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Optimizing Oil Recovery With Minimal Environmental Impact: Importance in Nigeria's Brownfields

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ABSTRACT

The Nigerian Oil and Gas industry is faced with a dual faceted challenge: a need to increase oil production in depleting mature brownfields and as well ensuring environmental sustainability during its exploitation processes. With brownfields, comprising 60-70% of the nation's remaining proven reserves, these assets exhibit significant volumes of bypassed, unrecovered hydrocarbons due to high reservoir compartmentalization and declining pressures. This paper explores the intersection of production engineering and environmental management to develop a strategic framework for sustainable Enhanced Oil Recovery (EOR). A comprehensive evaluation of EOR techniques reveals that while conventional thermal recovery is physically unsuited for the light sweet crudes of the Agbada Formation, advanced miscible gas injection (such as CO_2-WAG), with integration of Carbon Capture, Utilization, and Storage (CCUS) and green chemical flooding offer substantial promise. Furthermore, the study highlights the transformative role of digital optimization technologies in facilitating real-time decision-making and performance forecasting. Despite favorable laboratory and simulation outcomes, full-scale implementation remains bottlenecked by acute technical, economic, and regulatory barriers. To overcome these constraints, this paper proposes an integrated screening framework tailored to the Niger Delta, alongside recommendations for brownfield readiness assessments, targeted tax credits, streamlined inter-agency approvals, and robust local capacity development. Ultimately, this research provides the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) and local operators with evidence-based benchmarks to operationalize sustainable asset management, bridging the gap between national energy security and environmental stewardship.

Keywords: Niger Delta Brownfields, Enhanced Oil Recovery (EOR), Petroleum Industry Act (PIA), CCUS Integration, Green Formulations, Digital Optimization.

INTRODUCTION

The Nigerian oil and gas industry has been crucial to the national economy for over six decades, accounting for the majority of government revenue and foreign exchange earnings (Nigerian National Petroleum Corporation, 2020). The bulk of this production originates from the Niger Delta region, a fragile ecosystem of freshwater swamps, mangrove forests, and coastal barriers. After decades of intensive exploitation, a significant portion of Nigeria's hydrocarbon assets have matured into brownfields. Brownfields refer to fields that are past their peak production plateau, characterized by declining reservoir pressure, increasing water cut, and aging infrastructure. These brownfields still hold an estimated 60–70% of the country's remaining proven reserves (PwC Nigeria, 2021), making their effective management not just an operational necessity but a matter of national economic survival.

These brownfields present a critical and dual-faceted problem. On one hand, the natural decline rates in these fields average between 10 to 15% annually (Ekejiuba, 2018), threatening the country’s ability to meet its OPEC production quota and fund its national budget. On the other hand, the conventional methods employed to achieve this enhanced recovery often exacerbate the already weakening environmental situation in the Niger Delta. But the core of the problem lies in the historical separation of production goals from environmental management. Forced production through high-volume waterflooding, for instance, generates vast quantities of produced water contaminated with hydrocarbons and heavy metals, which, when treated inadequately or discharged, affects aquatic life and soil quality (Ogunbiyi et al., 2018). Also, most field development plans for brownfields treat environmental compliance as a regulatory afterthought, rather than a design parameter to be optimized, therefore there's a need to bridge this gap.

With the imperative to stem the hydrocarbon decline and increase the recovery factor from a current average of 25 to 35% to a global best-practice target of over 50% (Nigerian Upstream Petroleum Regulatory Commission [NUPRC], 2022). This study holds profound significance in providing replicable strategies for sustained production, energy security and translating sustainability goals of the Petroleum Industry Act (PIA) into measurable field practices. Also, by analyzing real-world EOR pilots and the practicalities of PIA compliance within Nigeria’s local capabilities, the research provides the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) with evidence-based benchmarks to operationalize the environmental provisions of the PIA (Federal Republic of Nigeria, 2021), in order to support sustainable practices in mature asset management.

Ultimately, this study is focused on the intersection of production engineering and environmental management. It investigates the optimization of hydrocarbon recovery and environmental impact mitigation in Nigeria’s brownfields, exploring how technological innovation, regulatory frameworks, and operational best practices can create a more sustainable future for the nation’s mature basins.

Overview of Nigeria's Brownfields

Geological and Reservoir Properties of Niger Delta Brownfields

Nigeria's brownfields are concentrated within the *Niger Delta Basin*, one of the world's most prolific hydrocarbon provinces. Situated on the passive continental margin of West Africa, the basin contains a sedimentary succession exceeding 12 km in parts and hosts three principal formations: the *Akata* (source rock), the *Agbada* (reservoirs and seals), and the *Benin* (overlying continental sands) (Doust & Omatsola, 1990). Hydrocarbon accumulation is primarily confined to the Agbada Formation, which contains the sandstone reservoir units responsible for the bulk of Niger Delta production.

Most of these fields are mature brownfields that have been under production for several decades. Their geological architecture is dominated by growth faults, rollover anticlines, and fault-assisted closures, all of which drive reservoir compartmentalization and leave significant volumes of hydrocarbons bypassed during conventional recovery (Amodu et al., 2025). Additionally, thin oil rims associated with large gas caps and active aquifer systems create operational challenges such as gas coning and water encroachment.

The reservoir rocks are predominantly unconsolidated to moderately consolidated sandstones deposited in fluvial, deltaic, distributary channel, and shallow marine environments. These reservoirs generally exhibit favorable petrophysical properties; however, heterogeneity arising from facies variability and diagenetic overprinting adversely affects sweep efficiency (Agbasi et al., 2023). Table 2.1 summarizes the key reservoir properties and their implications for EOR applicability.

Production History and Remaining Oil in Place (ROIP)

Commercial oil production in Nigeria commenced in 1958 and has since been anchored in the Niger Delta Basin. The majority of the fields were discovered between the 1960s and 1980s and have now reached advanced maturity. As these assets age, operators face reservoir pressure depletion, rising water cut, gas breakthrough, and declining production rates - all symptoms of waning primary and secondary recovery performance (Amodu et al., 2025).

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Production in the Niger Delta has historically relied on natural drive mechanisms (solution gas drive, gas-cap expansion, and water drive), with waterflooding implemented selectively as a secondary recovery measure. Despite these efforts, conventional methods globally recover only *20–40% of the original oil in place (OOIP)*, leaving a substantial proportion of hydrocarbons behind (Sheng, 2021). In the Niger Delta specifically, recovery factors commonly range between 20% and 35%, implying that *65–80% of OOIP may remain unrecovered* in many mature reservoirs.

Remaining Oil in Place (ROIP) encompasses residual oil trapped by capillary forces, oil bypassed due to poor sweep efficiency, and hydrocarbons isolated within fault-bounded compartments. Recent evaluations of mature Niger Delta fields have identified significant bypassed hydrocarbon accumulations tied to unswept zones and poorly drained reservoir compartments (Ekong et al., 2025). Recovering even a modest fraction of this ROIP through Enhanced Oil Recovery (EOR) would contribute meaningfully to national reserves replacement and production sustainability, without the environmental and financial costs of frontier exploration.

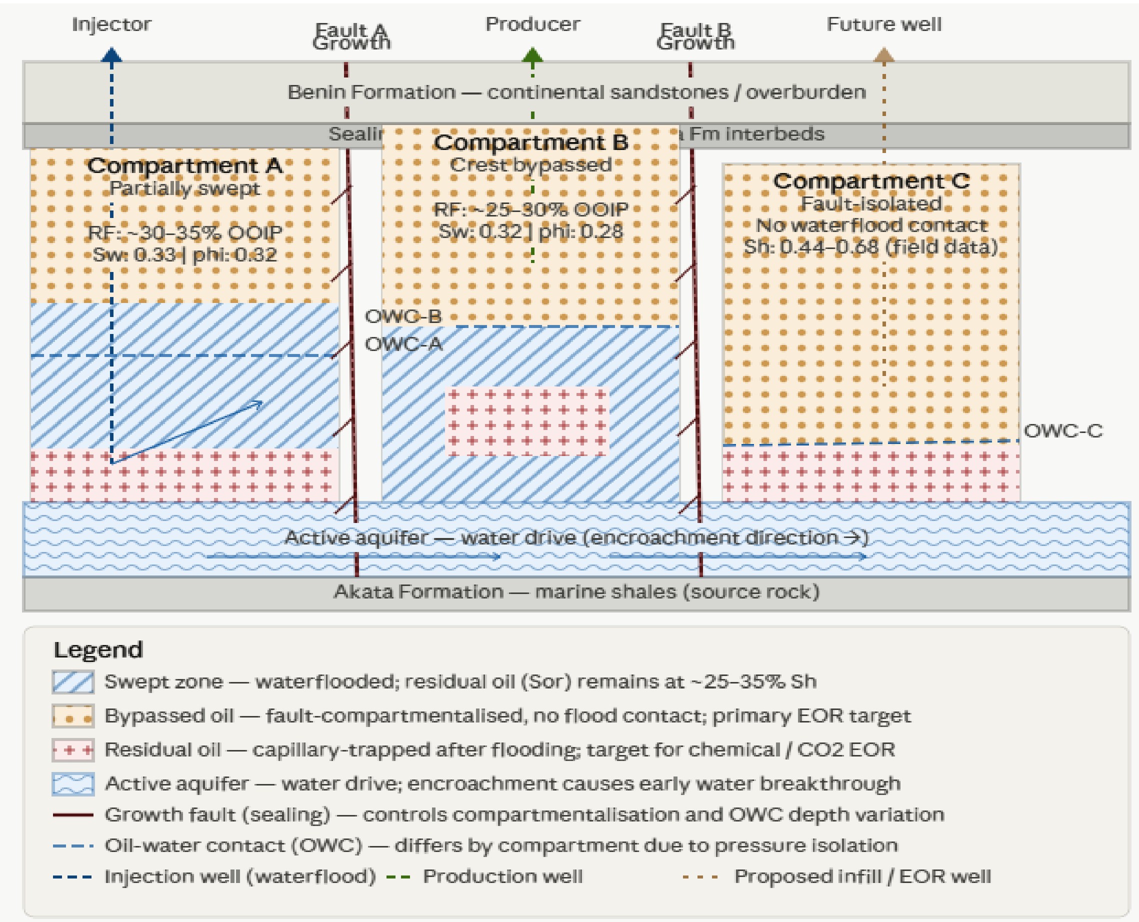

Fig. 2.1 : Schematic cross-section: ROIP distribution in a compartmentalised Niger Delta brownfield (Agbada Fm.).Adapted from Ekong et al. (2025), Agbasi et al. (2023), Amodu et al. (2025), and SEG Wiki Niger Delta.

EOR Applications in the Niger Delta: Progress and Gaps

The increasing maturity of Niger Delta oilfields has elevated interest in EOR as a strategic tool for improving recovery factors and extending field life. Studies consistently indicate that conventional recovery in many Niger Delta reservoirs retrieves only around 30–35% of OOIP, reinforcing the case for tertiary recovery interventions. Despite this recognized potential, EOR deployment in Nigeria remains nascent relative to major producing regions such as North America, the Middle East, and Asia (Kerunwa et al., 2024).

Most production enhancement activities in the Niger Delta have historically been confined to infill drilling, waterflood optimization, and well intervention techniques rather than full-scale EOR programs (Ugbedeojo et al., 2016). Nonetheless, growing reservoir depletion has stimulated a body of research into chemical, gas, microbial, and hybrid EOR technologies applicable to Niger Delta conditions.

Chemical EOR, particularly alkaline-surfactant-polymer (ASP) flooding, has demonstrated technical promise in mobilizing residual oil by reducing interfacial tension and improving sweep efficiency. Laboratory investigations using locally sourced chemical formulations have highlighted opportunities to reduce costs and support local content development (Kerunwa et al., 2024). Gas injection (including ethane and flue-gas injection) has also shown favorable technical and economic outcomes in feasibility studies for light-oil reservoirs, simultaneously offering a pathway for monetizing associated gas resources (Sanusi, 2017; Djossou, 2021). Emerging technologies such as nanofluid flooding and electrokinetic-assisted recovery have further demonstrated incremental recovery potential at laboratory scale (Onyemachi et al., 2020; Idudje et al., 2025). Table 2.2 provides a comparative overview of EOR technologies and their current deployment status in Nigeria.

Table 2.1: Status of EOR Technologies in the Niger Delta - Progress, Barriers, and Opportunities

EOR Method	**Current Stage in Nigeria**	**Key Barriers**	**Opportunities**
Chemical EOR (ASP / Polymer / Surfactant)	Laboratory & simulation	High salinity/temperature; chemical cost	Locally sourced biopolymers, green surfactants
Gas Injection (CO_2, ethane, flue gas)	Screening & feasibility studies	Gas supply, infrastructure, miscibility	CCUS integration; associated gas monetization
Nanofluid Flooding	Laboratory (analogue cores)	Scalability; cost of nanomaterials	Wettability alteration; hybrid formulations
Microbial EOR (MEOR)	Conceptual / early lab	Reservoir conditions; microbial control	Low cost; indigenous microbial consortia
Electrokinetic-Assisted EOR	Laboratory	Energy demand; scale-up complexity	Enhanced displacement efficiency
Waterflood Optimization	Field scale (limited)	Reservoir heterogeneity; sweep efficiency	Digital surveillance and infill drilling

Sources: Kerunwa et al. (2024); Sanusi (2017); Djossou (2021); Onyemachi et al. (2020); Idudje et al. (2025)

Despite these promising research outcomes, significant gaps persist. Most published studies remain at laboratory, simulation, or screening stages, and field-scale pilot projects are scarce - leaving insufficient operational data for evaluating long-term technical and economic performance under real reservoir conditions (Mbusube, 2024). Reservoir heterogeneity, fault compartmentalization, and complex fluid properties further complicate EOR design. Economic barriers - including high capital costs for chemical procurement, injection infrastructure, and reservoir surveillance - continue to deter investment, particularly amid oil price volatility. Regulatory uncertainties and shortages of local EOR expertise compound these challenges (Djossou, 2021).

Closing these gaps will require integrated reservoir characterization, systematic pilot-scale testing, and stronger collaboration between industry, academia, and government. A supportive regulatory framework, as partly enabled by Nigeria's Petroleum Industry Act (PIA) local content provisions, will be essential to accelerating the transition from laboratory studies to commercially deployable EOR programs in Nigerian brownfields.

Enhanced Oil Recovery (EOR) Methods

Classification of EOR Techniques

Hydrocarbon recovery from oil reservoirs typically progresses through three distinct phases: primary, secondary, and tertiary recovery (Green & Willhite, 2018). Primary recovery relies strictly on natural reservoir energy, such as gas cap expansion, solution gas drive, or natural water influx, to displace oil towards the wellbore (Green & Willhite, 2018). As natural pressure depletes, secondary recovery techniques predominantly waterflooding or immiscible gas injection are implemented to maintain reservoir pressure and physically displace mobile oil (Lake et al., 2014).

However, these conventional methods typically leave behind up to 50% to 70% of the original oil in place (OOIP) as residual oil, trapped by capillary forces or bypassed due to reservoir heterogeneity (Green & Willhite, 2018; Lake et al., 2014). Enhanced Oil Recovery (EOR), or tertiary recovery, alters the physical and chemical properties of the reservoir fluids or the rock-fluid interface to mobilise this trapped residual oil (Sheng, 2011). EOR techniques are broadly categorised into four primary types based on their underlying mechanisms: gas injection, chemical flooding, thermal recovery, and microbial methods.

Gas Injection Methods

Gas injection is currently the most widely applied EOR method globally (Green & Willhite, 2018). It involves injecting gases such as carbon dioxide (CO_2), natural gas (methane), or nitrogen into the reservoir (Sheng, 2011). This process operates under either miscible or immiscible conditions:

Miscible Gas Injection: Occurs when the injected gas dissolves completely into the crude oil at or above the Minimum Miscibility Pressure (MMP) (Green & Willhite, 2018). This eliminates the interfacial tension (IFT) between the oil and gas phases, causes the oil to swell, drastically reduces oil viscosity, and allows the mixture to flow smoothly as a single phase (Sheng, 2011).

Immiscible Gas Injection: When reservoir pressure is below the MMP, the gas does not mix entirely with the oil (Green & Willhite, 2018). Instead, it provides pressure maintenance and relies on gas expansion and gravity drainage to push the oil towards production wells (Sheng, 2011).

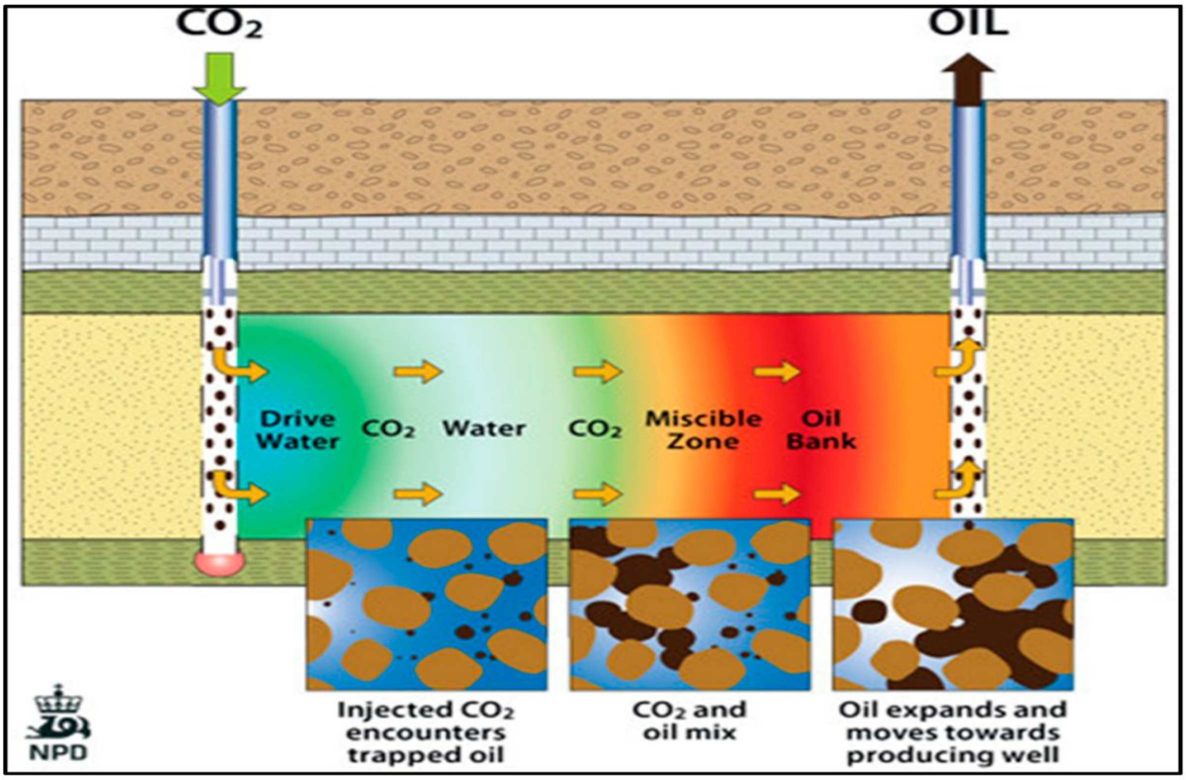

Figure 3.1: EOR illustration for carbon dioxide and water used in flushing residual oil from the reservoir (K. Oglesby, 2014).

Chemical EOR Methods

Chemical flooding relies on injecting specialised chemical formulations to improve macroscopic sweep efficiency or microscopic displacement efficiency (Lake et al., 2014).

Polymer Flooding: Long-chain polymers are added to injected water to increase its viscosity (Green & Willhite, 2018). This reduces the mobility ratio between the water and the oil, preventing "fingering" (where water bypasses oil through high-permeability zones). Beyond viscosity modification, polymers also improve macroscopic sweep efficiency through viscoelastic effects, which exert pulling forces on trapped oil droplets, and by diverting subsequent fluid injection into lower-permeability zones (Lake et al., 2014).

Surfactant Flooding: Surfactants lower the interfacial tension between trapped oil and water, reducing the capillary forces holding oil in the pore spaces, thereby releasing trapped droplets (Sheng, 2011).

Alkaline–Surfactant–Polymer (ASP) Flooding: A synergistic method in which alkali reacts with naturally occurring naphthenic acids in the crude oil to generate petroleum soaps. These soaps act as in-situ co-surfactants, working alongside injected surfactants to achieve ultra-low IFT, whilst polymers maintain mobility control (Lake et al., 2014).

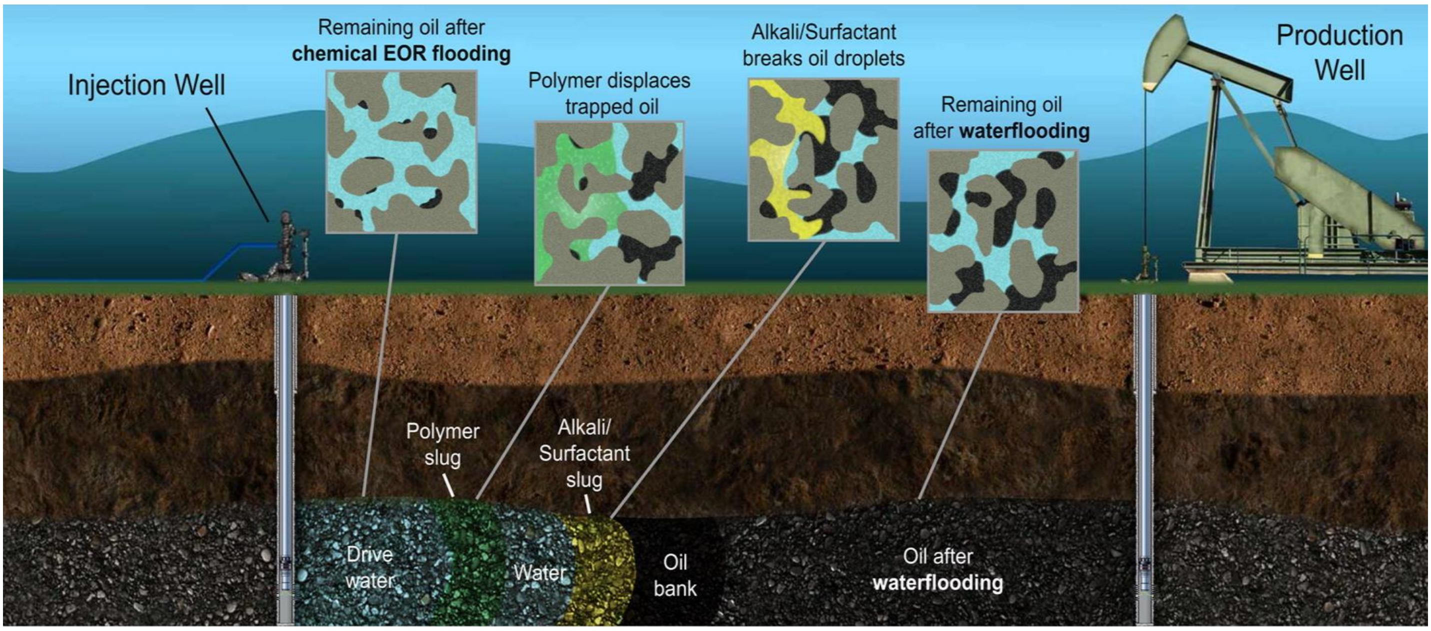

Figure 3.2: Illustration of Chemical EOR method (P. Druetta et al., 2019)

Thermal EOR Methods

Thermal methods introduce heat into the reservoir to reduce the viscosity of highly viscous crude oils (Green & Willhite, 2018). Common techniques include Continuous Steam Injection, Cyclic Steam Stimulation (CSS), Steam-Assisted Gravity Drainage (SAGD), and In-Situ Combustion (Green & Willhite, 2018). Heat breaks the complex molecular bonds of heavy crudes, transforming thick oil into a free-flowing fluid (Sheng, 2011). Whilst highly effective for heavy oils, thermal methods require massive energy inputs to generate steam, resulting in significant greenhouse gas footprints (Green & Willhite, 2018).

Consequently, thermal methods are fundamentally unsuited for typical Niger Delta operations (Olalekan & Olafuyi, 2021; Isehunwa & Oyeneyin, 2019). Because Nigerian reservoirs host light-to-medium sweet crudes rather than heavy tar sands, there is no physical justification for steam injection (Olalekan & Olafuyi, 2021).

Microbial EOR (MEOR) Methods

Microbial EOR is an emerging tertiary technique that introduces or stimulates indigenous subsurface microorganisms within the reservoir. These microbes metabolise nutrients to produce in-situ biopolymers, biosurfactants, biomethanol, and organic acids. These biological by-products actively lower IFT, improve sweep efficiency, and alter rock wettability, presenting a low-cost, environmentally friendly alternative to traditional chemical methods (Agi et al., 2020).

Applicability and Screening for Niger Delta Reservoirs

Implementing EOR in Nigeria's brownfields requires strict technical screening, as the geology and fluid properties of the Niger Delta dictate which methods can succeed (Olalekan & Olafuyi, 2021). The Niger Delta basin is characterised by thick, Tertiary-age Agbada Formation sandstones, which are typically unconsolidated or poorly consolidated, high-permeability, and highly compartmentalised by syn-depositional faults (Olalekan & Olafuyi, 2021; Isehunwa & Oyeneyin, 2019).

Technical Evaluation of Gas Injection

Miscible gas injection presents the highest immediate technical feasibility for Nigerian brownfields (Isehunwa & Oyeneyin, 2019). The light, low-viscosity nature of Nigerian crude blends such as Bonny Light, which typically exhibits a benchmark API gravity of 32.9° to 36° ensures that miscibility can be achieved at realistic reservoir conditions (Olalekan & Olafuyi, 2021). For typical Niger Delta targets, the Minimum Miscibility Pressure (MMP) for CO_2 injection ranges between 2,200 psi and 3,500 psi depending on reservoir temperature and fluid composition, which is safely below initial fracturing pressures (Isehunwa & Oyeneyin, 2019).

To control the high mobility of gas and prevent early gas breakthrough in the highly permeable Agbada sands, field applications favour Water-Alternating-Gas (WAG) injection. WAG alternates slugs of water and gas to provide stable displacement fronts and improve both vertical and areal sweep efficiency (Isehunwa & Oyeneyin, 2019). Furthermore, CO_2-WAG injection offers carbon capture benefits; however, claims of permanent sequestration must be heavily qualified. Long-term trapping in the Niger Delta remains highly contingent upon cap rock seal integrity, strict injection pressure management, and long-term monitoring to prevent leakage through the basin's extensive network of syn-depositional growth faults (Adeniyi & Utome, 2023).

Technical Evaluation of Chemical EOR

Chemical EOR holds strong potential for the Niger Delta due to high rock permeabilities, which allow chemical slugs to propagate easily through the sandstone matrix without causing severe plugging (Olalekan & Olafuyi, 2021; Agi et al., 2020). However, harsh subsurface conditions present significant hurdles:

Thermal Degradation: Many standard synthetic polymers break down at temperatures exceeding 80°C, which is common in deep Niger Delta targets (Agi et al., 2020).

Salinity and Adsorption: High-salinity formation waters can render standard surfactants ineffective, causing them to precipitate or adsorb onto sandstone grain surfaces instead of reducing oil–water IFT (Olalekan & Olafuyi, 2021; Agi et al., 2020).

Low-Impact and Sustainable EOR Technologies

Chemical EOR with Green Formulations

EOR chemicals, particularly polymers, surfactants and Alkalines, improve sweep efficiency and reduce interfacial tension (IFT) between oil and water. However, traditional synthetic polymers like Hydrolyzed Polyacrylamide (HPAM) often suffer from degradation in high salinity, high temperature reservoir conditions in Niger Delta, thereby leading to poor performance and potential environmental persistence (Gbadamosi et al., 2019).

Polymer injection is one of the most cost-effective chemical EOR method for enhancing yield, as it increases the viscosity of the injected water and improves oil recovery (Said et al., 2021). Green formulations address these limitations through organic and renewable alternatives. Biopolymers such as xanthan gum, guar gum and schizophyllan enhance viscosity with better shear stability, biodegradability and high resistance to salinity and temperature. These have shown promising mobility control in laboratory studies while reducing toxicity compared to synthetics (Kamal, 2025).

Likewise, biosurfactants (e.g., rhamnolipids, sophorolipids, and those from sugarcane bagasse or microbial sources) effectively lower IFT to ultra-low values (<0.01 mN/m) and alter wettability with minimal adsorption on rock surfaces. They are usually produced from feedstocks or agricultural waste, supporting the economy principles and local content development in Nigeria (Purwasena et al., 2024; Sarafzadeh et al., 2026; Shaikhah et al., 2024).

Also, the use of eco-friendly surfactants have also demonstrated valuable results. Nafisifar et al. (2021) successfully synthesized a novel anionic surfactant using linseeds (called PELS), a natural raw material for application EOR processes. The synthesis was validated through Fourier Transform Infrared (FT-IR), Nuclear Magnetic Resonance (NMR) and Thermogravimetric Analysis (TGA), confirming both the accuracy of the synthesis and thermal stability (up to 300ºC) of the surfactant.

In Alkaline Surfactant Polymer (ASP) systems, combining green surfactants and polymers with alkali (or low-concentration alternatives) has demonstrated incremental recoveries of 15–25% OOIP in core floods, with reduced chemical consumption and relatively easier produced water treatment due to higher biodegradability (Al-Jaber et al., 2025; Al-Ghamdi et al., 2022). For brownfields, these formulations mitigate challenges like polymer degradation and surfactant loss, while lowering the risk of groundwater contamination. Pilot-scale deployment could leverage local sourcing of biomaterials, enhancing economic viability and compliance with PIA local content requirements.

Carbon dioxide (CO_2) EOR and CCUS Integration

This method leverage eco-friendly gas technology to improve recovery efficiency and overall productivity in oil extraction processes. It utilizes green and clean technologies to reduce the negative impact to the environment

CO_2 EOR involves injecting carbon dioxide to swell oil, reduce viscosity, and improve displacement efficiency. It is particularly suited for light-to-medium crude, which is found in many Niger Delta reservoirs. When integrated with Carbon Capture, Utilization, and Storage (CCUS), it transforms EOR into a net-carbon-reducing process. The Niger Delta offers substantial potential, with the 2025 Nigerian CO_2 Storage Atlas estimating over 10.7 Gt of prospective storage capacity, primarily in depleted fields and saline aquifers (IFC, 2025; Umar et al., 2020).

Consequentially, when miscible or near-miscible CO_2 injection are often combined with Water Alternating Gas (WAG), it can yield 8–20% incremental recovery while sequestering 0.3–0.6 tonnes of CO_2 per barrel of oil produced (Núñez-López et al., 2019). This integration supports Nigeria's dual goals of reserves growth and decarbonization, turning brownfields into carbon sinks while extending field life.

Hybrid and Digital Technologies (AI/ML Optimization)

Hybrid EOR combines multiple mechanisms (e.g., chemical plus gas, smart water plus nanoparticles, or microbial with chemical) in order to overcome limitations of using a single method, which can be integrated in Nigeria based on the type of reservoir. Examples include Nano-fluids for IFT reduction and wettability alteration, or solar-powered injection systems to lower the carbon intensity of operations (Maleki et al., 2025; Hosseinifard et al., 2025).

Also, digital technologies, such as Artificial Intelligence (AI) and Machine Learning (ML), are transformative for optimization. ML models excel in history matching, predicting EOR performance, optimizing injection strategies (e.g., slug sizes, WAG ratios), and uncertainty quantification in heterogeneous reservoirs. Techniques such as Random Forest, XGBoost, and physics-informed neural networks (PINNs) have achieved high accuracy ($R^2 > 0.99$) in forecasting oil recovery and CO_2 sequestration (Mepaiyeda et al., 2025; Zhuang et al., 2025).

Ultimately, AI enables real-time decision-making, predictive maintenance of injection facilities, and co-optimization of oil recovery with carbon storage. This reduces operational costs, chemical usage, and environmental risks by minimizing trial-and-error in field implementation. For Nigerian operators, adopting these tools bridges the gap between limited data and complex reservoir dynamics, accelerating sustainable reserves growth (Lal, 2021)

Table 4.1: Benefits and Limitations of the Sustainable EOR Technologies.

Sustainable EOR Technologies	Benefits	Limitations
Chemical and Green Formulations	I. Yields significant incremental recovery (typically 5-20% OOIP) in suitable reservoirs. II. Customizable to specific reservoir conditions (e.g. salinity, temperature)	I. High upfront chemical costs II. Performance variability challenges
CO_2 EOR and CCUS	I. Proven incremental recovery (5-20% OOIP) (IEA, 2019) II. It supports climate goals while generating revenue from additional oil.	I. High capital and operational expenditures, for capture, compression, etc. II. Potential risks in leakage, if containment fails.
Hybrid and AI Optimization	I. AI enables faster screening, data driven optimization and uncertainty reduction. II. It reduces ambiguity by adapting more than one method.	I. Increased design complexities II. Upfront investments in technology and integration hurdles.

Sources: DOE, 2021; Gbadamosi et al., 2022; Ghorbanpour et al., 2025; IEA 2019; kamel et al., 2025; Omefe et al., 2025.

Alignment with Nigeria's Energy Transition Goals

Nigeria's Energy Transition Plan (ETP) targets net-zero emissions by 2060 while expanding energy access and sustaining oil and gas revenues during the transition (Federal Republic of Nigeria, 2022). Sustainable EOR directly supports this by enabling low-carbon oil production, utilizing captured CO_2, and reducing flaring through gas management. CCUS-EOR projects can generate carbon credits, improve project economics, and create jobs in a just transition framework.

By prioritizing green EOR in brownfields, Nigeria can extend the life of mature assets responsibly, align with NDCs, and position itself as a regional CCUS hub in Africa. This balanced approach ensures energy security and environmental stewardship, contributing meaningfully to both reserves growth and climate objectives (Dioha, 2022; Ekpotu et al., 2024).

EOR Pilots and Local Capabilities in Nigerian Brownfields

Review of EOR Pilots in Nigerian Brownfields

Nigeria's brownfield landscape, dominated by mature onshore and shallow-offshore assets across the Niger Delta, presents a compelling, if challenging, context for enhanced oil recovery (EOR) pilots. These fields, many of which have been producing since the 1950s and 1960s under operators such as Shell Petroleum Development Company (SPDC), TotalEnergies, and the Nigerian Agip Oil Company (NAOC), have experienced sustained production decline averaging 5–15% per annum in recent years. Primary and secondary recovery methods have, in many cases, reached their operational ceiling, leaving significant residual oil in place (ROIP) that only targeted tertiary recovery techniques can mobilise (Akpabio et al., 2021).

Several EOR pilot programmes have been initiated in this environment, with water flooding remaining the most widely deployed method due to its relative cost-effectiveness and operational familiarity. The Forcados Yorki field and segments of the Bonny Oil Field have seen water injection programmes that extended plateau production, though reservoir heterogeneity and sand management challenges frequently limited sweep efficiency (Nwachukwu & Okeke, 2020). More advanced chemical EOR pilots, involving polymer flooding and surfactant-polymer combinations, have been trialled in selected reservoirs where the oil viscosity and wettability profile were deemed amenable. Results from these pilots suggest incremental recovery factors of 8–15% beyond secondary recovery, though operational complexities, particularly chemical degradation under high-temperature, high-salinity reservoir conditions, have constrained scalability (Adeyemi et al., 2022).

Gas injection, particularly miscible gas EOR using associated natural gas (ANG), has also been explored, most notably in deep Niger Delta reservoirs where reservoir pressure and crude composition favour miscibility. The Nigerian National Petroleum Company Limited (NNPCL) has flagged gas re-injection pilots as a priority not only for EOR purposes but also as a mechanism to curtail gas flaring, a persistent environmental liability. Initial reservoir simulation studies from joint venture assets indicated potential recovery improvements of 12–22% in reservoirs with favourable API gravity profiles (Okafor et al., 2023). However, full-field deployment has been hampered by inadequate gas-handling infrastructure and the longstanding challenge of gas monetization economics.

Thermally-based EOR methods, including cyclic steam stimulation and steam-assisted gravity drainage (SAGD), remain largely experimental in the Nigerian context. Heavy oil deposits in certain onshore Niger Delta localities present a theoretical basis for steam injection, yet the high water requirement, energy intensity, and associated surface footprint create significant environmental and logistical barriers in a region where land access, community relations, and water resource stewardship are already fraught issues (Obiechina & Ihejirika, 2021). Microbial EOR (MEOR) has attracted academic interest as a potentially low-cost and environmentally benign technique, with laboratory-scale studies from the University of Port Harcourt and Covenant University demonstrating indigenous microbial consortia capable of biosurfactant production and interfacial tension reduction; yet field-scale validation remains absent (Eze & Nwosu, 2022).

Despite the technical promise demonstrated by various pilot projects, a major challenge remains the limited availability of publicly accessible performance data. Much of the operational knowledge generated from EOR pilots is retained within international oil companies and joint venture partnerships, with only a small proportion appearing in peer-reviewed literature. This restricts knowledge transfer to indigenous operators and hinders the development of locally calibrated reservoir models for future EOR applications. As asset ownership increasingly shifts from international operators to Nigerian companies, access to such knowledge will become even more important for informed investment and technology selection (Adeyemi et al., 2022; Okafor et al., 2023).

Overall, EOR pilot projects in Nigerian brownfields have demonstrated technical feasibility across several recovery mechanisms. However, progress from pilot testing to full-scale implementation remains constrained by infrastructure deficiencies, operational complexity, environmental considerations, and limited dissemination of knowledge. Addressing these issues is essential if EOR is to become a significant contributor to Nigeria's future oil production strategy.

Role of Local Capabilities and PIA Compliance

The enactment of the Petroleum Industry Act (PIA) 2021 marked a significant shift in Nigeria's approach to petroleum sector governance. The Act introduced new fiscal, environmental, and institutional frameworks that directly influence the planning and implementation of EOR projects in brownfields. Beyond regulatory compliance, the PIA provides an opportunity to strengthen indigenous participation and develop the technical capabilities required to sustain long-term EOR deployment (Federal Republic of Nigeria, 2021). Building upon the Nigerian Oil and Gas Industry Content Development Act (NOGICDA) 2010, the legislation encourages greater utilisation of Nigerian expertise, services, and materials throughout the project lifecycle. For EOR projects, this means operators are expected to engage Nigerian engineering firms, support local procurement where feasible, and incorporate knowledge-transfer programmes into technical service agreements.

The Nigerian Content Development and Monitoring Board (NCDMB) has intensified efforts to ensure compliance with these requirements. Reservoir simulation studies, chemical evaluation programmes, pilot project design, and other specialised technical activities increasingly require the participation of certified Nigerian service providers (NCDMB, 2022). These requirements are particularly relevant as indigenous companies such as Seplat Energy, Aiteo Eastern E&P, and Renaissance Africa Energy continue to acquire mature assets previously operated by international oil companies. Although these acquisitions have expanded indigenous participation in upstream operations, they have also exposed significant capability gaps. Many local operators possess extensive experience in conventional production and secondary recovery techniques but have limited exposure to advanced EOR technologies. Expertise in areas such as chemical formulation design, injectant compatibility analysis, and advanced reservoir simulation remains relatively scarce. Addressing these deficiencies will require sustained investment in workforce development, specialised training programmes, industry-academic partnerships, and technology transfer initiatives (Nwachukwu & Okeke, 2020).

Environmental compliance constitutes another important aspect of EOR implementation under the PIA. The Act requires operators to prepare Environmental Management Plans (EMPs) that include baseline environmental assessments, risk management strategies, spill response procedures, and community impact mitigation measures. For chemical EOR projects, compliance extends to the evaluation of chemical toxicity, produced-water treatment requirements, and waste management systems. Gas injection projects must also demonstrate consistency with national gas-flaring reduction targets and broader climate commitments under Nigeria's Nationally Determined Contributions (NDCs) (Federal Republic of Nigeria, 2021; NUPRC, 2023).

The establishment of the Nigeria Upstream Petroleum Regulatory Commission (NUPRC) has further strengthened regulatory oversight. Operators proposing EOR projects are now required to submit detailed technical studies, production forecasts, economic evaluations, and environmental assessments as part of field development plan amendments. While these requirements improve project quality and accountability, they also increase compliance costs and may present challenges for smaller indigenous operators with limited technical and regulatory resources.

Ultimately, the successful implementation of EOR in Nigerian brownfields depends on the interaction between technical capability and regulatory compliance. The PIA provides a framework for achieving this balance by promoting local participation, strengthening environmental governance, and encouraging more rigorous project evaluation. Its long-term effectiveness, however, will depend on consistent enforcement and continued investment in indigenous technical capacity.

Challenges and Recommendations for Sustainable Recovery

Technical, Economic, and Regulatory Challenges

The implementation of Enhanced Oil Recovery (EOR) in Nigerian brownfields faces a combination of technical, economic, and regulatory challenges that collectively limit project viability. Although EOR offers a pathway to increase recovery from mature reservoirs, these constraints continue to impede large-scale deployment.

Technical Challenges

One of the most significant technical obstacles is the geological complexity of the Niger Delta reservoirs. Many brownfields are characterised by fault compartmentalisation, reservoir heterogeneity, and variations in rock and fluid properties over short distances. Such conditions complicate reservoir characterisation and reduce the accuracy of reservoir simulation models used to design and optimise EOR projects. Consequently, achieving uniform injectant distribution and effective sweep efficiency remains difficult in many fields (Adeyemi et al., 2022).

The effectiveness of chemical EOR is further constrained by reservoir conditions. High temperatures and salinity levels common in several Niger Delta reservoirs accelerate the degradation of polymers and surfactants, reducing their performance and increasing operational costs. These conditions often require specialised chemical formulations that may not be readily available or economically viable for widespread application. Infrastructure limitations represent another major barrier. Many Nigerian brownfields rely on ageing production facilities, deteriorated pipelines, and obsolete injection systems that were not designed for advanced recovery operations, thereby prompting further optimization.

Economic Challenges

The economics of EOR projects remain challenging, particularly for indigenous operators managing mature assets. EOR implementation typically requires substantial investment in injectants, facility upgrades, well interventions, reservoir monitoring systems, and specialised technical expertise. Depending on the recovery method employed, incremental recovery costs may range between $20 and $60 per barrel, creating significant financial exposure for operators (Okafor et al., 2023).

Access to long-term financing remains limited. Many indigenous companies face debt obligations inherited through asset acquisitions and operate in a financial environment where lenders increasingly consider environmental, social, and governance (ESG) risks when evaluating hydrocarbon projects. These conditions make it difficult to secure affordable financing for projects with extended payback periods. Oil price volatility further complicates investment decisions.

Regulatory Challenges

Although the Petroleum Industry Act (PIA) has improved the regulatory environment, several challenges remain. The transition from the former Department of Petroleum Resources (DPR) to the Nigeria Upstream Petroleum Regulatory Commission (NUPRC) has been accompanied by implementation challenges, including capacity constraints and evolving regulatory procedures. Operators often face delays associated with approvals, licensing requirements, and compliance reviews.

Another limitation is the absence of dedicated fiscal incentives for EOR projects. Unlike some petroleum-producing countries that provide tax credits or other incentives for tertiary recovery activities, Nigeria currently offers limited mechanisms specifically designed to encourage EOR investment. As a result, operators must bear significant technical and financial risks without corresponding fiscal support (Akpabio et al., 2021).

Practical Recommendations for Sustainable Recovery

Overcoming the barriers to EOR implementation requires an integrated approach that balances production optimisation with environmental responsibility, economic viability, and social sustainability. The following recommendations are proposed to support long-term recovery from Nigeria's brownfields.

Technical and Operational Measures

A priority should be the development of a standardised EOR screening framework tailored to the Niger Delta reservoirs. Such a framework should incorporate local geological and fluid characteristics, lessons from previous pilot projects, and probabilistic reservoir modelling to improve technology selection and reduce investment uncertainty. The ongoing collaboration between NNPCL and NUPRC provides an appropriate platform for developing and implementing such a framework (NUPRC, 2023).

Gas reinjection should receive particular attention because it can improve oil recovery while reducing gas flaring. In reservoirs where pressure and fluid properties support miscible displacement, gas injection can enhance both production and environmental performance. Incorporating gas re-injection feasibility assessments into field development planning would encourage wider adoption of this approach and support national emissions-reduction objectives. Before implementing any EOR programme, operators should undertake comprehensive brownfield readiness assessments. These evaluations should examine well integrity, injection facilities, pipeline conditions, and produced-water handling systems to ensure that existing infrastructure can safely support enhanced recovery operations. Where deficiencies are identified, rehabilitation should be completed before project deployment. Such an approach would reduce environmental risks and improve project reliability. Investment in monitoring and data acquisition technologies is equally important. Improved reservoir surveillance systems, digital field technologies, and advanced modelling tools can enhance operational decision-making, increase recovery efficiency, and reduce uncertainty throughout the project lifecycle.

Fiscal and Investment Measures

Government support will be critical in improving EOR economics. The introduction of targeted fiscal incentives, such as investment tax credits, accelerated capital allowances, or royalty adjustments for approved EOR projects, could significantly improve project attractiveness. Such measures have successfully stimulated tertiary recovery investments in other mature petroleum-producing regions and could encourage broader adoption in Nigeria (Okafor et al., 2023). Access to financing should also be strengthened through partnerships with development finance institutions such as the Africa Finance Corporation (AFC) and the African Development Bank (AfDB). These institutions can provide long-term financing, technical assistance, and risk-sharing mechanisms that improve project bankability. Their involvement would be particularly valuable for indigenous operators seeking to implement technically demanding EOR projects while meeting environmental and social performance standards.

Governance and Community Measures

Regulatory efficiency should be improved through greater coordination among relevant agencies. Establishing a streamlined approval process or a single regulatory coordination platform for brownfield EOR projects would reduce administrative delays while maintaining environmental oversight. Clearer regulatory procedures would improve investment predictability and encourage private-sector participation. Community engagement must also become a central component of EOR project planning and implementation. Host communities should be involved from the early stages of project development through consultation, environmental monitoring, and benefit-sharing arrangements. Transparent communication regarding project objectives, environmental safeguards, and expected benefits can strengthen trust and reduce the likelihood of operational disruptions.

Finally, sustained investment in local capacity development is essential. Industry operators, regulators, and academic institutions should collaborate to establish specialised training programmes focused on reservoir engineering, EOR technologies, environmental management, and project economics. Developing a strong domestic knowledge base will reduce dependence on foreign expertise and support the long-term sustainability of Nigeria's brownfield recovery efforts.

In summary, sustainable EOR deployment in Nigerian brownfields requires coordinated action across technical, financial, regulatory, and social dimensions. By strengthening infrastructure, improving investment conditions, enhancing regulatory efficiency, and building local expertise, Nigeria can maximise recovery from mature fields while minimising environmental impacts and supporting broader national development objectives.

CONCLUSION

Nigeria's mature brownfields represent a critical strategic opportunity to sustain national hydrocarbon production while advancing environmental stewardship during the energy transition. While these assets hold substantial remaining oil in place (ROIP), conventional recovery methods fall short of maximizing recovery and continue to cause gas flaring, produced-water management issues, and severe ecosystem degradation across the Niger Delta.

This study demonstrates that low-impact Enhanced Oil Recovery (EOR) technologies, such as green chemical formulations, CO_2-EOR integrated with Carbon Capture, Utilization, and Storage (CCUS), hybrid systems, and AI-driven optimization, can unlock these vital reserves responsibly. These sustainable methods increase recovery efficiency while drastically reducing carbon emissions, chemical toxicity, and operational waste. However, transitioning from successful laboratory and pilot scales to full commercial deployment remains hindered by reservoir complexity, aging infrastructure, financial barriers, regulatory gaps, and a shortage of local technical expertise. The Petroleum Industry Act (PIA) of 2021 provides a robust framework to navigate these challenges by enforcing stricter environmental governance, promoting local content development, and elevating project evaluation standards.

Ultimately, achieving sustainable asset management requires an integrated approach that merges technological innovation with regulatory compliance and capacity building. Strategic investments in advanced reservoir characterization, digital tools, gas-handling infrastructure, local research, and workforce development are essential. By embedding sustainability directly into reservoir management decisions, Nigeria can secure its energy future, extend field longevity, and meet its national climate and energy transition goals, thereby transforming declining assets into models of responsible resource development.

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