World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

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Low-Purity CO_2 utilization for sustainable enhanced oil recovery: A comparative assessment of CO_2-WAG and Carbonated Water Injection Techniques

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World Journal of Advanced Engineering Technology and Sciences, 2025, 15(03), 2404-2411

Publication history: Received on 10 April 2025; revised on 21 June 2025; accepted on 23 June 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.3.1166

Abstract

The sustainable exploitation of offshore hydrocarbon reserves requires innovative integration of carbon utilization technologies with enhanced oil recovery (EOR) processes. This study evaluates and compares the technical, economic, and environmental viability of two CO_2-based EOR techniques—Carbonated Water Injection (CWI) and Immiscible CO_2 Water Alternating Gas (WAG) injection—using low-purity CO_2 streams (20%, 50%, and 70%) sourced from flue gas on offshore Floating Production Storage and Offloading (FPSO) units. Leveraging Aspen HYSYS for surface facility modeling and CMG for reservoir and core-scale simulations, the Norne field E-Segment was used as a representative offshore case study. Simulation results demonstrate that oil recovery efficiency increases with higher CO_2 purity and injection rates for both EOR methods. CO_2-WAG achieved the highest recovery (58.2% of Original Oil in Place) under 70% CO_2 purity and optimal injection parameters, while CWI yielded the best economic outcome with a net present value (NPV) of $830 million under 50% CO_2 purity. Additionally, a novel hybrid method—Carbonated Water Alternating Gas (CWAG)—was introduced, outperforming both CWI and CO_2-WAG in preliminary trials with a recovery factor exceeding 70% OOIP. Environmental benefits were assessed using the Time-Adjusted Value of Carbon Sequestration (TVCS) framework, which revealed significant CO_2 sequestration potential across all scenarios. The CO_2-WAG scenario with highest recovery sequestered over 0.3 million tons of CO_2, providing measurable emissions reductions. This work offers a scalable framework for integrating carbon capture and reuse into offshore operations, advancing both energy efficiency and environmental responsibility. The findings position low-purity CO_2-based EOR not only as a viable recovery method but also as a transitional technology supporting decarbonized offshore oil production in alignment with global sustainability goals.

Keywords: Low-Purity CO_2 Utilization; Offshore Oil Production; Membrane-Based CO_2 Separation; Floating Production Storage and Offloading; Carbon Sequestration; Enhanced Oil Recovery

1. Introduction

The global energy landscape is undergoing a significant transformation driven by the dual imperatives of increasing energy demand and urgent climate mitigation. As renewable energy sources grow, hydrocarbons remain indispensable for meeting base-load energy and industrial feedstock needs. Therefore, maximizing oil recovery from existing reservoirs using low-carbon technologies has become a priority in aligning fossil energy production with sustainability goals. Among these technologies, carbon dioxide (CO_2)-based enhanced oil recovery (EOR) stands out for its potential to increase oil recovery while simultaneously sequestering anthropogenic CO_2, turning a liability into a strategic asset (IEA, 2022; Bhattarai et al., 2020). Offshore production facilities, particularly Floating Production Storage and Offloading (FPSO) units, present a unique opportunity to integrate carbon capture, utilization, and storage (CCUS) into

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operational frameworks. CO_2-rich flue gases are routinely emitted onboard FPSOs from power generation turbines, and these emissions often remain underutilized despite their potential value in EOR (Yan et al., 2021). The isolation and logistical complexity of offshore platforms make transportation of high-purity CO_2 impractical and uneconomical. As such, harnessing low-purity CO_2 directly from onboard flue gas streams for reinjection represents a promising avenue for carbon utilization and sustainable hydrocarbon recovery (Ho et al., 2018; Hu et al., 2023).

Traditionally, EOR operations involving CO_2, such as Water Alternating Gas (WAG) injection, have relied on high-purity CO_2 to achieve miscibility with oil, thereby enhancing recovery. However, miscible CO_2-EOR is often infeasible offshore due to the cost and infrastructure required to source and purify CO_2 to the levels needed. Consequently, immiscible CO_2-WAG and Carbonated Water Injection (CWI) have emerged as viable alternatives that operate effectively with lower CO_2 purities. Immiscible CO_2-WAG combines gas and water injection in slugs to control gas mobility and improve sweep efficiency, while CWI involves dissolving CO_2 in brine before injection, improving oil recovery via viscosity reduction, oil swelling, and interfacial tension (IFT) reduction (Sohrabi et al., 2017; Al-Shalabi & Sepehrnoori, 2018). Recent advancements in membrane-based separation technologies have made it possible to achieve modular, energy-efficient CO_2 capture offshore without the need for extensive infrastructure. Membranes such as Na-ZSM-5 have demonstrated strong CO_2/N_2 selectivity and are well suited to offshore modularization due to their compact design and low energy footprint (Datta & Sen, 2023; Bernal et al., 2020). These systems can enrich flue gases to usable CO_2 purities (20–70%), which, while below traditional miscibility thresholds, are sufficient for immiscible WAG and CWI applications, especially when paired with smart injection strategies and hybrid methods.

Despite the potential of low-purity CO_2-based EOR methods, limited studies have comprehensively evaluated their technical viability, economic performance, and environmental benefits, particularly in offshore reservoirs where space, energy, and CO_2 supply are constrained. This research addresses that gap through a comparative investigation of CO_2-WAG and CWI, utilizing simulated injection streams of varying purities (20%, 50%, and 70%) derived from FPSO flue gas processing. The study uses the Norne field E-Segment, a well-characterized North Sea reservoir, as a representative offshore system to simulate reservoir response. Surface facilities were modeled using Aspen HYSYS to design and optimize CO_2 capture and injection systems, while CMG simulations were employed for reservoir and core-scale analysis.

A novel aspect of this study is the introduction of Carbonated Water Alternating Gas (CWAG) injection, a hybrid technique that combines the benefits of both CO_2-WAG and CWI. Preliminary results from CMG simulations indicate that CWAG may outperform standalone methods in terms of oil recovery and CO_2 sequestration, offering a new pathway for offshore EOR innovation. Furthermore, this work integrates an extended environmental assessment based on the Time-Adjusted Value of Carbon Sequestration (TVCS) framework, accounting for lifecycle emissions, carbon retention timelines, and sequestration durability (Bankes & Brennan, 2021). This study is motivated by the urgent need to reduce the carbon intensity of offshore oil production, a sector often overlooked in the broader CCUS discourse. By reimagining flue gas as a feedstock rather than a waste stream, and evaluating EOR methods that are compatible with impure CO_2, we present a blueprint for aligning offshore oil production with long-term decarbonization targets. The findings contribute to the advancement of carbon-integrated energy systems—a critical bridge technology in the transition toward net-zero energy portfolios.

In summary, this work aims to provide an in-depth comparison of CWI and CO_2-WAG under realistic offshore conditions using impure CO_2 streams, assess the economic viability of each method, evaluate carbon sequestration potential, and propose innovative hybrid strategies. The integration of carbon utilization, process simulation, and reservoir engineering offers a holistic framework for enhancing oil recovery while supporting global sustainability goals—an imperative well-aligned with the mission of Advanced Energy Conversion Materials.

2. Methodology

This study integrates process simulation, reservoir modeling, and experimental validation to evaluate the feasibility of utilizing low-purity CO_2 for Enhanced Oil Recovery (EOR) in offshore settings. The methodological framework is structured around four key components: (i) CO_2 capture and enrichment from FPSO flue gas; (ii) reservoir-scale EOR simulations; (iii) core-scale laboratory validation; and (iv) carbon sequestration and economic assessment.

2.1. CO_2 Enrichment and Surface Facility Design

Flue gas generated onboard the SeaRose FPSO was used as a source of low-purity CO_2. Aspen HYSYS was employed to simulate a compact CO_2 capture process optimized for offshore application. The process included:

- Dehydration using triethylene glycol (TEG) absorption to remove water vapor;
- Heat recovery integration via a Power Recovery Turbine (PRT) and steam regeneration to improve energy efficiency;
- Membrane separation using a Na-ZSM5-based two-stage configuration to enrich CO_2 content to 20%, 50%, and 70%.

The modularity, energy recovery, and minimal footprint of membrane-based separation systems made them suitable for offshore retrofitting and contributed to reducing operational emissions.

2.2. Injection Strategy and System Configuration

Injection strategies for both Carbonated Water Injection (CWI) and Immiscible CO_2 Water Alternating Gas (WAG) were designed to align with offshore injection constraints. Injection parameters—including gas purity, slug sizes (0.1–0.3 pore volumes), and flow rates—were based on availability from the surface facility model. For CWI, CO_2 was dissolved in brine under pressure in a surface mixing unit. For CO_2-WAG, alternating cycles of CO_2 and brine were modeled to maintain immiscibility while maximizing sweep efficiency. A hybrid method, Carbonated Water Alternating Gas (CWAG), was also conceptualized to combine the advantages of both techniques.

2.3. Reservoir Simulation and History Matching

Reservoir simulations were conducted using the Norne Field E-Segment as a representative offshore reservoir. The compositional reservoir model was developed in CMG GEM following conversion from Eclipse format. History matching ensured the model aligned with production data and reservoir characteristics. Simulations evaluated 27 CO_2-WAG cases and 9 CWI cases with varying CO_2 purities and injection volumes.

2.4. Core-Scale Experimental Validation

To validate simulation trends, core-scale experiments were performed using Berea sandstone cores and dead Hibernia crude oil. Laboratory-scale CO_2-WAG tests were carried out under room temperature and high-pressure conditions (1850 psia), using CO_2/N_2 mixtures (70%/30%) to replicate impure injection conditions. A brine-to-gas slug ratio of 1.6:1 was used, consistent with simulation inputs. Waterflooding and post-WAG oil recovery were measured and compared to simulation results for trend validation and parameter calibration.

2.5. Economic and Environmental Evaluation

Capital and operating costs were derived from Aspen HYSYS and vendor data for process equipment, utilities, and materials. Net Present Value (NPV) was calculated for each EOR scenario over a 7.5-year project life, considering oil prices, operational expenses, and CO_2 capture costs. Carbon sequestration was assessed using the Time-Adjusted Value of Carbon Sequestration (TVCS) framework. This lifecycle-based method accounts for full-cycle carbon emissions (FCCE), including indirect emissions from process energy, transportation, and fugitive CO_2 losses, enabling a comparative evaluation of the long-term environmental impact of each EOR method.

3. Results and Discussion

This section presents the comparative performance of Carbonated Water Injection (CWI), CO_2 Water Alternating Gas (CO_2-WAG), and a hybrid Carbonated Water Alternating Gas (CWAG) method under low-purity CO_2 scenarios. Evaluations include recovery efficiency, economic viability, and carbon sequestration potential, with figures illustrating key trends to support the adoption of sustainable, carbon-integrated EOR solutions.

3.1. Oil Recovery Performance at Reservoir Scale

Simulations of CWI and CO_2-WAG revealed that recovery efficiency improves with increasing CO_2 purity, injection rate, and slug size. Waterflooding, used as a baseline, achieved a final recovery factor of 42.2% of OOIP (Original Oil in Place).

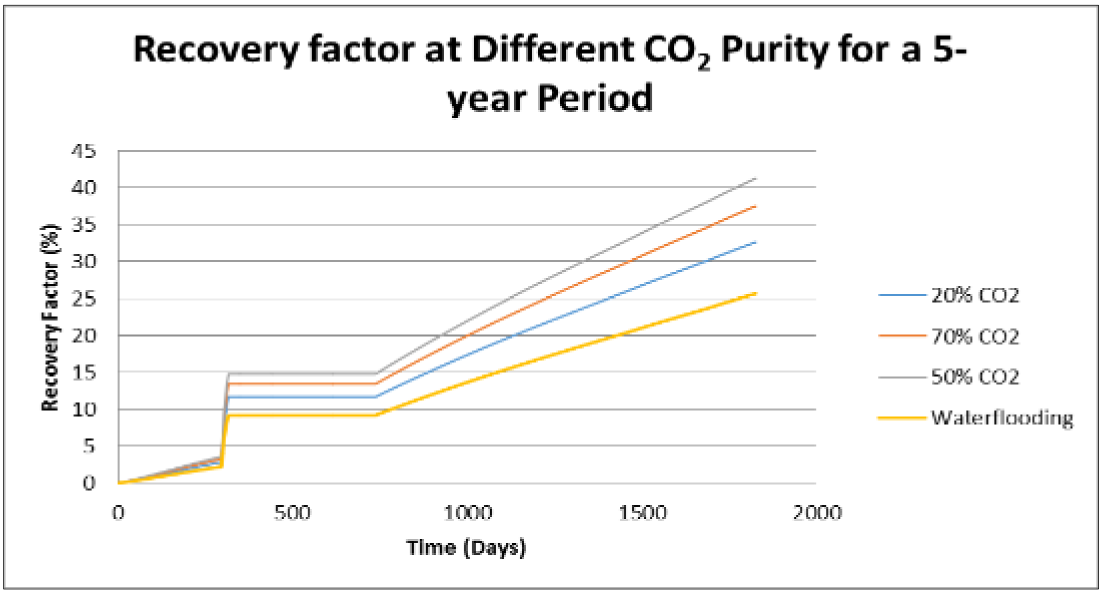

Figure 1 Oil Recovery vs. Time for CWI (5-Year Injection Period)

CWI showed incremental improvements as CO_2 purity increased from 20% to 70%, with a maximum recovery of 48.8% OOIP at 70% purity. The relatively small recovery gain beyond 50% purity highlights diminishing returns in solubility-limited systems.

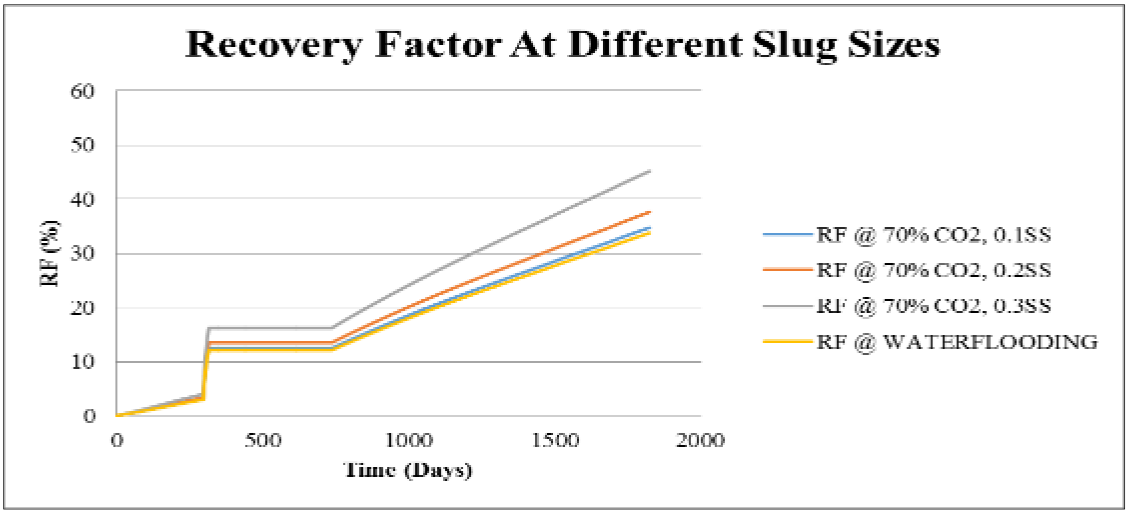

Figure 2 Oil Recovery with Varying Slug Sizes in CO_2-WAG (70% CO_2)

At fixed purity (70%), larger slug sizes significantly enhanced recovery. A 0.3 PV slug yielded a recovery of 58.2% OOIP—16% above waterflooding—due to improved macroscopic sweep and oil mobilization.

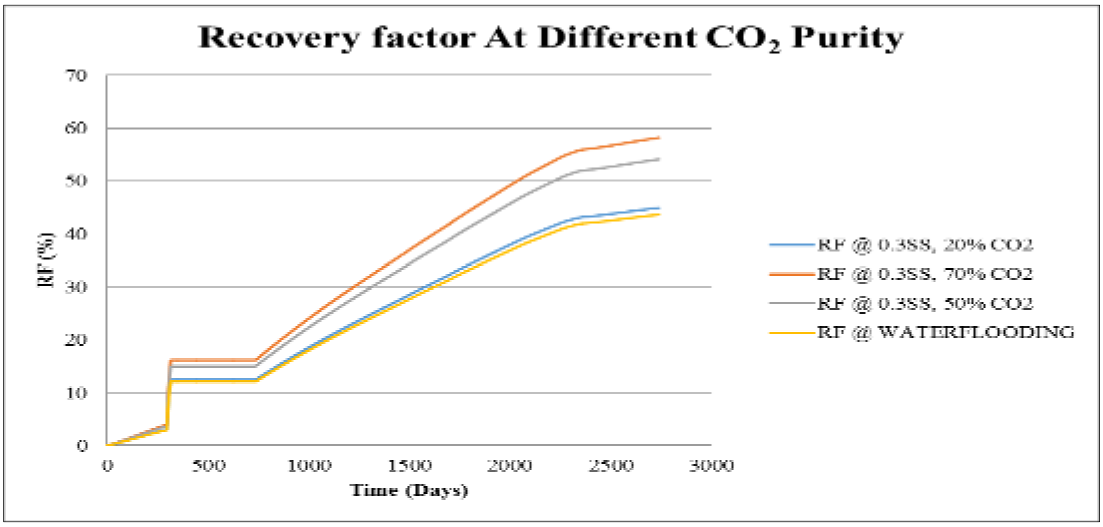

Figure 3 Recovery Sensitivity to CO_2 Purity in WAG

Recovery increased with CO_2 purity, but differences between 50% and 70% were modest (~3%). This suggests that 50% purity may represent an optimal tradeoff between process complexity and recovery efficiency.

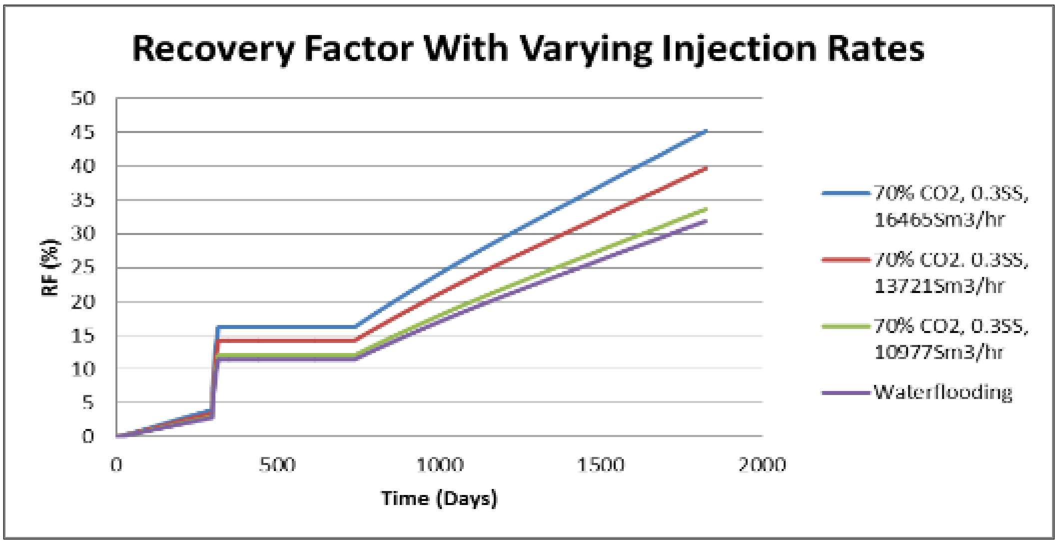

Figure 4 Recovery Variation with Injection Rate (WAG, 0.3 PV Slug)

Injection rate had a strong influence on performance. Higher rates increased reservoir pressure and contact efficiency, with the best result at 16,465 sm^3/hr.

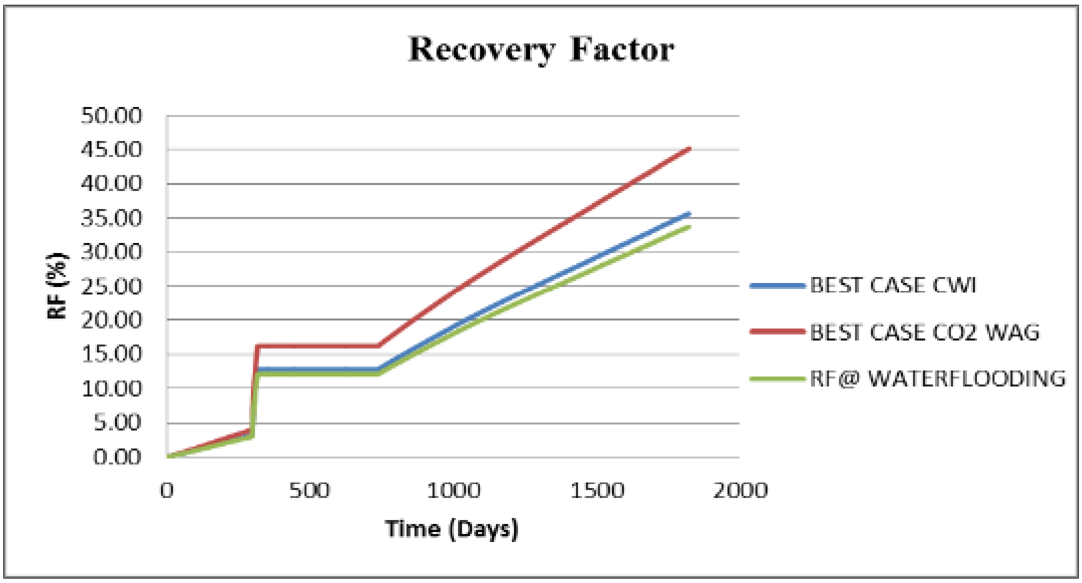

Figure 5 Overall Recovery Comparison – CWI vs. WAG vs. Waterflooding

WAG outperformed CWI in the base Norne model due to direct gas-oil contact and higher CO_2 volumes. CWI's advantage lies in ease of deployment and cost, particularly where direct gas injection is restricted.

3.2. Economic Performance

Economic assessment across 36 EOR scenarios identified CWI with 50% CO_2 purity and a 5,833 sm^3/hr injection rate as the most economically favorable, with a Net Present Value (NPV) of $830 million. CO_2-WAG's highest NPV case reached $530 million, reflecting higher capital expenditures due to gas compression and membrane separation.

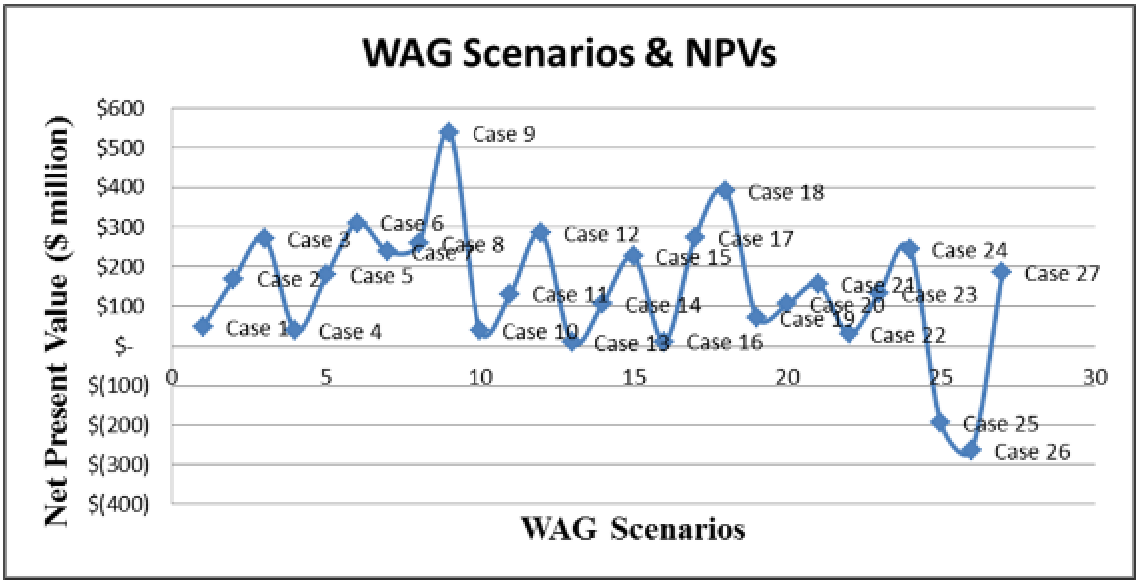

Figure 6 NPV for CO_2-WAG Scenarios

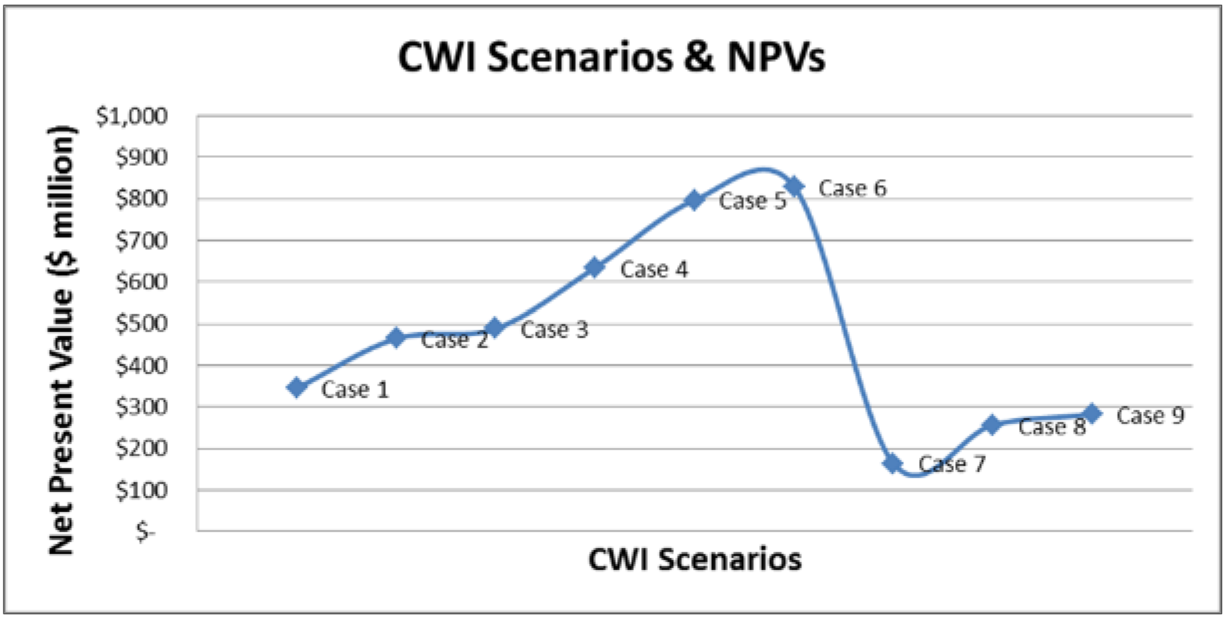

Figure 7 NPV for CWI Scenarios

3.3. CO_2 Sequestration and Environmental Impact

A key sustainability outcome was the quantification of CO_2 permanently stored in the reservoir. The best-performing CO_2-WAG scenario sequestered 0.308 million tonnes of CO_2 over 7.5 years, contributing to long-term emissions reduction.

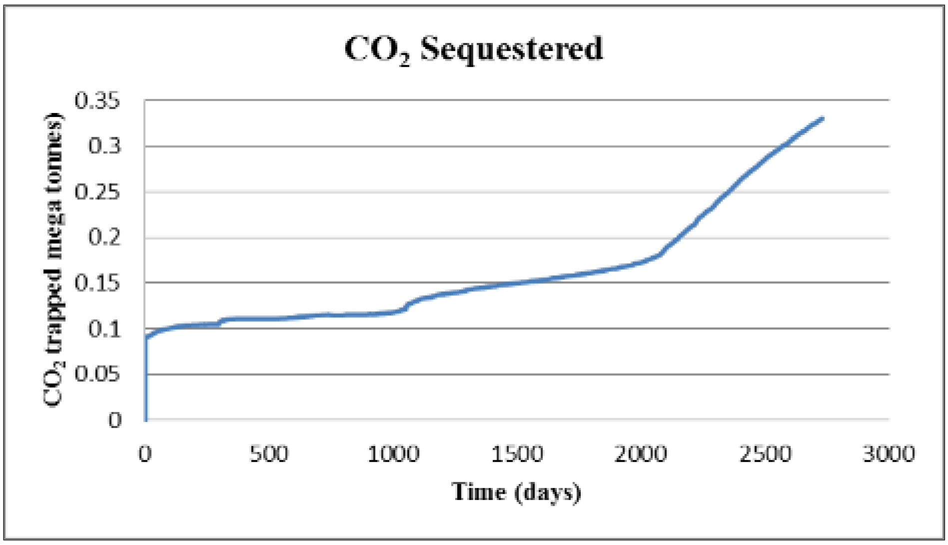

Figure 8 CO_2 Sequestered in Best-Case WAG Scenario

Environmental performance was further assessed using the Time-Adjusted Value of Carbon Sequestration (TVCS) and Full-Cycle Carbon Emissions (FCCE). These metrics capture the lifecycle benefits of using waste CO_2 for energy recovery and long-term geological storage—key considerations for offshore carbon management frameworks.

3.4. Implications for Energy Innovation and Sustainability

This study demonstrates that low-purity CO_2 streams, typically vented from FPSOs, can be re-engineered into a sustainable resource for offshore EOR. By leveraging modular membrane separation, energy recovery systems, and hybrid injection designs like CWAG, offshore operations can:

- Improve oil recovery beyond conventional methods,

- Sequester meaningful volumes of CO_2,
- Reduce full-cycle carbon emissions,
- Enhance return on investment with limited infrastructure.

4. Conclusion

This study presents a comprehensive assessment of low-purity CO_2 utilization in offshore Enhanced Oil Recovery (EOR), demonstrating how strategically engineered injection methods can convert flue gas emissions from FPSO units into valuable resources for both hydrocarbon recovery and long-term carbon storage. By comparing Carbonated Water Injection (CWI), Immiscible CO_2 Water Alternating Gas (WAG), and the hybrid Carbonated Water Alternating Gas (CWAG) method, the research offers an innovative framework for integrating energy production with carbon management in space- and resource-constrained offshore environments. Simulation results showed that CO_2-WAG, particularly at 70% CO_2 purity and optimal slug sizes, achieved the highest oil recovery (up to 58.2% OOIP), while CWI provided superior economic performance at mid-level CO_2 purities due to its simpler surface processing and injection requirements. The introduction of CWAG—combining the strengths of both techniques—resulted in the highest recovery performance (~71% OOIP), highlighting its potential as a next-generation EOR strategy.

Beyond oil recovery, this work quantifies the environmental value of CO_2 reuse. The best-performing WAG scenario sequestered over 0.3 million tonnes of CO_2, demonstrating that even sub-miscible, impure CO_2 streams can meaningfully contribute to decarbonization. Life cycle-based metrics, including the Time-Adjusted Value of Carbon Sequestration (TVCS), affirmed the broader climate benefits of reusing process emissions in offshore reservoirs. By integrating modular CO_2 capture (via membrane systems), energy recovery from flue gas treatment, and smart injection design, this research underscores the feasibility of circular carbon strategies within existing offshore infrastructure. The findings support the strategic shift from emissions disposal to emissions utilization—converting FPSOs from point sources of CO_2 into platforms for climate-aligned oil production.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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