pressure, temperature, and saturation levels, to refine injection strategies in real-time (Farooq t al., 2024). This data-driven approach allows for adaptive strategies that can respond to the changing conditions of the reservoir, ensuring that injection operations are continuously optimized. Additionally, simulation models can be used to design and test hybrid injection strategies, such as combining continuous CO_2 injection with WAG or foam-assisted methods, providing a more tailored approach to reservoir conditions and ensuring both high recovery rates and long-term CO_2 storage stability. The optimization of CO_2 injection strategies is crucial for achieving both enhanced oil recovery and effective CO_2 sequestration. Techniques such as continuous injection, cyclic injection, WAG, and foam-assisted CO_2 injection each offer unique advantages depending on the reservoir conditions and recovery objectives (Onukwulu *et al*., 2021). By integrating these strategies with advanced reservoir simulation models, the oil and gas industry can improve recovery rates, maximize CO_2 storage, and minimize environmental risks, ultimately contributing to the development of more sustainable and efficient hybrid CCUS-EOR systems. These strategies represent a key component in the transition to cleaner energy production and the reduction of atmospheric CO_2 levels.

2.3 Storage Stability and Monitoring of Injected CO_2

The secure and long-term storage of injected CO_2 is a critical aspect of Carbon Capture, Utilization, and Storage (CCUS) technologies. Ensuring that CO_2 remains contained within geological formations without leakage is essential to achieving both effective CO_2 sequestration and environmental protection. A range of factors, including geological conditions and trapping mechanisms, play a role in ensuring the stability of CO_2 storage (Onita *et al*., 2023). Coupled with these factors are advanced monitoring techniques that provide real-time data to assess the integrity of storage sites and detect potential leaks, enhancing the confidence in CO_2 sequestration as a viable climate change mitigation strategy.

Key factors influencing the long-term retention of injected CO_2 include capillary trapping, mineralization, and solubility trapping. Capillary trapping occurs when CO_2 is injected into a reservoir and, due to the capillary pressure differences between CO_2 and the formation fluid, the CO_2 becomes immobilized in the pore spaces of the rock. This mechanism ensures that CO_2 cannot easily migrate, providing a stable long-term containment. Mineralization, another important trapping mechanism, involves the chemical reaction between CO_2 and the minerals present in the reservoir, forming stable carbonates (Digitemie and Ekemezie, 2024). This process is a form of permanent CO_2 storage, as the carbon is incorporated into the rock in an irreversible manner. The ability of a reservoir to undergo mineralization is strongly influenced by its geological composition, including the presence of reactive minerals like olivine and serpentine.

Solubility trapping is another critical mechanism in ensuring the safe storage of CO_2. In this process, CO_2 dissolves into the formation water in the reservoir, forming a CO_2-rich fluid. This trapping mechanism is important for long-term CO_2 retention, as the dissolved CO_2 is less likely to migrate compared to free-phase CO_2. The solubility of CO_2 is influenced by factors such as pressure, temperature, and the composition of the formation water, making the selection of suitable reservoirs for sequestration crucial to ensuring that CO_2 remains in solution and does not escape into the atmosphere. Together, capillary trapping, mineralization, and solubility trapping form a robust suite of mechanisms that work synergistically to ensure the stability and security of CO_2 storage over time. Despite these mechanisms, the risk of CO_2 leakage remains a concern. Leakage can occur if CO_2 migrates through fractures or faults in the caprock, or if the seal integrity is compromised. Therefore, assessing and mitigating leakage risks is a critical aspect of CO_2 sequestration projects. A comprehensive leakage risk assessment typically includes a detailed analysis of the geological formation's permeability, caprock integrity, and potential fault lines (Onukwulu *et al*., 2024). Reservoir models are employed to predict the behavior of injected CO_2 and identify potential leakage pathways. Furthermore, monitoring systems can provide real-time data to detect any signs of CO_2 movement outside the designated storage zone. Mitigation strategies may include sealing fractures, enhancing the integrity of the caprock, or employing alternative reservoir management techniques such as pressure control and CO_2 injection optimization.

Advanced monitoring techniques are essential for ensuring the safety and stability of CO_2 storage sites. One of the most widely used methods is 4D seismic imaging, which provides dynamic, high-resolution images of the subsurface over time. By monitoring changes in the seismic signatures of the reservoir, 4D seismic imaging allows for the tracking of injected CO_2, detecting any migration or leakage (Johnson *et al*., 2024). This technique offers valuable insights into the distribution of CO_2 within the reservoir, helping to assess the efficiency of injection strategies and the integrity of the storage site. Pressure and tracer monitoring are other critical techniques for tracking the movement and behavior of injected CO_2. Pressure monitoring involves measuring changes in the pressure of the reservoir over time, which can indicate the presence of CO_2 migration or leakage. If there is a significant drop in pressure, it may signal that CO_2 is escaping from the storage site. Tracer monitoring involves injecting non-reactive tracers along with CO_2 during the injection process. The movement of these tracers can be tracked using various detection methods, providing a detailed picture of how CO_2 is moving through the reservoir and whether it is staying within the designated storage zone. Together, pressure and tracer monitoring provide a comprehensive method for detecting potential issues related to CO_2 migration and ensuring the long-term stability of the storage site.

Satellite and remote sensing technologies are increasingly being utilized for large-scale monitoring of CO_2 storage sites. These technologies offer the advantage of being able to observe vast areas from a distance, providing an overview of surface-level changes that may indicate CO_2 leakage or other anomalies (Ekemezie and Digitemie, 2024). Satellite-based remote sensing techniques, such as ground deformation and gas detection, can identify subtle shifts in the landscape or atmospheric changes that may signal the presence of CO_2 escaping from the storage reservoir. These technologies can complement traditional subsurface monitoring techniques, providing a holistic approach to managing and monitoring CO_2 sequestration sites. Ensuring the long-term stability of CO_2 storage is crucial for the success of CCUS technologies in mitigating climate change. Mechanisms such as capillary trapping, mineralization, and solubility trapping provide robust methods for securing CO_2 in geological formations (Egbumokei *et al*., 2024). However, the risk of leakage necessitates comprehensive risk assessments and the implementation of effective mitigation strategies. Advanced monitoring techniques, including 4D seismic imaging, pressure and tracer monitoring, and satellite-based remote sensing, offer essential tools for detecting and addressing potential issues related to CO_2 storage (Onukwulu *et al*., 2022). These monitoring systems not only enhance the confidence in CO_2 sequestration but also play a critical role in ensuring that CCUS remains a safe and effective solution for reducing atmospheric CO_2 levels.

2.4 Environmental and Economic Implications of Hybrid CCUS-EOR

The integration of Carbon Capture, Utilization, and Storage (CCUS) with Enhanced oil recovery (EOR) has the potential to significantly reduce greenhouse gas emissions, mitigate climate change, and contribute to sustainable economic development. Hybrid CCUS-EOR systems not only enhance oil recovery but also provide a means to sequester CO_2 in geological formations, reducing the environmental impact of industrial activities (Basiru *et al*., 2022). This dual-purpose approach has broad environmental and economic implications, including carbon footprint reduction, climate change mitigation, the economic viability of CO_2-EOR projects, and the role of government policies in incentivizing CCUS technologies.

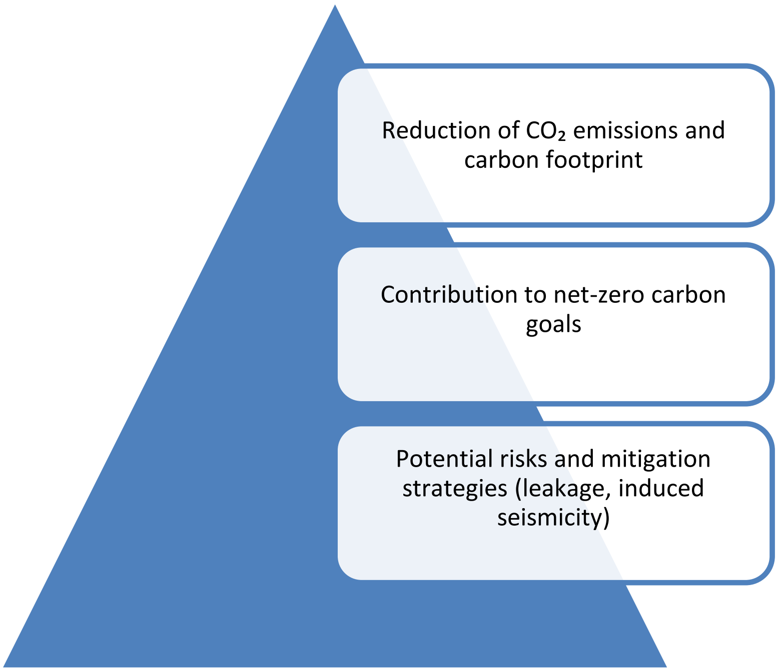

Figure 3: Environmental benefits of hybrid CO_2 sequestration and EOR

One of the primary environmental benefits of hybrid CCUS-EOR is the reduction of the carbon footprint (Digitemie and Ekemezie, 2024). By capturing CO_2 emissions from industrial sources such as power plants, refineries, and natural gas processing facilities, and injecting it into oil reservoirs for EOR, these systems can prevent significant amounts of CO_2 from being released into the atmosphere. The captured CO_2 is injected into geological formations where it can be permanently stored, significantly reducing net emissions and contributing to climate change mitigation efforts (Fredson *et al*., 2022). This process helps offset the environmental impact of fossil fuel extraction by minimizing the greenhouse gases associated with both oil production and power generation, making CCUS-EOR an essential tool in achieving global climate goals, such as those set by the Paris Agreement.

The climate change mitigation potential of hybrid CCUS-EOR is further amplified when considering the long-term stability of CO_2 storage. Geological formations such as depleted oil and gas fields, deep saline aquifers, and unminable coal seams offer secure and permanent storage sites for CO_2. The sequestration of CO_2 in these formations can continue for decades or even centuries, preventing its release back into the atmosphere. As such, hybrid CCUS-EOR systems represent a dual benefit: they help increase oil recovery while simultaneously serving as a means for safe, long-term CO_2 storage, making them an important component of a broader portfolio of solutions for combating climate change (Basiru *et al*., 2023). From an economic perspective, the viability of CO_2-EOR projects is influenced by several factors, including the cost of CO_2 capture, transportation, and injection, as well as the market price of oil (Ekemezie and Digitemie, 2024). While the upfront investment in CO_2 capture technologies and the infrastructure required for transportation and injection can be significant, the revenue generated from enhanced oil recovery can offset these costs. The injection of CO_2 into oil reservoirs boosts oil production by reducing the viscosity of the oil, improving sweep efficiency, and increasing reservoir pressure, which in turn enhances the profitability of existing oil fields. Therefore, hybrid CCUS-EOR projects can offer a win-win scenario: they provide an economic incentive for oil producers to implement CCUS technologies while contributing to global emissions reduction.

In addition to the revenue from increased oil recovery, government policies and incentives play a crucial role in enhancing the economic viability of hybrid CCUS-EOR projects. Policies such as carbon credit systems and tax credits for CO_2 sequestration can provide additional financial incentives for companies to invest in these technologies. For instance, the U.S. 45Q tax credit offers financial incentives for both CO_2 capture and storage, which can significantly reduce the costs associated with CO_2-EOR projects (Onukwulu *et al*., 2023). These types of government incentives are vital for encouraging the adoption of CCUS technologies, especially given the high initial costs and the long payback periods often associated with large-scale CO_2 injection projects. By providing subsidies or credits for the captured CO_2, governments can stimulate the development of hybrid CCUS-EOR projects, making them more economically competitive with traditional oil extraction methods.

Several successful case studies of hybrid CCUS-EOR projects around the world demonstrate the feasibility and benefits of this approach (Weldegeorgis *et al*., 2024; Johnson *et al*., 2024). One such example is the Weyburn-Midale project in Canada, one of the largest and most successful CCUS-EOR projects globally. This project has been operational since 2000 and has injected millions of tons of CO_2 into a depleted oil reservoir in Saskatchewan. The injected CO_2 has not only enhanced oil recovery by increasing production but has also resulted in the permanent sequestration of CO_2, preventing its release into the atmosphere (Basiru *et al*., 2023). The project has proven to be economically viable, with the additional oil production offsetting the cost of CO_2 capture and injection, while also contributing to carbon footprint reduction.

Another notable example is the Sleipner CO_2 storage project in the North Sea, which has been operational since 1996. This project involves the injection of CO_2 into a saline aquifer beneath the seabed, with the aim of reducing the emissions from natural gas production. The project has successfully sequestered over 20 million tons of CO_2 to date, showcasing the potential of geological storage to mitigate climate change. While the Sleipner project does not involve enhanced oil recovery, it provides valuable insights into the effectiveness and feasibility of long-term CO_2 storage and highlights the potential of hybrid CCUS-EOR systems to achieve similar outcomes. The environmental and economic implications of hybrid CCUS-EOR systems are profound. These technologies not only contribute to reducing the carbon footprint and mitigating climate change but also offer an economically viable method for boosting oil recovery while ensuring secure CO_2 storage (Johnson *et al*., 2024). The success of existing projects, coupled with supportive government policies and carbon credit incentives, has demonstrated the potential for hybrid CCUS-EOR to be a key component of a sustainable energy future. By continuing to invest in and scale up these technologies, it is possible to achieve both environmental and economic benefits, helping to address the dual challenges of reducing emissions and meeting global energy demands.

2.5 Challenges and Future Directions

The integration of Carbon Capture, Utilization, and Storage (CCUS) with Enhanced Oil Recovery (EOR) presents significant potential for mitigating climate change by reducing CO_2 emissions while enhancing oil production (Basiru *et al*., 2023). However, several challenges remain that must be addressed to optimize and scale these technologies effectively. These challenges include technical and geological considerations for CO_2 storage integrity, infrastructure and cost barriers to large-scale deployment, the role of artificial intelligence (AI) and machine learning in optimizing CO_2 injection and monitoring, and the integration of direct air capture (DAC) with CO_2-EOR systems.

One of the foremost challenges in CO_2-EOR and storage is ensuring the long-term integrity of CO_2 storage sites. CO_2 must remain securely trapped in geological formations to prevent leakage back into the atmosphere. This requires careful selection of suitable storage sites, such as depleted oil and gas fields or deep saline aquifers, and ensuring that these formations exhibit favorable characteristics, such as high porosity, permeability, and a stable caprock that can effectively seal the injected CO_2. However, even in optimal conditions, uncertainties exist regarding the behavior of CO_2 in underground reservoirs, particularly concerning potential leakage pathways through fractures or faults in the caprock (Onukwulu *et al*., 2021). Additionally, CO_2 may interact with the surrounding rock and fluids over time, leading to chemical reactions that could impact storage stability. Addressing these technical and geological challenges requires continuous monitoring, advanced modeling, and research into the long-term behavior of CO_2 in subsurface environments.

Infrastructure and cost remain significant barriers to the large-scale deployment of CCUS-EOR projects (Onukwulu *et al*., 2021). The initial capital investment required for CO_2 capture, transportation, and injection infrastructure can be substantial, particularly in regions with limited pre-existing infrastructure. The transportation of captured CO_2 from industrial sites to injection wells often requires the construction of pipelines or other forms of infrastructure, which can be costly and face regulatory and public acceptance challenges. In addition, the economic viability of these projects depends on the price of CO_2 emissions reductions, oil market conditions, and the cost-effectiveness of the CO_2-EOR process itself (Johnson *et al*., 2024). Despite the potential revenue from enhanced oil recovery, upfront costs, coupled with uncertainties regarding long-term storage security and regulatory frameworks, pose a significant challenge to the widespread adoption of hybrid CCUS-EOR systems.

Artificial intelligence (AI) and machine learning (ML) technologies offer promising solutions for optimizing CO_2 injection and monitoring, addressing both technical and cost challenges (Fredson *et al*., 2021). AI and ML algorithms can be used to analyze large datasets collected from CO_2 injection sites, including seismic data, pressure and temperature measurements, and geochemical data, to predict CO_2 behavior and optimize injection strategies. These technologies can enhance real-time decision-making by identifying patterns and anomalies in the data, enabling more efficient and effective management of CO_2 injection processes. AI models can also assist in reservoir simulation and forecasting, helping to optimize CO_2 sweep efficiency and reduce the risk of storage failure. By leveraging AI and ML, operators can improve the performance and safety of CCUS-EOR systems, potentially reducing costs and increasing the feasibility of large-scale deployment (Daramola *et al*., 2023).

Another promising development is the potential integration of Direct Air Capture (DAC) technologies with CO_2-EOR. DAC involves capturing CO_2 directly from the ambient air, rather than from industrial point sources, offering a scalable solution to reduce atmospheric CO_2 concentrations (Onita *et al*., 2023; Farooq *et al*., 2024). The integration of DAC with CO_2-EOR could provide a means of offsetting emissions from hard-to-decarbonize sectors, such as aviation and heavy industry. By capturing CO_2 from the air and injecting it into oil reservoirs, DAC could provide a dual benefit: reducing atmospheric CO_2 levels and increasing oil recovery (Onukwulu *et al*., 2022). However, challenges remain in optimizing the cost-effectiveness of DAC technologies and ensuring that the captured CO_2 can be efficiently utilized for EOR. Integrating DAC into existing CCUS-EOR systems would require advancements in both technologies to make the process economically viable and scalable. While the hybrid approach of CCUS-EOR presents a promising avenue for addressing climate change and enhancing oil recovery, several challenges must be overcome. Technical issues related to CO_2 storage integrity, infrastructure and cost barriers, and the optimization of CO_2 injection strategies remain key hurdles. However, the potential role of AI and ML in optimizing these processes, along with the integration of DAC technologies, offers promising directions for future advancements. As research and technological development continue to progress, overcoming these challenges will be critical in realizing the full potential of hybrid CCUS-EOR systems and their role in sustainable energy solutions (Ekemezie and Digitemie, 2024; Johnson *et al*., 2024).

CONCLUSION

Hybrid Carbon Capture, Utilization, and Storage (CCUS) strategies, particularly when integrated with Enhanced Oil Recovery (EOR), present significant advancements in mitigating climate change while optimizing oil production. Key findings indicate that CO_2-EOR not only boosts oil recovery by reducing viscosity and improving sweep efficiency but also serves as a viable means for long-term CO_2 sequestration. The development of optimized CO_2 injection techniques, such as water-alternating-gas (WAG) injection and foam-assisted CO_2 injection, has demonstrated enhanced storage capacity and reduced mobility, improving both recovery and storage stability. Furthermore, successful case studies, such as Weyburn-Midale and Sleipner, showcase the potential of hybrid CCUS-EOR projects in real-world applications, emphasizing the dual environmental and economic benefits.

Looking ahead, the future of sustainable CCUS implementation in oil and gas operations lies in overcoming several challenges, including storage integrity, infrastructure, and cost-related barriers. Advancements in monitoring techniques, such as 4D seismic imaging and AI-driven optimization, offer promising solutions for efficient CO_2 injection and long-term storage management. The integration of Direct Air Capture (DAC) with CO_2-EOR could further enhance the scalability of CCUS, helping address global emissions more comprehensively.

To ensure the successful adoption of hybrid CCUS-EOR systems, several policy, research, and industry actions are necessary. Governments should provide financial incentives, such as carbon credit systems and tax credits, to make CCUS technologies more economically viable. Research must continue to focus on improving the efficiency of CO_2 capture and storage technologies while addressing technical uncertainties in long-term storage stability. Industry adoption will require collaboration across sectors, with investment in infrastructure and the development of cost-effective solutions for large-scale deployment. Through continued innovation, supportive policies, and cross-sector collaboration, hybrid CCUS-EOR can play a critical role in advancing sustainable energy solutions and mitigating climate change.

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