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Development of Scalable CO2 Conversion Systems Enhancing Oil Recovery while Reducing Atmospheric Carbon Emissions Nationwide

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Abstract: The increasing concentration of atmospheric carbon dioxide (CO_2) presents a critical challenge to global climate stability, prompting the need for innovative solutions that address emissions while supporting energy demands. This study explores the development of scalable CO_2 conversion systems, emphasizing their application in enhancing oil recovery (EOR) and contributing to national carbon management strategies. It examines the fundamental principles of CO_2 capture and utilization, the integration of CO_2-EOR technologies within Nigeria's oil sector, and the relevance of renewable energy in powering these systems. The analysis highlights Nigeria's emissions profile, existing policy frameworks, and the strategic opportunity to align CO_2 conversion with sustainable oil production. Key technological advancements, economic considerations, and environmental impacts are discussed, with attention to cost-benefit analysis and risk mitigation. The paper also underscores the importance of stakeholder collaboration, regulatory support, and future research directions necessary for nationwide scalability. Ultimately, this work demonstrates that CO_2 conversion for EOR offers a viable path to reduce net carbon emissions while improving oil recovery, positioning it as a dual-benefit strategy for climate action and energy development in carbon-intensive economies like Nigeria.

Keywords: *CO_2 Conversion, Enhanced Oil Recovery (EOR), Carbon Emissions Reduction, Renewable Energy Integration and Climate Change Mitigation.*

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I. INTRODUCTION

➢ *Overview of CO_2 Emissions and Climate Change*

Carbon dioxide (CO_2) emissions are the primary driver of anthropogenic climate change, accounting for over 75% of global greenhouse gas emissions. These emissions result primarily from fossil fuel combustion for energy, industrial processes, and deforestation (IPCC, 2021). The increasing concentration of atmospheric CO_2 has led to significant global warming, ocean acidification, and disruption of weather patterns. The Intergovernmental Panel on Climate Change (IPCC) warns that without drastic reductions in CO_2 emissions, the planet is on track to exceed the 1.5°C warming threshold, with devastating environmental and socio-economic consequences (IPCC, 2021).

As of 2023, global CO_2 emissions have reached record highs, exceeding 36.8 billion metric tons, driven by industrialized nations and emerging economies (IEA, 2023). In oil-producing countries like Nigeria, CO_2 emissions are exacerbated by gas flaring, petroleum refining, and energy inefficiencies (Ogbodo et al., 2022). These activities not only threaten environmental sustainability but also hinder national efforts to meet global climate targets.

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Addressing CO_2 emissions requires scalable solutions that combine environmental and economic benefits. Converting CO_2 into useful products and injecting it into depleted oil fields for enhanced oil recovery (EOR) presents a promising dual-purpose strategy to reduce atmospheric carbon while boosting energy production (Liu et al., 2020).

➢ *Relevance of CO_2 Conversion to Oil Recovery*

The conversion of CO_2 for use in enhanced oil recovery (EOR) presents a strategic solution that addresses both climate and energy challenges. In CO_2-EOR, captured carbon dioxide is injected into mature oil reservoirs to increase pressure and reduce the viscosity of crude oil, thereby improving extraction efficiency (Alvarado & Manrique, 2010). This method not only boosts oil production from declining fields but also provides a pathway for long-term CO_2 storage, effectively reducing net emissions (Godec et al., 2013).

By integrating CO_2 conversion technologies such as transforming captured CO_2 into usable fuels or chemicals alongside EOR operations, the economic value of carbon is enhanced while atmospheric accumulation is mitigated. Countries with substantial oil reserves, like Nigeria, stand to benefit from this synergy by extending the lifespan of oil fields and complying with emission reduction commitments (Ajayi & Ajayi, 2021).

Moreover, the reuse of CO_2 in oil fields reduces the need for fresh CO_2 sources, creating a circular carbon economy that is both sustainable and economically viable (Han et al., 2019).

➢ *Purpose and Scope of the Study*

The purpose of this study is to explore the development of scalable CO_2 conversion systems that can be effectively integrated into enhanced oil recovery (EOR) operations across the country. It aims to examine how converting captured carbon dioxide into a usable form for injection into oil fields can simultaneously improve oil extraction and contribute to reducing atmospheric CO_2 levels. The study focuses on identifying practical technologies, evaluating their environmental and economic benefits, and assessing the feasibility of nationwide deployment. By addressing both energy production and carbon mitigation, the research intends to provide a comprehensive framework for implementing CO_2-EOR strategies that align with national climate goals and energy security priorities.

➢ *Structure of the Paper*

This paper begins by establishing the background and relevance of CO_2 emissions and their connection to climate change, followed by a discussion on the role of CO_2 conversion in enhancing oil recovery and the overarching objectives of the study. It then presents a review of existing literature on CO_2 capture, utilization technologies, and their integration into oil production systems. The national context is explored through an analysis of Nigeria's oil sector, emissions profile, and policy environment, highlighting opportunities for CO_2-EOR deployment. The technological component covers recent advancements, smart infrastructure integration, and the role of renewable energy in supporting CO_2 conversion systems. The environmental and economic implications are evaluated, focusing on emission reductions, cost-effectiveness, and risk management strategies. Lastly, the paper outlines policy frameworks, stakeholder involvement, and long-term research prospects necessary to support the large-scale implementation of CO_2 conversion systems for sustainable development.

II. LITERATURE REVIEW

Previous studies have emphasized the potential of CO_2 utilization technologies in mitigating climate change while enhancing oil recovery. CO_2-EOR has been shown to significantly increase oil production from mature fields and serve as a viable carbon sequestration method (Godec et al., 2013). Recent advancements in CO_2 conversion systems highlight their scalability and integration with energy infrastructures, offering economic and environmental benefits (Liu et al., 2020).

➢ *CO_2 Capture and Utilization Fundamentals*

CO_2 capture and utilization (CCU) represents a critical component of global efforts to reduce greenhouse gas emissions. The process begins with capturing CO_2 from large point sources such as power plants, cement factories, or refineries, using methods like post-combustion, pre-combustion, and oxy-fuel combustion techniques as presented in table 1 (Boot-Handford et al., 2014). Once captured, the CO_2 can be compressed, transported, and either stored underground or converted into valuable products such as fuels, chemicals, and building materials (Ononiwu et al., 2023).

Utilization technologies are advancing rapidly, focusing on both chemical and biological conversion pathways. Chemical conversion involves catalytic or electrochemical reactions to transform CO_2 into hydrocarbons or alcohols, while biological pathways use microorganisms or algae to produce biofuels (Aresta et al., 2013). These processes not only offer a means of reducing emissions but also help close the carbon loop by reintroducing CO_2 into industrial cycles.

In the context of enhanced oil recovery (EOR), captured CO_2 can be injected into depleted oil fields to increase pressure and improve oil displacement, making it both a climate and energy solution (Gao et al., 2019).

Table 1 The Summary of CO_2 Capture and Utilization Fundamentals

Concept	Description	Technologies Involved	Industrial Application
CO_2 Capture	Separation of CO_2 from industrial or natural sources before it enters the atmosphere.	Post-combustion, pre-combustion, oxy-fuel combustion	Power plants, cement factories, steel industries
CO_2	Movement of captured CO_2 to storage or	Pipeline transport, shipping,	CO_2 pipeline networks,

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Transportation	utilization sites.	compression systems	offshore oil fields
CO_2 Utilization	Use of CO_2 as a raw material for useful products or energy applications.	EOR, synthetic fuels, mineralization, chemical conversion	Oil recovery, chemical production, construction
Environmental Benefit	Mitigates greenhouse gas accumulation and supports circular carbon economy.	Combined CCU-EOR systems, carbon recycling processes	Emission reduction projects, sustainable industries

➢ *Integration with Enhanced Oil Recovery (EOR)*

The integration of CO_2 conversion systems with Enhanced Oil Recovery (EOR) presents a viable approach to simultaneously boost oil production and reduce atmospheric carbon emissions. In CO_2-EOR, captured carbon dioxide is injected into mature or declining oil reservoirs, where it mixes with crude oil, reduces its viscosity, and increases reservoir pressure resulting in improved oil displacement and extraction rates as represented in figure 1 (Alvarado & Manrique, 2010). This method not only extends the productive life of oil fields but also serves as a form of carbon sequestration, as a significant portion of the injected CO_2 remains trapped underground.

Modern advancements in CO_2 utilization technologies allow for the integration of conversion units at or near oil fields, enabling the direct transformation of industrial CO_2 into injectable fluid for EOR (Godec et al., 2013). Such integration is particularly beneficial in countries with existing petroleum infrastructure, reducing transportation costs and emissions. Furthermore, it supports a circular carbon economy by reusing waste CO_2 in energy production processes (Han et al., 2019), thereby aligning energy development with environmental sustainability goals.

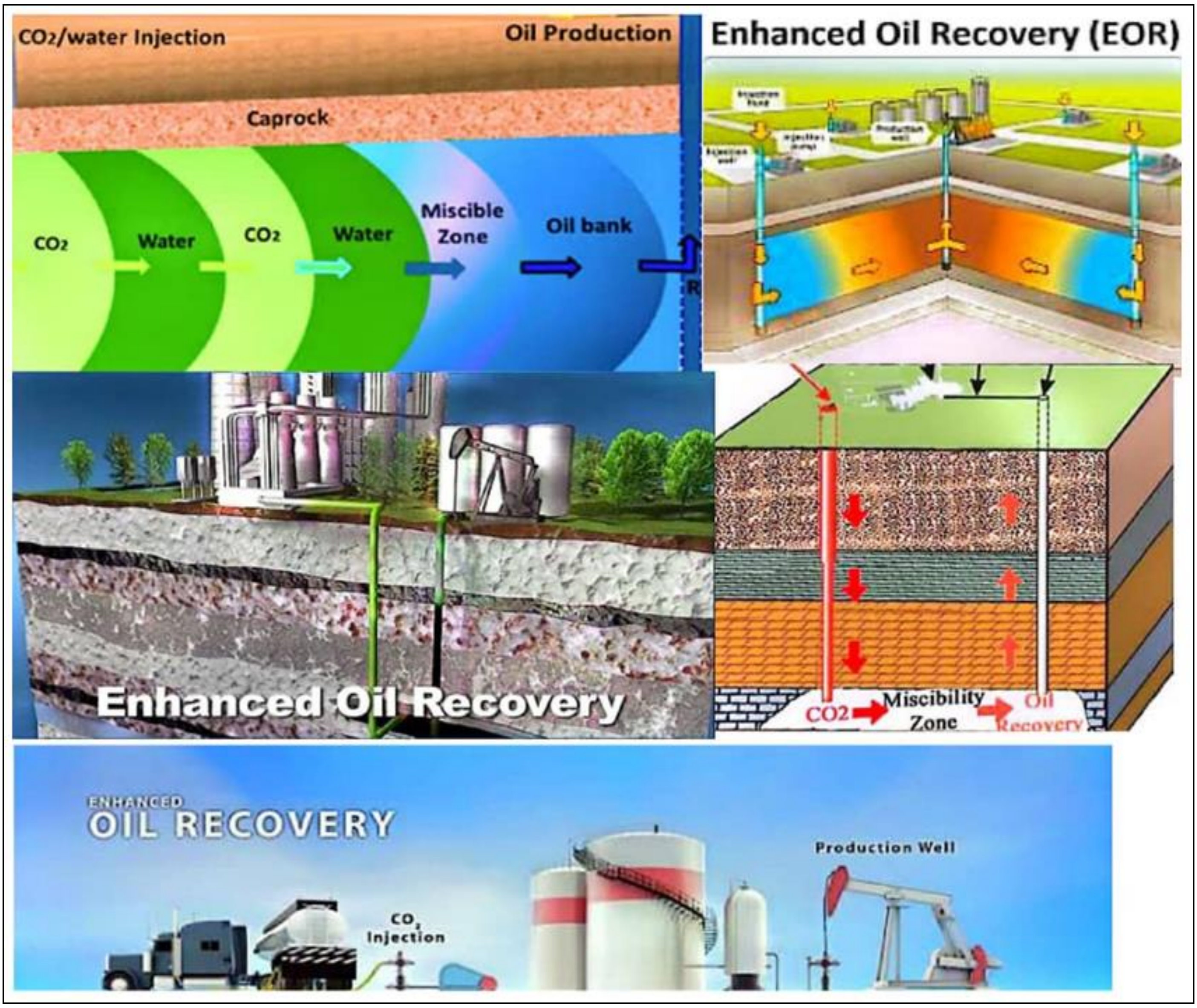

Fig 1 Illustrates Integration with Enhanced Oil Recovery (EOR) (Alvarado & Manrique, 2010).

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Figure 1: Provides a comprehensive overview of Enhanced Oil Recovery (EOR) techniques, with a focus on CO_2 and water injection methods used to extract additional oil from reservoirs. The upper left section illustrates the process where CO_2 and water are injected into the reservoir, separated by a caprock to trap the fluids. This injection creates distinct zones: CO_2 moves forward, followed by water, forming a miscible zone where CO_2 mixes with oil to reduce its viscosity, and an oil bank that drives the oil toward production wells. The central image depicts this process in a 3D view, showing how the injected fluids interact with the reservoir layers to enhance oil displacement.

The right side of the diagram further elaborates on EOR, highlighting the technical aspects of CO_2 injection in a cross-sectional view of the reservoir. It shows how CO_2 is injected into the miscibility zone, where it mixes with oil to improve recovery, with arrows indicating the flow toward production wells. The lower section ties the concept together with a practical scene of oil recovery operations, featuring CO_2 injection equipment and production wells, emphasizing the industrial application. Together, these elements illustrate how EOR, particularly with CO_2, extends the life of oil fields by recovering oil that traditional methods cannot access.

- *Scalability and Deployment Models*

The scalability of CO_2 conversion systems and their integration into enhanced oil recovery (EOR) depend on flexible deployment models that align with varying geological, industrial, and infrastructural conditions (Azonuche et al,. 2023). Modular systems, which involve small, distributed units for CO_2 capture and conversion, offer scalability in regions lacking centralized infrastructure (Mac Dowell et al., 2017). These units can be co-located with emission sources such as power plants and industrial facilities, enabling on-site conversion and immediate CO_2 injection into nearby oil fields.

Centralized deployment models, on the other hand, rely on large-scale CO_2 hubs and pipeline networks that collect, process, and distribute CO_2 to multiple injection sites. This model is cost-effective in regions with dense industrial activity and established oil infrastructure (IEA, 2020).

Key factors influencing deployment include economic feasibility, technological readiness, regulatory frameworks, and access to geological storage sites. Effective scalability requires coordinated efforts among stakeholders to ensure that CO_2 conversion technologies are adapted to local contexts while maintaining environmental and economic benefits (Idoko et al., 2024).

III. NATIONAL CONTEXT AND STRATEGIC RELEVANCE

Nigeria, as a major oil-producing nation, faces the dual challenge of sustaining energy production while addressing rising CO_2 emissions from industrial activities and gas flaring (Ajayi & Ajayi, 2021). Integrating CO_2 conversion with enhanced oil recovery offers a strategic opportunity to extend the lifespan of aging oil fields while aligning with national climate commitments under the Paris Agreement (NDC, 2021).

- *Nigeria's Oil Industry and CO_2 Emissions Profile*

Nigeria's oil and gas sector is a critical component of the national economy, accounting for over 90% of export revenues and a substantial portion of government income (Azonuche et al., 2023). However, it is also a major contributor to the country's carbon dioxide (CO_2) emissions, primarily through activities such as gas flaring, oil refining, and inefficient energy use (Ogbodo et al., 2022). Gas flaring alone emits millions of tons of CO_2 annually, making Nigeria one of the highest gas-flaring nations globally.

Despite efforts to curb emissions, the industry continues to operate with outdated infrastructure and limited carbon management strategies, leading to high environmental costs (Ajayi & Ajayi, 2021). As Nigeria seeks to meet its Nationally Determined Contributions (NDCs) under the Paris Agreement, reducing emissions from the oil sector is crucial. Integrating CO_2 conversion systems into the petroleum value chain can offer a pathway to achieving this goal by turning waste CO_2 into a valuable resource for enhanced oil recovery (EOR), while simultaneously reducing the country's overall carbon footprint (James et al., 2024).

- *Existing Policies on Emissions Reduction*

Nigeria has implemented several policy frameworks aimed at reducing greenhouse gas emissions, particularly CO_2, in alignment with its commitments under the Paris Agreement as presented in table 2 (Adeleke, 2022). The country's updated Nationally Determined Contribution (NDC) targets a 20% unconditional and 47% conditional reduction in greenhouse gas emissions by 2030, relative to business-as-usual levels (Federal Ministry of Environment, 2021). This goal emphasizes emission reductions from the energy, transportation, agriculture, and waste sectors, with the oil and gas industry playing a central role.

Key initiatives include the National Gas Policy (2017), which seeks to eliminate routine gas flaring by 2030 and promote gas-based industrialization, and the Nigeria Climate Change Act (2021), which legally mandates emission control strategies and establishes the National Council on Climate Change (Okoh et al., 2025). Additionally, incentives such as the Gas Flare Commercialisation Programme (NGFCP) encourage private sector investment in capturing and utilizing flared gas (James et al., 2024).

While these policies are commendable, enforcement remains a challenge. Integrating CO_2 conversion technologies into oil operations would support policy goals and enhance compliance with international environmental standards.

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Table 2 The Summary of Existing Policies on Emissions Reduction

Policy/Initiative	Description	Implementing Agency	Impact on CO_2 Emission Reduction
Nationally Determined Contribution (NDC)	Nigeria's climate action plan under the Paris Agreement aiming to cut emissions by 20% unconditionally by 2030.	Federal Ministry of Environment	Guides national decarbonization strategy and investment focus.
Nigeria Climate Change Act (2021)	Legal framework to mainstream climate action across all sectors.	National Council on Climate Change (NCCC)	Institutionalizes emission control measures.
Gas Flare Commercialization Programme	Targets elimination of routine gas flaring through private sector involvement.	Nigerian Upstream Petroleum Regulatory Commission (NUPRC)	Reduces methane and CO_2 emissions in the oil and gas sector.
Energy Transition Plan (ETP) 2022	Aims for carbon-neutral economy by 2060 through clean energy adoption.	Office of the Vice President (Energy Transition Office)	Promotes renewable energy and low-carbon technologies.

➢ *Opportunity for CO_2-EOR Projects*

Nigeria presents significant potential for implementing CO_2-enhanced oil recovery (CO_2-EOR) projects due to its extensive network of aging and declining oil fields as represented in figure 2 (Omachi et al., 2025). Many of these fields have experienced reduced production efficiency, making them suitable candidates for secondary recovery methods like CO_2-EOR (Duru et al., 2020). The country also has abundant industrial CO_2 sources from gas flaring, cement production, and refineries which could serve as feedstock for CO_2 injection processes.

Implementing CO_2-EOR not only revitalizes mature reservoirs but also offers a viable carbon sequestration method, supporting Nigeria's climate targets while boosting oil output. According to research by Aghamelu and Duru (2021), CO_2-EOR could increase oil recovery by 7–15% in certain Nigerian fields, representing a major economic incentive for adoption.

Furthermore, leveraging CO_2-EOR aligns with the Nigerian government's interest in diversifying oil recovery methods and reducing dependence on conventional drilling. With appropriate policy support, investment incentives, and infrastructure development, CO_2-EOR can serve as a strategic bridge between environmental responsibility and energy security in Nigeria.

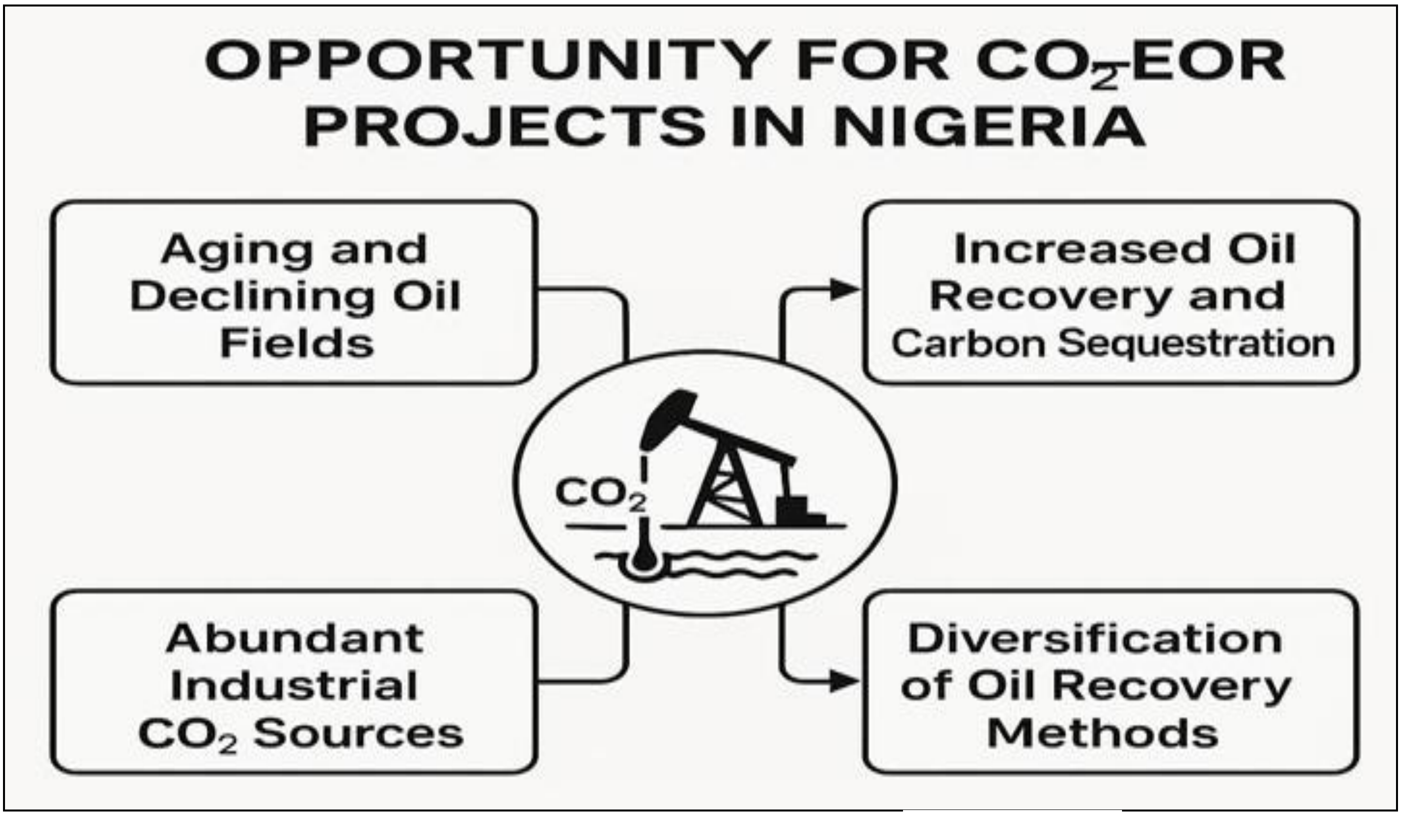

Fig 2 The Diagram of Opportunity for CO_2-EOR Projects (Omachi et al., 2025).

Figure 2: Iillustrates the potential benefits and enabling factors of Carbon Dioxide Enhanced Oil Recovery (CO_2-EOR) in the region. It highlights aging and declining oil fields as a key opportunity, where CO_2 injection can boost recovery. Abundant industrial CO_2 sources provide the necessary raw material for this process. The central image of

an oil rig with CO_2 injection symbolizes the core technique, which leads to two main advantages: increased oil recovery and carbon sequestration, helping to mitigate environmental impact, and diversification of oil recovery methods, enhancing operational flexibility. Aging oil fields, a common challenge in mature oil-producing regions, can be revitalized through CO_2 injection, extending their productive life and maximizing resource extraction. The availability of industrial CO_2 sources, likely from nearby industrial activities, supports the feasibility of large-scale implementation without significant additional infrastructure costs. Together, these elements position CO_2-EOR as a dual-purpose solution, addressing both economic goals through enhanced oil recovery and environmental concerns via carbon sequestration, while also fostering innovation in recovery techniques.

IV. TECHNOLOGICAL DEVELOPMENT AND INNOVATION

Recent advancements in CO_2 capture, conversion, and injection technologies have significantly improved the feasibility of CO_2-enhanced oil recovery (EOR) projects Azonuche et al,. (2023). Innovations such as nanomaterial-based catalysts, modular electrochemical reactors, and smart monitoring systems have increased the efficiency of CO_2 utilization while reducing operational costs (Zhang et al., 2020). Additionally, digital tools powered by artificial intelligence now optimize CO_2 flow rates and reservoir performance, making large-scale deployment of CO_2-EOR more practical and sustainable (Chen et al., 2021).

➢ *Advances in CO_2 Conversion Technologies*

Significant progress has been made in CO_2 conversion technologies, enabling the transformation of carbon dioxide into valuable products such as synthetic fuels, chemicals, and construction materials as presented in table 3 (Qiao et al., 2014). One of the most notable developments is the use of advanced catalytic systems, including nanomaterials and metal-organic frameworks (MOFs), which enhance the efficiency and selectivity of CO_2 reduction reactions (Zhang et al., 2020). These catalysts facilitate the electrochemical and thermochemical conversion of CO_2 into carbon monoxide, methane, methanol, and other hydrocarbons, supporting circular carbon utilization.

Electrochemical CO_2 conversion systems, in particular, are gaining traction due to their compatibility with renewable energy sources like solar and wind, offering a sustainable route for low-emission fuel production (Azonuche et al ., 2023). Furthermore, innovations in reactor design such as flow reactors and membrane-separated systems have improved scalability and energy efficiency, making industrial deployment more feasible.

These technological breakthroughs provide a solid foundation for integrating CO_2 conversion into enhanced oil recovery (EOR) operations, enabling dual benefits: carbon mitigation and increased oil production.

Table 3 The Summary of Advances in CO_2 Conversion Technologies

Technology Type	Description	Key Innovation	Industrial Application
Thermochemical Conversion	Converts CO_2 into fuels or chemicals using heat and catalysts.	Solid oxide electrolysis and reverse water-gas shift	Production of syngas, methanol, and other hydrocarbons.
Electrochemical Reduction	Utilizes electricity (often from renewables) to reduce CO_2 into value-added products.	CO_2-to-ethanol and CO_2-to-formate electrolysis	Used in chemical manufacturing and fuel generation.
Photocatalytic Conversion	Uses solar energy and catalysts to split CO_2 molecules.	Semiconductor-based photocatalysts (e.g., TiO_2)	Green chemical production with minimal energy input.
Biological Conversion	Employs microorganisms or enzymes to fix CO_2 into biomass or chemicals.	Genetically engineered microbes for high-yield output	Sustainable production of biofuels and biodegradable plastics.

➢ *Smart Integration with Oil Infrastructure*

Integrating CO_2 conversion technologies with existing oil infrastructure is critical for cost-effective and scalable deployment of CO_2-enhanced oil recovery (EOR) systems as represented in figure 3 (Omachi et al., 2025). Smart integration involves retrofitting existing facilities such as refineries, gas processing plants, and pipelines with CO_2 capture, conversion, and injection components to minimize infrastructure investment and operational disruptions (Godec et al., 2013). This approach leverages established oilfield networks, reducing the need for extensive new development (Omachi et al., 2025).

Advancements in automation and digital technologies such as real-time monitoring systems, Internet of Things (IoT) sensors, and artificial intelligence (AI) have significantly improved the precision and efficiency of CO_2 injection and reservoir management (Chen et al., 2021). These systems optimize injection rates, monitor pressure variations, and detect potential leakage, thereby ensuring environmental safety and improving oil recovery performance (Okoh et al., 2025).

Moreover, mobile CO_2 conversion units designed for on-site use enable flexible deployment across multiple oilfields. This modular integration model is particularly valuable in regions like Nigeria, where field distribution is widespread and infrastructure varies significantly (Agama et al., 2025).

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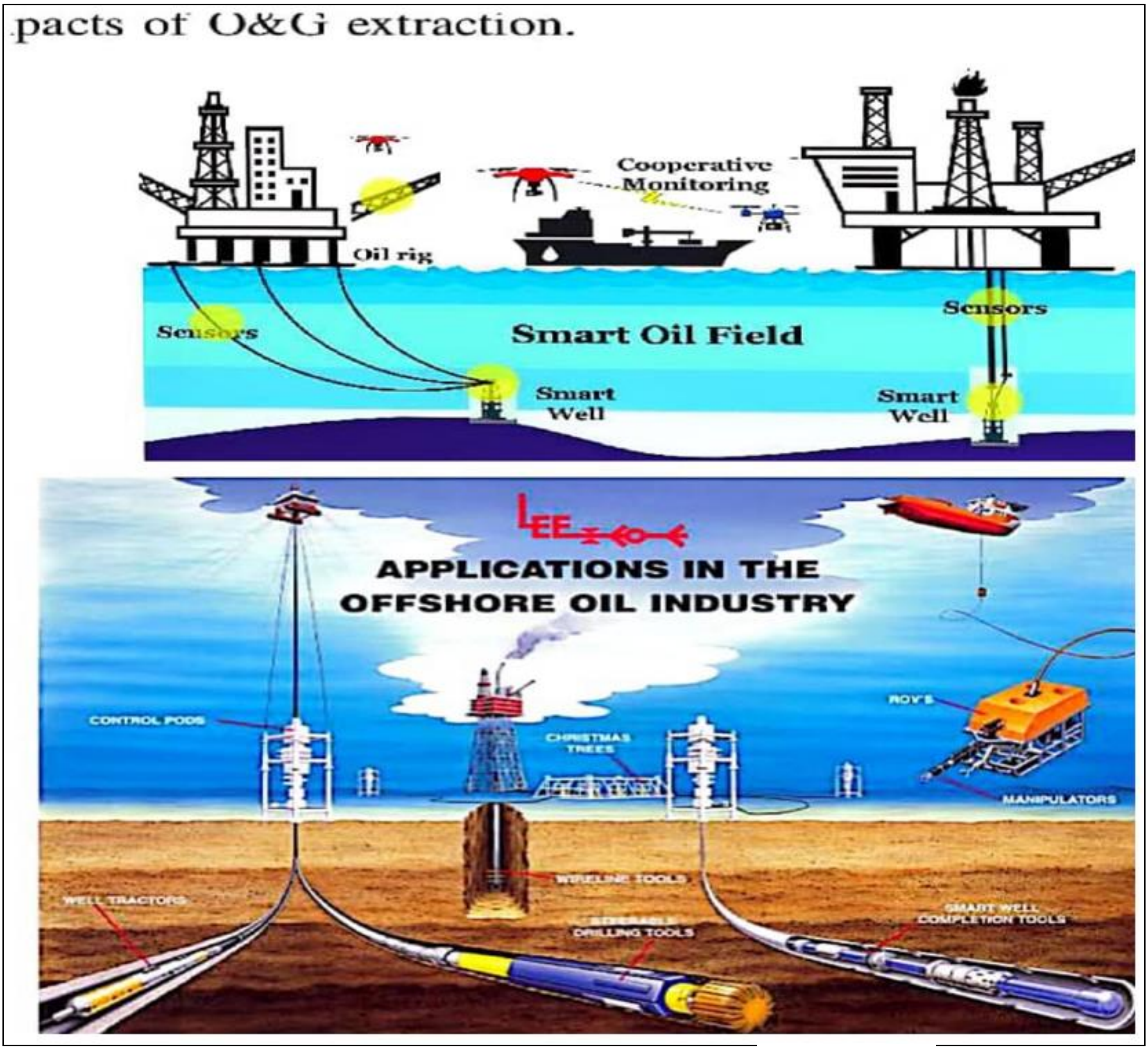

Fig 3 The Picture of Smart Integration with Oil Infrastructure (Omachi et al., 2025).

Figure 3: Illustrate the overview of advanced technologies used in offshore oil and gas (O&G) extraction. The upper section illustrates a smart oil field setup, featuring an oil rig equipped with sensors and cooperative monitoring systems, including drones and a ship. These technologies, labeled as Smart Oil Field and Smart Well, enhance the efficiency and safety of extraction by integrating real-time data collection and monitoring across the offshore environment. Sensors are deployed both above and below the water surface, indicating a comprehensive approach to managing the extraction process The lower section delves into specific applications in the offshore oil industry, highlighting the use of advanced equipment such as ROVs (Remotely Operated Vehicles) with manipulators, control pods, and various well tractors. It also showcases tools like wireline tools, drilling tools, and smart well completion tools, which are essential for operations beneath the seabed. The inclusion of a Christmas tree (a wellhead control system) and other infrastructure underscores the complexity and technological sophistication involved in maintaining and optimizing offshore oil production, ensuring both productivity and safety in this challenging environment.

➢ *Role of Renewable Energy in Powering CO_2 Conversion*

Renewable energy plays a vital role in making CO_2 conversion technologies more sustainable and carbon-neutral. Electrochemical CO_2 reduction, one of the most promising conversion methods, requires a significant amount of electricity, which can be efficiently supplied by renewable sources such as solar, wind, or hydropower (Jhong et al., 2013). Utilizing clean energy to drive CO_2 conversion processes reduces the carbon footprint of the entire system, making the output products like synthetic fuels and chemicals more environmentally friendly (Sunday et al., 2025).

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The integration of renewable energy with CO_2 conversion also improves energy security and reduces dependency on fossil fuels, especially in countries like Nigeria with abundant solar resources. Hybrid systems combining photovoltaic panels with modular CO_2 electrolyzers are being developed for deployment in off-grid or remote oil-producing areas (De Luna et al., 2019). Such setups can facilitate localized CO_2 utilization while minimizing transmission losses and infrastructure costs, making them ideal for scalable deployment in oilfields.

V. ENVIRONMENTAL AND ECONOMIC IMPACT

The integration of CO_2 conversion with enhanced oil recovery (EOR) offers dual benefits: reducing greenhouse gas emissions and boosting economic returns. Environmentally, it enables long-term CO_2 sequestration and helps nations meet climate targets (IEA, 2020). Economically, CO_2-EOR increases oil recovery by up to 20%, extending the life of mature fields and generating additional revenue (Godec et al., 2013). This synergy makes CO_2-EOR a viable pathway toward low-carbon economic development.

➢ *Reduction in Net Atmospheric CO_2 Emissions*

The integration of CO_2 conversion and enhanced oil recovery (EOR) significantly contributes to reducing net atmospheric carbon dioxide emissions. In CO_2-EOR operations, a substantial portion of the injected CO_2 remains permanently trapped in underground reservoirs, acting as a form of geological carbon sequestration as presented in table 4 (IEA, 2020). Studies estimate that up to 60% of injected CO_2 can be stored long-term in oil fields, depending on reservoir conditions and operational practices (Godec et al., 2013).

When coupled with CO_2 capture from industrial sources and renewable-powered conversion processes, the overall carbon footprint of oil production can be dramatically lowered. This approach transforms CO_2 from a pollutant into a valuable resource, helping countries like Nigeria offset emissions from sectors such as energy, manufacturing, and transport (Ajayi & Ajayi, 2021).

Moreover, CO_2-EOR supports national climate strategies by contributing to the achievement of emissions reduction targets under the Paris Agreement, making it a critical tool for low-carbon development and energy transition (Omachi et al., 2025).

Table 4 The Summary of Reduction in Net Atmospheric CO_2 Emissions

Approach	Description	Mechanism of CO_2 Reduction	Environmental Impact
CO_2-EOR (Enhanced Oil Recovery)	Injects captured CO_2 into oil reservoirs to boost extraction.	CO_2 is trapped underground in geological formations	Reduces atmospheric CO_2 while increasing oil production.
Carbon Mineralization	Converts CO_2 into stable carbonates through chemical reaction with minerals.	Permanent fixation of CO_2 in solid form	Long-term storage with negligible leakage risk.
Bioenergy with Carbon Capture (BECCS)	Combines biomass energy use with CO_2 capture.	Absorbs CO_2 via photosynthesis, then captures emissions	Achieves negative emissions, especially in power generation.
Direct Air Capture (DAC)	Extracts CO_2 directly from ambient air using chemical sorbents.	Isolates low-concentration CO_2 for storage or reuse	Addresses dispersed emissions, complements other mitigation paths.

➢ *Cost-Benefit Analysis of CO_2 Conversion in EOR*

The implementation of CO_2 conversion in Enhanced Oil Recovery (EOR) presents both economic opportunities and initial financial challenges (Atalor et al., 2019). On the cost side, the capital investment required for CO_2 capture, compression, transport, and injection infrastructure can be significant, especially in regions where such systems are not yet developed (IEA, 2020). Additionally, the operation and maintenance of these facilities involve considerable ongoing expenses. However, these costs can be offset over time through increased oil production, which enhances revenue streams for oil operators (Godec et al., 2013).

Economically, the use of CO_2-EOR allows for the extraction of 10–20% more oil from mature reservoirs, extending the life of existing fields and reducing the need for new exploration (Alvarado & Manrique, 2010). Moreover, the monetization of captured CO_2 through carbon credits or incentives under emissions trading schemes could provide additional financial returns (IPCC, 2018). When combined with environmental benefits and policy support, CO_2-EOR systems offer a viable pathway for sustainable oil production and climate-friendly economic development.

➢ *Environmental Risks and Mitigation Strategies*

While CO_2 conversion and its use in Enhanced Oil Recovery (EOR) offer environmental benefits, such as reducing net atmospheric emissions, there are notable environmental risks that require careful mitigation as represented in figure 4 (Zoback & Gorelick, 2012).

One primary concern is the potential leakage of stored CO_2 from geological formations, which could undermine long-term climate benefits and pose hazards to nearby ecosystems and human settlements (Benson & Cole, 2008). Additionally, the pressurization of reservoirs during CO_2 injection could induce seismic activities, especially in tectonically active regions (Omachi et al., 2025). There are also risks related to groundwater contamination if CO_2 migrates into freshwater aquifers, particularly in cases of

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poor well integrity or fractured caprock (Celia et al., 2005). To address these issues, stringent monitoring protocols, risk assessments, and improved site selection criteria have been developed (Idika et al., 2024). For instance, the application of advanced subsurface imaging, pressure monitoring, and integrity testing of wells helps ensure long-term containment (IEA, 2020). Regulatory frameworks such as environmental impact assessments (EIA) and long-term liability guidelines are essential tools in mitigating these risks and ensuring the safe deployment of CO_2-EOR technologies.

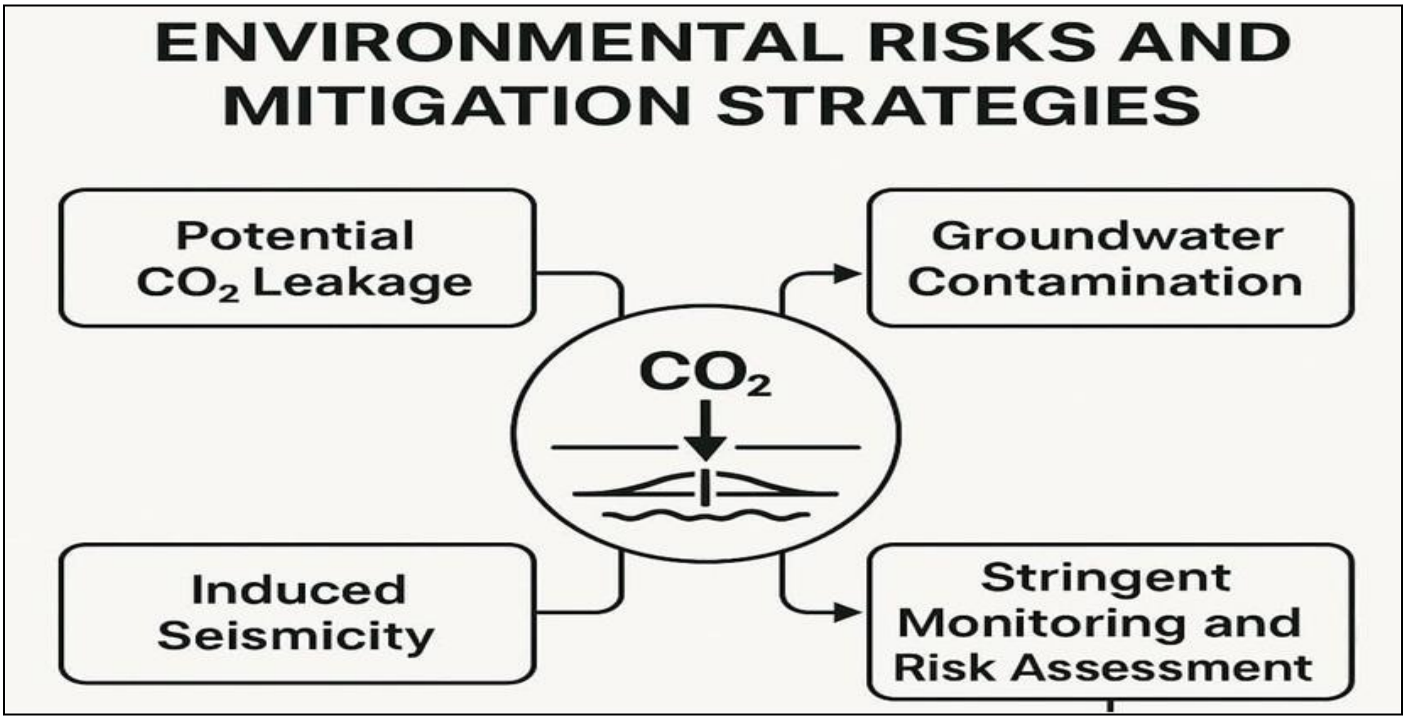

Fig 4 The Diagram Showing Environmental Risks and Mitigation Strategies (Zoback & Gorelick, 2012).

Figure 4: Outlines the potential environmental challenges associated with CO_2 injection, a technique often used in enhanced oil recovery and carbon sequestration projects. It identifies potential CO_2 leakage and induced seismicity as primary risks originating from the underground storage of CO_2, which can lead to significant issues such as groundwater contamination. The central image of CO_2 descending into the earth visually represents the injection process, underscoring the importance of managing these risks to prevent environmental harm.

To address these challenges, the diagram emphasizes the implementation of stringent monitoring and risk assessment as essential mitigation strategies. These measures are designed to detect and respond to any leakage or seismic activity promptly, ensuring the safety of surrounding ecosystems and water resources. Given the current date and time of 01:34 PM WAT on Friday, August 08, 2025, such proactive strategies are particularly relevant for ongoing and future CO_2-related projects in regions like Nigeria, where environmental stewardship is critical alongside economic development.

VI. POLICY SUPPORT AND FUTURE PROSPECTS

Effective policy support is crucial for the widespread adoption of scalable CO_2 conversion technologies linked with enhanced oil recovery (Igwea et al., 2025). Future prospects depend on strategic investments, regulatory incentives, and strong public-private partnerships. As global and national climate goals intensify, CO_2-EOR projects can become a cornerstone of carbon management strategies (Idoko et al., 2024). Advancements in technology, coupled with favorable policy environments, are expected to accelerate the transition toward a low-carbon economy, ensuring both environmental sustainability and continued energy security (Azonuche et al., 2025).

➢ *Regulatory Framework for Scalable Deployment*

A robust regulatory framework is essential for enabling the scalable deployment of CO_2 conversion technologies integrated with enhanced oil recovery (EOR) as represented in figure 5 (Ononiwu et al., 2025). Such a framework should clearly define legal ownership of captured CO_2, outline safety standards for transportation and storage, and establish long-term liability for underground sequestration (Omachi et at., 2025). Regulatory clarity will foster investor confidence and reduce operational risks associated with project implementation (Omachi et al., 2025). Moreover, streamlined permitting processes and supportive zoning regulations can minimize delays in infrastructure development and facilitate quicker deployment. Incentives such as carbon credits, tax reliefs, and low-interest green financing can further encourage private sector participation and innovation in the field (James et al., 2023). Establishing performance benchmarks and environmental monitoring protocols will ensure accountability and transparency in project execution (Idoko et al., 2024). Additionally, harmonization of national regulations with international

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climate commitments can enhance global cooperation and attract foreign investment (Atalor et al., 2025). A well-structured policy environment can thus serve as a catalyst, promoting widespread adoption of CO_2-EOR systems while aligning economic growth with environmental sustainability objectives.

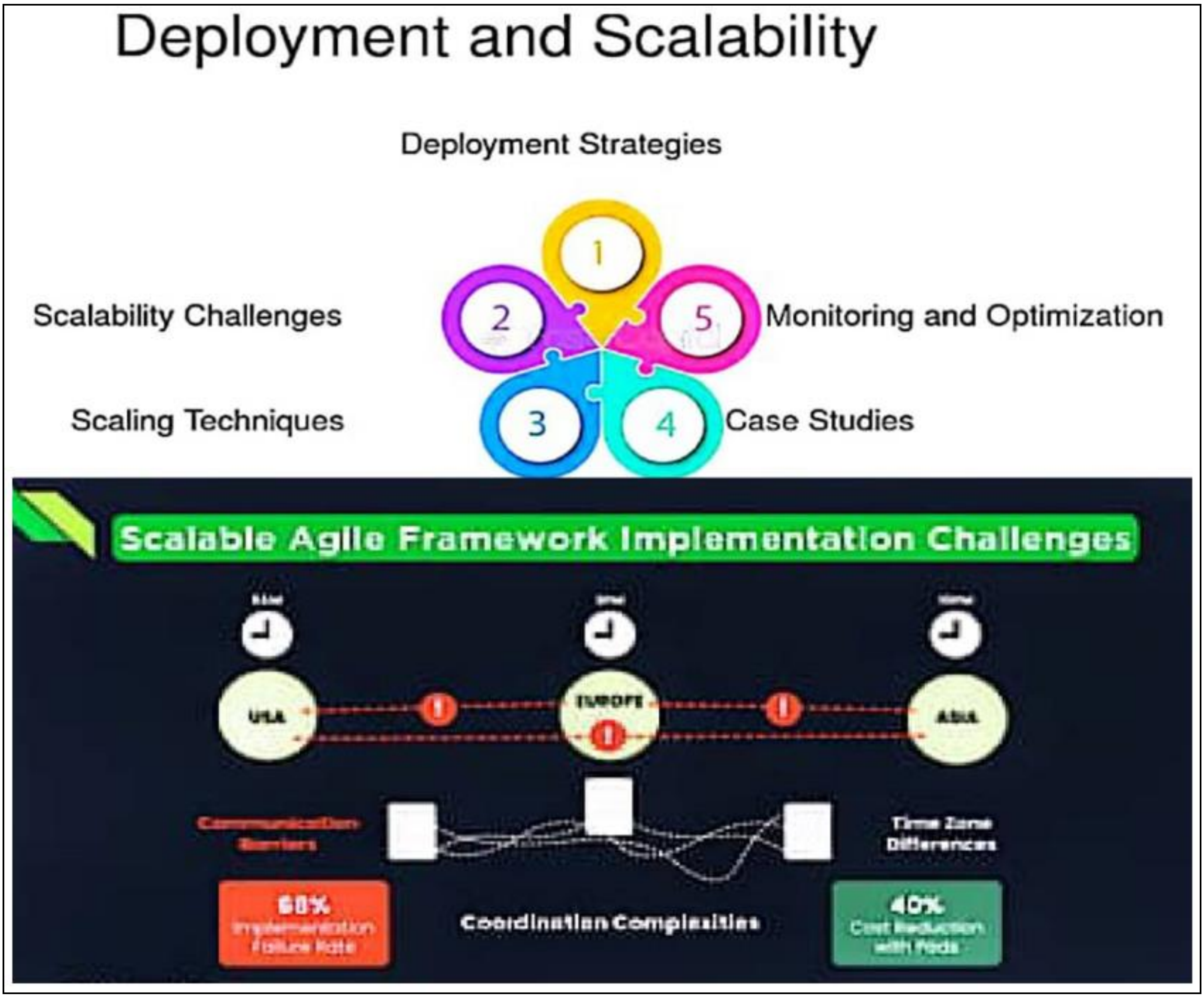

Fig 5 The picture showing Regulatory Framework for Scalable Deployment (Ononiwu et al., 2025).

Figure 5: Illustrates an overview of key strategies and challenges involved in implementing scalable systems, likely in a technological or organizational context. The upper section outlines five interconnected components: Deployment Strategies, Scalability Challenges, Scaling Techniques, Monitoring and Optimization, and Case Studies. These are visually represented as a central circle surrounded by numbered circles (1 to 5), suggesting a holistic approach where deployment strategies (1) are supported by scaling techniques (3) and monitoring efforts (5), while addressing scalability challenges (2) and drawing insights from case studies (4). This framework emphasizes a structured process for managing growth and efficiency. The lower section focuses on "Scalable Agile Framework Implementation Challenges," detailing specific issues in adopting such frameworks. It highlights three entities ULA, Swarm, and Alba connected by lines indicating coordination complexities. Key challenges include a 68% increase in failure rate, attributed to these complexities, and a 40% cost increase with pods, as noted in the context of Three Zone differences. The diagram uses icons and color coding to differentiate the entities and challenges, underscoring the need for effective coordination and resource management to mitigate implementation hurdles in scalable agile environments.

> *Stakeholder Involvement and Industrial Collaboration*

Successful implementation of scalable CO_2 conversion systems for enhanced oil recovery (EOR) requires the active involvement of diverse stakeholders, including government agencies, oil and gas companies, research institutions, financial bodies, and local communities (Ononiwu et al., 2023). Government bodies play a critical role in formulating enabling policies and offering incentives, while oil companies provide the infrastructure and operational expertise necessary for field deployment (Idika et al., 2024).

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Academic and research institutions contribute through technological innovation and feasibility studies, ensuring that solutions remain efficient and environmentally sound. Financial institutions can drive progress by funding large-scale pilot projects and offering favorable credit terms for clean energy investments (Ononiwu et al., 2025). Local communities must be engaged to ensure transparency, address environmental concerns, and promote social acceptance of the projects (Idoko et al., 2024). Collaborative platforms that encourage joint ventures, knowledge-sharing, and risk-sharing will accelerate progress and reduce duplication of efforts (Idika et al., 2024). A unified and inclusive approach will help build trust, ensure regulatory compliance, and ultimately increase the scalability and impact of CO_2-EOR projects across the country (Imoh et., 2025).

➢ *The Integration of Technologies to Enhance Productivity*

Integrating advanced CO_2 conversion technologies with oil recovery operations can significantly improve both efficiency and sustainability (Omachi et al., 2025) By combining thermochemical, electrochemical, and biological conversion methods, operators can optimize CO_2 utilization across various stages of production (Ononiwu et al., 2024). Smart monitoring systems, powered by artificial intelligence and IoT sensors, can track injection efficiency, reservoir performance, and CO_2 storage integrity in real time (Raphael et al,. 2025). Linking these systems with existing oil infrastructure reduces downtime, minimizes operational costs, and enhances recovery rates (Imoh et al., 2023). Additionally, coupling CO_2 conversion units with renewable energy sources such as solar or wind ensures a cleaner energy supply for continuous operation (Atalor et al., 2023). Hybrid models, where CO_2 is simultaneously used for EOR and processed into marketable products like synthetic fuels or chemicals, further increase project profitability (Ononiwu et al., 20205). This multi-technology integration not only maximizes resource use but also supports long-term emission reduction goals, positioning the oil industry for a more sustainable and competitive future.

VII. CONCLUSION AND RECOMMENDATIONS

The development of scalable CO_2 conversion systems integrated with enhanced oil recovery offers a strategic pathway to simultaneously address climate change and optimize resource utilization. By capturing and reusing CO_2 in oil production, emissions can be significantly reduced while maintaining energy security and economic benefits. Nigeria's oil sector, with its substantial CO_2 emissions profile, presents a strong opportunity for adopting such technologies, supported by existing policies and emerging innovations. However, large-scale deployment requires coordinated efforts across technological, regulatory, and financial dimensions. It is recommended that investment be directed toward advanced CO_2 conversion research, with a focus on efficiency, cost reduction, and renewable energy integration. Stronger policy incentives and clear regulatory frameworks should be established to encourage industrial adoption. Collaboration among government, industry, and academia will be essential to ensure scalability, environmental safety, and long-term sustainability, positioning CO_2-EOR as a key component of a low-carbon future.

➢ *Summary of the Key Concepts*

This study focuses on the integration of scalable CO_2 conversion systems with enhanced oil recovery (EOR) to address both environmental and energy challenges. It highlights the fundamentals of CO_2 capture, transportation, and utilization, emphasizing their role in reducing atmospheric carbon levels while boosting oil production efficiency. The national context examines Nigeria's oil industry, its emissions profile, and the policy landscape that supports low-carbon initiatives. Technological advancements such as thermochemical, electrochemical, photocatalytic, and biological conversion are discussed, along with their potential for smart integration into existing oil infrastructure and renewable energy systems. The environmental and economic impacts are explored, showing benefits in emissions reduction, cost-effectiveness, and risk mitigation. The paper also stresses the importance of robust regulatory frameworks, stakeholder collaboration, and continuous research to ensure long-term scalability. Together, these concepts present CO_2-EOR as a practical and strategic solution for climate change mitigation and sustainable resource management.

➢ *Research Directions and Long-Term Vision*

Future research on scalable CO_2 conversion systems should focus on optimizing catalyst efficiency, reducing operational costs, and improving integration with existing oil recovery infrastructure. Advanced material science can play a crucial role in developing more effective and durable catalysts for CO_2 conversion. Research should also explore novel reactor designs that enhance conversion rates while maintaining energy efficiency. In addition, long-term field studies are needed to assess the environmental sustainability and economic viability of large-scale deployment in diverse geological settings. Digital technologies, such as artificial intelligence and real-time monitoring systems, offer promising avenues for automating and optimizing CO_2-EOR operations. A forward-looking vision should also include the development of circular carbon economies, where CO_2 becomes a feedstock for various industries beyond oil recovery. Ultimately, the goal is to transform CO_2 from a waste product into a valuable resource, creating an energy ecosystem that supports economic growth while reducing climate impact. Establishing strong linkages between academic research, industry needs, and national development goals will be key to achieving this vision.

➢ *Strategic Recommendations for Stakeholders*

Stakeholders in government, industry, and academia should adopt a coordinated approach to accelerate the deployment of scalable CO_2 conversion systems for enhanced oil recovery. Government agencies should establish clear regulatory guidelines, provide tax incentives, and integrate CO_2-EOR into national energy and climate strategies. Oil and gas companies should invest in advanced capture and conversion technologies, prioritize pilot projects to test scalability, and adopt renewable energy solutions to power operations. Financial institutions should create dedicated funding mechanisms to support low-carbon technology adoption. Research institutions should focus on improving conversion efficiency, reducing operational costs, and developing environmentally safe storage methods. Collaboration platforms should be formed to share technical expertise, best practices, and data. Community engagement is essential to build public trust and ensure social acceptance. By aligning policies, investments, and innovations, stakeholders can maximize the environmental benefits, economic returns, and long-term sustainability of CO_2-EOR projects.

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