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Techno-Economic Evaluation of CO_2 and N_2 Injection as Enhanced Oil Recovery Strategies for Oil Reservoirs. A Case Study of a Niger Delta Reservoir

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***Abstract*—** *This research presents a critical techno-economic evaluation of carbon dioxide (CO_2) and nitrogen (N_2) injection as enhanced oil recovery (EOR) strategies in a Niger Delta reservoir. Using Schlumberger's PIPESIM Production System Modeling software, reservoir inflow performance, wellbore hydraulics, and surface network behavior were integrated to assess injectivity, pressure response, and economic feasibility. Phase envelope analysis confirmed that CO_2 reaches a supercritical state at approximately 1,070 psia and 88 °F, enabling miscibility with crude oil, reducing viscosity, and improving displacement efficiency. However, this advantage is accompanied by operational challenges including corrosion risks, hydrate formation, and the need for strict thermodynamic control. N_2, with a critical point at 492 psia and –232 °F, remains a single-phase gas under reservoir conditions, simplifying operations and reducing flow assurance risks, though its immiscible nature limits displacement efficiency. Nodal analysis revealed higher injectivity for CO_2 (2,114 STB/day at 4,677 psia) compared to N_2 (1,652 STB/day at 3,441 psia), but also highlighted potential risks of formation fracturing at elevated pressures. Economic evaluation using a discounted cash flow (DCF) model produced negative Net Present Values (NPVs) for both injectants: –\$9.3 million for CO_2 and –\$5.5 million for N_2, driven largely by compression and operating costs. Beyond technical and economic outcomes, the research situates EOR within sustainability frameworks. CO_2 injection supports the Circular Carbon Economy (CCE) and contributes to SDG 13 (Climate Action) through carbon sequestration, while N_2 aligns with SDG 12 (Responsible Consumption and Production) by extending reservoir life with minimal environmental impact. The findings underscore the need for reservoir-specific strategies that balance recovery efficiency, cost, and sustainability objectives.*

***Keywords*—** *Enhanced Oil Recovery (EOR), Carbon Dioxide (CO_2) Injection, Nitrogen (N_2) Injection, Techno-Economic Evaluation, Circular Carbon Economy (CCE).*

I. INTRODUCTION

In oil reservoirs, a significant proportion of oil often 30–50% of the original oil in place (OOIP) remains unrecovered in reservoirs after conventional methods such as natural depletion and water flooding. These traditional approaches are limited by declining reservoir pressure, heterogeneity, and restricted permeability, which reduce efficiency and leave hydrocarbons trapped. To address these challenges, Enhanced Oil Recovery (EOR) techniques have been developed to maximize extraction, with gas injection using carbon dioxide (CO_2) or nitrogen (N_2) has emerged as one of the most promising strategies.

Gas injection utilizes the physical and chemical properties of gases to improve displacement and sweep efficiency, unlike traditional recovery methods that rely solely on reservoir energy or water flooding. Among the gases studied, carbon dioxide (CO_2) and nitrogen (N_2) have attracted significant attention. CO_2 injection is recognized for its miscibility with crude oil, which reduces viscosity and enhances mobility, while also contributing to carbon sequestration objectives.[1] Despite these benefits, CO_2 projects are often hindered by high costs, infrastructure demands, and operational risks such as corrosion and leakage [2].

N_2 injection presents a different dynamic, although immiscible and generally less effective in displacing oil compared to CO_2, N_2 can maintain reservoir pressure and mobilize hydrocarbons under certain conditions. Its inert nature and operational simplicity make it attractive where CO_2 is unavailable or economically impractical [3]. Furthermore, N_2 injection has been considered a less greenhouse gas-intensive option, providing a more sustainable alternative in specific contexts [4].

Although CO_2 has been shown to increase recovery factors by 5–15% beyond primary and secondary methods [5], the comparative performance of N_2 across different reservoir conditions remains less well understood. Recent studies emphasize the importance of reservoir-specific evaluations that balance technical efficiency, economic feasibility, and environmental responsibility [6], [7].

The evolution of Enhanced Oil Recovery (EOR) techniques particularly gas injection using carbon dioxide (CO_2) and nitrogen (N_2) has gained significant traction in recent decades. CO_2 injection, in particular, has been extensively studied for its ability to enhance oil recovery through its high solubility in crude oil. This solubility reduces oil viscosity and improves mobility, making CO_2 especially effective in complex or depleted reservoirs where conventional methods often fall short [1]. Studies have shown that CO_2 EOR can improve recovery factors by 5% to 15% beyond what is achieved through primary and secondary recovery processes [5].

In contrast, N_2 injection introduces a different mechanism. Although generally less efficient than CO_2 in terms of overall recovery, N_2 can help maintain reservoir pressure and mobilize oil due to its inert, non-hydrocarbon nature [3]. Its operational appeal lies in its availability and simplicity, particularly in scenarios where CO_2 is either economically unfeasible or logistically inaccessible. Moreover, N_2 injection has been recognized for its potential to reduce greenhouse gas emissions, offering a more environmentally sustainable option in specific applications [8].

Despite the extensive research on CO_2 injection, comparative studies that evaluate both gases under varying reservoir conditions remain limited. While CO_2 has demonstrated clear advantages in miscible flooding, recent findings suggest that reservoir-specific factors such as pressure, temperature, permeability, and oil composition can significantly influence the performance of each gas [6]. This underscores the need for a more tailored approach to EOR design, rather than relying on generalized assumptions.

Environmental considerations have also become increasingly relevant in evaluating EOR strategies. As the energy sector shifts toward sustainability, the ecological impact of gas injection particularly CO_2 sequestration and the long-term behavior of injected gases has come under greater scrutiny. Balancing environmental responsibility with economic feasibility is now a central concern in EOR planning [9].

II. METHODOLOGY

A. Research Design

The research adopts Schlumberger's PIPESIM Production System Modeling software as the primary simulation tool to evaluate the performance of CO_2 and N_2 injection in a Niger Delta reservoir. The software enabled the integration of reservoir inflow dynamics, wellbore hydraulics, and surface network behavior, enabling a comprehensive analysis of injectivity, pressure response, and flow assurance.

B. Simulation of CO_2 and N_2 Injection Scenarios

Two simulation sets were executed:

1. CO_2 Injection Scenario
2. N_2 Injection Scenario

Each scenario was applied to a common reservoir framework, encompassing a range of reservoir types including depleted, over pressured, and tight oil systems. Key variables such as injection pressure, reservoir permeability, gas composition, and temperature were systematically varied to assess their influence on recovery performance.

C. Evaluation of Comparative Recovery Efficiency

Simulation outputs were analyzed to determine:

1. Incremental oil recovery (barrels/year)
2. Recovery factor under identical reservoir conditions
3. Pressure maintenance effectiveness
4. Gas breakthrough timing
5. Sweep efficiency

These metrics were analyzed to determine the relative performance of CO_2 and N_2 injection, with emphasis on identifying the optimal injectant for each reservoir condition.

D. Economic Evaluation

A techno-economic model was developed to assess the financial viability of both injection strategies. Key performance indicators included:

1. Net Present Value (NPV)
2. Internal Rate of Return (IRR)
3. Cost per incremental thousand cubic feet (Mcf) recovered
4. Payback period

The analysis incorporated differences in CAPEX and OPEX between CO_2 and N_2 injection, particularly the costs associated with gas procurement, compression, and handling. A Python-based automated Discounted Cash Flow (DCF) model was employed to enhance computational accuracy.

E. DCF Model Assumptions

The economic model was based on the following assumptions:

TABLE 1: Economic model assumptions for CO_2 and N_2 injection projects.

Parameter	CO_2 Injection	N_2 Injection
Initial CAPEX	\$15 million	\$8 million
Annual OPEX	\$2 million	\$1 million
Incremental oil production	5,000 barrels/year	3,500 barrels/year
Oil price	\$70/barrel	\$70/barrel
Project life	10 years	10 years
Discount rate	10%	10%
Carbon credit value (if applicable)	\$10/ton CO_2 stored	\$0
CO_2 stored per barrel of oil	0.2 tons/barrel	0

F. Revenue and Cash Flow Calculations

Annual revenues were computed using the following expressions:

Oil Revenue

Oil Revenue = Incremental Barrels × Oil Price

Carbon Credit Revenue

Carbon Credit = Incremental Barrels × CO_2 Stored per Barre × Credit Price

Total Annual Revenue

Total Revenue = Oil Revenue + CO_2 Credit price

Net Cash Flow per Year

Net Cash Flow = Total Revenue × Annual OPEX

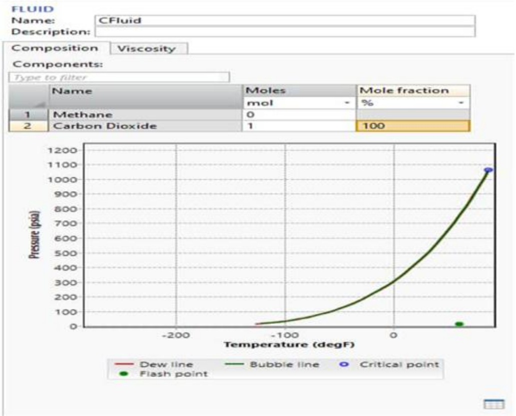
2.7 Net Present Value (NPV) Calculation

$$NPV = -CAPEX + \sum_{t=1}^{T} \frac{Net\ Cash\ Flow}{(1+r)^t}$$

T = Project life (10 years)

r = Discount rate (10%)

III. RESULT AND DISCUSSION



FLUID

Name: CFluid

Description:

Composition | Viscosity

Components:

	Name	Moles mol	Mole fraction %
1	Methane	0	
2	Carbon Dioxide	1	100

Fig. 1. CO_2 Injection Phase Envelope

A. CO_2 Thermodynamic Characterization

Figure 1 illustrates the phase envelope for pure CO_2 injection. Methane was excluded to simplify the system into a single-component fluid, consistent with sequestration and EOR studies [2].

In the P-T phase diagram, the bubble line (blue curve) represents the onset of vaporization at constant pressure, while the dew line (red curve) marks the beginning of condensation. The critical point (blue dot) is located at approximately 1,070 psia and 88 °F (31.1 °C), as reported by [10]. Below this point lies the two-phase region, while conditions above the dome represent single-phase states.

Operating above the critical threshold ensures CO_2 remains in its supercritical state, exhibiting gas like diffusivity and liquid-like density properties that enhance reservoir penetration and sweep efficiency [11]. However, the steep curvature of the bubble and dew lines in the subcritical region highlights CO_2's sensitivity to pressure and temperature fluctuations, which can lead to hydrate formation, slugging, or injectivity loss if not properly managed [12].

Pipeline transport and surface storage must avoid the two-phase region to prevent corrosion and flow assurance problems [13]. Thus, maintaining injection conditions firmly within the supercritical domain is essential for operational stability and equipment integrity.

B. Nodal Analysis of CO_2 Injection

Figure 2 presents the inflow and outflow curves for the CO_2 injection scenario. The inflow curve (blue) represents reservoir acceptance of injected CO_2, while the outflow curve (red) reflects surface system hydraulics.

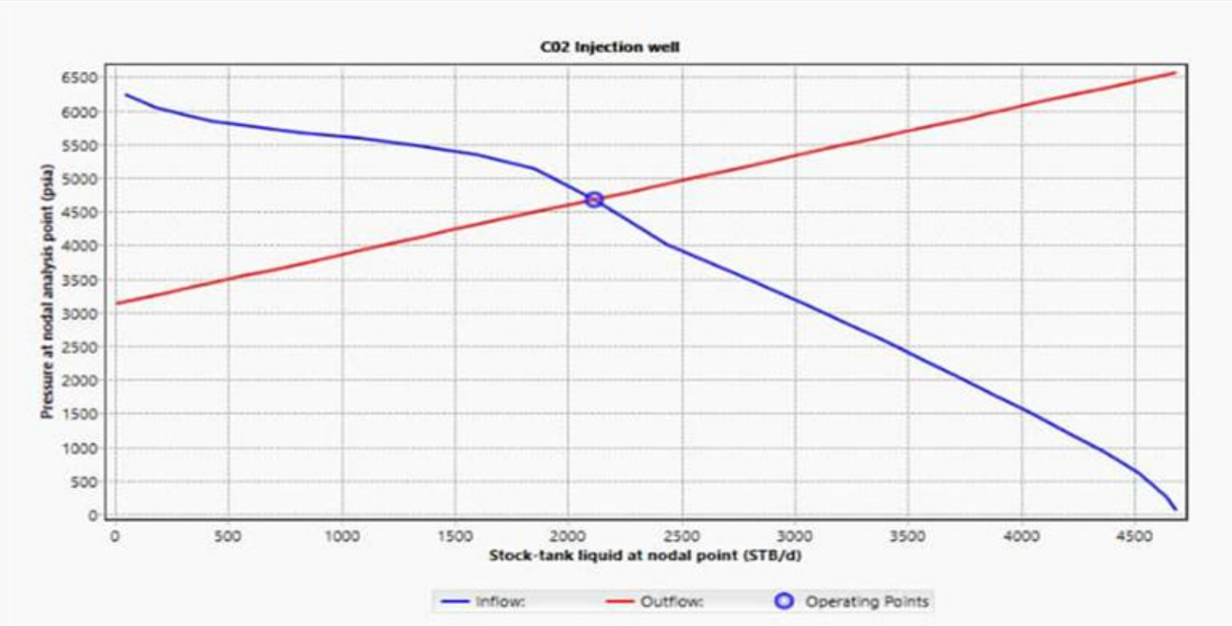


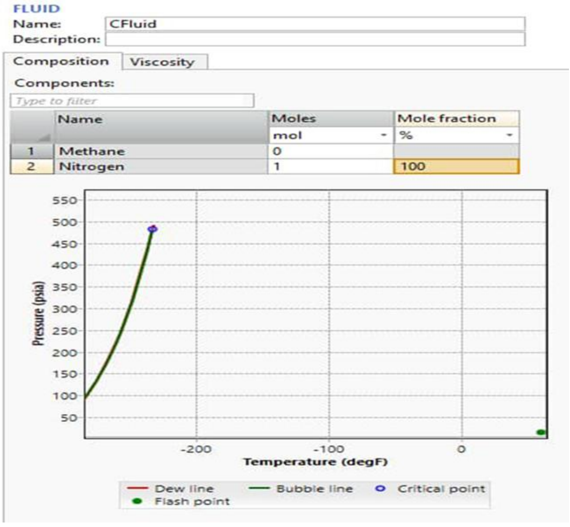
Fig. 2: Inflow and outflow curve for CO_2 injection Scenario

At the operating point (blue circle), equilibrium is achieved at approximately 2,114 STB/day and 4,677 psia. This indicates stable injection performance. However, the inflow curve declines sharply below 2,000 STB/day, suggesting injectivity constraints typical of tight or pressure-sensitive formations [14].

The linear rise of the outflow curve reflects frictional losses in tubing and wellbore [15]. While the system can sustain injection at the operating point, further increases risk exceeding formation parting pressures, potentially causing fracturing [2]. Long-term monitoring is therefore critical, as supercritical CO_2 compressibility and interactions with residual fluids may alter injectivity over time [11].

C. N_2 Thermodynamic Characterization

Figure 3 shows the phase envelope for pure N_2 injection. The critical point is located at 492 psia and –232 °F, far below typical reservoir conditions [16]. Consequently, nitrogen remains in the gas phase during injection, eliminating risks of condensation or hydrate formation [2].


FLUID
Name: CFluid
Description:

Components:

	Name	Moles mol	Mole fraction %
1	Methane	0	
2	Nitrogen	1	100

Fig. 3. N_2 Injection Phase Envelope

The narrow dome indicates minimal two-phase behavior, simplifying pipeline transport and surface facility design. Unlike CO_2, N_2 requires less separation equipment and incurs lower compression costs due to its light molecular weight [17]. Its inert nature further reduces chemical reactivity risks, making it suitable for pressure maintenance and gas-cap expansion [12].

D. Nodal Analysis of N_2 Injection

Figure 4 presents the nodal analysis for N_2 injection. The operating point occurs at 1,652 STB/day and 3,441 psia, where inflow and outflow curves intersect This intersection illustrates steady injection conditions since it shows the only scenario in which inflow equals outflow [15].

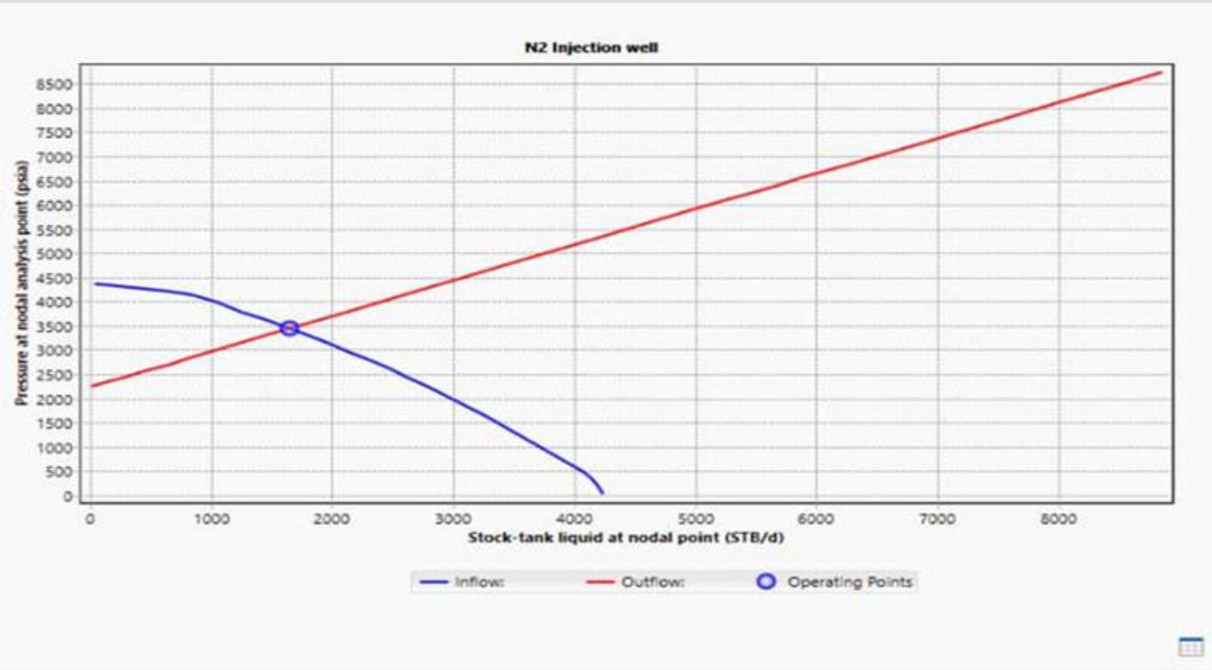


Fig. 4: Inflow and Outflow Curve for N_2 Injection Scenario

The Vertical Lift Performance (VLP) curve rises steeply with increasing flowrate, reflecting higher frictional losses due to N_2's compressibility [14]. Meanwhile, the Inflow Performance Relationship (IPR) curve declines steadily, indicating restricted injectivity and potential non-Darcy flow behavior at higher rates [18]. Although stable at the operating point, scalability is limited. Any increase in injection rate would demand significantly higher pressures, potentially exceeding compressor capacity or tubular ratings. Thus, N_2 injection is constrained by surface system limitations rather than reservoir acceptance [19].

E. CO_2 vs. N_2 Phase Behavior & Injection Performance

TABLE 2: summarizes the comparative performance of CO_2 and N_2 injection.

Criteria	CO_2 (Carbon Dioxide)	N_2 (Nitrogen)
Critical Point	1,070 psia and 88 °F (Span & Wagner, 1996)	492 psia and –232 °F [16]
Typical Reservoir Phase	Supercritical	Gas phase
Phase Envelope Shape	Wide dome; large two-phase region	Narrow dome; negligible two-phase region
Phase Stability Risk	High hydrate/corrosion risks [13]	Very low inert, dry gas behavior
Injectivity (Nodal Analysis)	2,114 STB/day at 4,677 psia	1,652 STB/day at 3,441 psia
Inflow Curve Behavior	Strong initial injectivity; sharp decline [14]	Steady decline; non-Darcy flow [18]
Outflow Curve Behavior	Linear increase dense fluid friction losses	Steep increase high compressibility losses
System Limitation	Reservoir injectivity at high rates	Surface compression/tubular capacity
Surface Design Complexity	High corrosion-resistant materials needed [20]	Low simpler compression systems [17]
Scalability Risk	High risk of fracturing [2]	Moderate compressor/tubular constraints
Suitability for EOR	Excellent miscible flooding, CCS potential	Moderate pressure maintenance, gas-lift
Chemical Reactivity	Reactive corrosive under wet conditions	Inert chemically stable
Long-Term Monitoring Need	Essential injectivity evolves with time	Minimal stable phase behavior

F. Economic Comparison

The economic evaluation was conducted using the Discounted Cash Flow (DCF) model.

TABLE 3: Calculated Annual Revenues

	CO_2 Injection	N_2 Injection
Oil Revenue ($/year)	5,000 × 70 = $350,000	3,500 × 70 = $245,000
CO_2 Stored (tons/year)	5,000 × 0.2 = 1,000	0
Carbon Credit Revenue ($/yr)	1,000 × 10 = $10,000	0
Total Annual Revenue	$360,000	$245,000

Table 4: Calculated Annual Net Cash Flow

Parameter	CO_2 Injection	N_2 Injection

Revenue	\$360,000	\$245,000
OPEX	\$2,000,000	\$1,000,000
Net Cash Flow (Yearly)	\$360,000 – \$2,000,000 = –\$1,640,000	\$245,000 – \$1,000,000 = –\$755,000

Results:
CO_2 Injection NPV = –\$9.3 million
N_2 Injection NPV = –\$5.5 million

The result shows that both projects show negative NPV under these simplified assumptions, meaning costs exceed direct incremental revenue from oil plus carbon credits. CO_2 injection has a larger upfront investment and operating cost, leading to a more negative NPV despite higher oil recovery and carbon credits. N_2 injection has lower costs but also lower revenue potential, so it shows a less negative NPV.

G. Sustainability and Circular Economy Implications

The evaluation of CO_2 and N_2 injection extends beyond technical and economic considerations into the broader framework of sustainability and the circular economy. As the energy industry transitions toward low-carbon systems, reservoirs are increasingly viewed not only as sources of hydrocarbons but also as potential sites for waste storage and carbon management. This dual role situates Enhanced Oil Recovery (EOR) within the concept of a closed-loop energy system, where production and environmental stewardship are integrated.

By examining CO_2 and N_2 injection through this lens, the research highlights how mature reservoirs in the Niger Delta can evolve into assets that simultaneously support energy security and contribute to climate action. CO_2 injection, in particular, offers the opportunity to align recovery operations with carbon sequestration, while N_2 provides a pathway for extending reservoir life with minimal environmental risk.

H. The Circular Carbon Economy (CCE)

The Circular Carbon Economy (CCE) framework emphasizes the reduction, reuse, recycling, and removal of carbon emissions. CO_2 injection directly supports this model by enabling carbon capture, utilization, and storage (CCUS). In practice, CO_2 injected into reservoirs not only enhances oil recovery through miscible displacement but also serves as a permanent storage mechanism, thereby reducing atmospheric emissions [11].

This dual functionality situates CO_2 injection as a cornerstone of the CCE, transforming reservoirs into carbon sinks while maintaining their role in energy production. Such integration is particularly relevant for Nigeria, where balancing hydrocarbon dependence with climate commitments is critical. By embedding CO_2 injection within the CCE, the Niger Delta can contribute to global climate goals while sustaining economic activity.

I. Sustainable Asset Management

Nitrogen injection, though lacking sequestration benefits, aligns with Sustainable Development Goal 12 (Responsible Consumption and Production) by extending the productive life of existing reservoirs. Its inert nature reduces flow assurance risks, corrosion, and chemical reactivity, thereby minimizing environmental impact. N_2 injection represents a pragmatic approach to sustainable asset management, ensuring that mature fields continue to deliver value without the need for extensive new infrastructure.

By maintaining reservoir pressure and supporting incremental recovery, N_2 injection exemplifies responsible resource utilization. It allows operators to maximize output from existing assets while avoiding premature abandonment, thereby reducing the environmental footprint associated with new field development. In this way, N_2 injection contributes to sustainable production practices, complementing CO_2's role in climate mitigation.

IV. CONCLUSION

This research has undertaken a detailed techno-economic evaluation of carbon dioxide (CO_2) and nitrogen (N_2) injection in a Niger Delta reservoir, integrating phase behavior analysis, nodal performance assessment, and discounted cash flow modeling. The results demonstrate that while both gases can enhance recovery, their technical behavior, economic feasibility, and sustainability implications differ significantly.

From a technical standpoint, CO_2 injection offers superior recovery potential due to its miscibility and supercritical properties, achieving higher injectivity and improved sweep efficiency. However, this advantage is tempered by operational challenges such as corrosion, hydrate formation, and the risk of fracturing at elevated pressures. N_2 injection, though immiscible and less efficient in displacement, provides operational simplicity, inert chemical behavior, and stable single-phase performance under reservoir conditions.

Economically, both injection strategies yielded negative Net Present Values (NPVs), with CO_2 at –\$9.3 million and N_2 at –\$5.5 million. These results were driven primarily by compression and operating costs, which outweighed incremental revenues from oil production and, in the case of CO_2, carbon credits. While CO_2 projects demand higher capital and operational expenditure, N_2 injection presents a comparatively lower financial burden, making it more pragmatic in cost-sensitive environments.

Sustainability considerations further distinguish the two approaches. CO_2 injection aligns with the Circular Carbon Economy (CCE) by enabling carbon capture, utilization, and storage (CCUS), thereby contributing to SDG 13 (Climate Action). N_2 injection, while lacking sequestration benefits, supports SDG 12 (Responsible Consumption and Production) by extending the productive life of mature reservoirs with minimal environmental risk. Together, these perspectives highlight the importance of situating EOR within the broader framework of the circular economy, where reservoirs serve dual roles in energy production and environmental stewardship.

Therefore, CO_2 injection remains the technically superior option for maximizing recovery and integrating carbon management, but its deployment requires robust infrastructure, careful operational control, and supportive policy frameworks. N_2 injection, although less efficient, offers a stable and cost-effective alternative for pressure maintenance in reservoirs where CO_2 supply chains are limited. Future research should explore hybrid CO_2–N_2 injection strategies, advanced monitoring technologies, and economic optimization models to enhance feasibility. By embedding EOR within sustainability goals, mature reservoirs in the Niger Delta can evolve into assets that simultaneously advance energy security and climate responsibility.

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