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Comparative Evaluation of Enhanced Oil Recovery Technologies Using Experimental Data

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ABSTRACT

Enhanced oil recovery (EOR) technologies are used to recover residual oil that remains trapped after primary and secondary recovery processes. Conventional recovery methods often leave 60–70% of the original oil in place because of capillary trapping, unfavourable mobility ratios, reservoir heterogeneity, and poor sweep efficiency [1]. This research paper evaluates major EOR methods, including thermal, chemical, gas injection, nanofluid, microbial, hybrid, and artificial intelligence-assisted EOR, using secondary experimental and field data compiled from the attached review article. The study focuses on recovery mechanisms, experimental performance, reservoir suitability, and operational limitations. Results show that thermal EOR is most effective for heavy oil reservoirs, with steam-assisted gravity drainage achieving 70–80% oil recovery under suitable conditions. Chemical EOR improves mobility control and interfacial tension reduction, with polymer flooding typically adding 5–15% original oil in place and alkaline-surfactant-polymer systems reaching 15–30% incremental recovery. Gas injection, especially CO_2 flooding, offers both oil recovery and carbon management benefits, although early gas breakthrough remains a major limitation. Nanofluid and microbial EOR show strong laboratory potential but require further field validation. Hybrid EOR methods provide the highest overall potential because they combine several displacement mechanisms. The paper concludes that future EOR development should focus on reservoir-specific hybrid systems, environmentally benign chemicals, scalable nanofluids, and physics-informed artificial intelligence models.

Keywords: Enhanced oil recovery, Chemical flooding, Chemical Injection, Polymer, Surfactants

INTRODUCTION

The global energy system is transitioning toward cleaner technologies, but crude oil remains essential for transportation, petrochemicals, and industrial development. Because many mature oil fields still contain large volumes of unrecovered oil, improving recovery from existing reservoirs is economically and strategically important. Primary recovery usually produces only 5–30% of the original oil in place, while secondary recovery, mainly water flooding or immiscible gas injection, can add another 20–40% under favorable conditions [2].

Enhanced oil recovery refers to processes that introduce fluids, materials, biological agents, or external energy into the reservoir to alter rock-fluid properties and increase production. Unlike the older idea of “tertiary recovery,” modern EOR is defined by the mechanism of recovery rather than by the timing of application. Therefore, EOR may be applied after water flooding or earlier in the reservoir life if it modifies the reservoir-fluid system to improve production [3].

The major EOR mechanisms include viscosity reduction, interfacial tension reduction, wettability alteration, miscible displacement, and mobility control. Thermal methods mainly reduce oil viscosity, chemical methods reduce interfacial tension and improve mobility, gas injection promotes miscibility and oil swelling, nanofluids alter wettability and stabilize interfaces, microbial EOR produces biosurfactants and gases in situ, and hybrid methods combine several of these effects [4].

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Research Aim and Objectives

The aim of this research paper is to evaluate the performance of major EOR technologies using experimental and field data reported in the attached review article.

The specific objectives are to compare the recovery mechanisms of different EOR methods, summarize experimental recovery data, analyze the advantages and limitations of each method, and identify which technologies show the strongest future potential for mature and complex reservoirs.

METHODOLOGY

This study uses a secondary-data research design. No new laboratory experiment was conducted. Instead, experimental, simulation, pilot, and field data were extracted from the attached review article, which synthesizes recent EOR literature on thermal, chemical, gas injection, nanofluid, microbial, hybrid, and AI-assisted recovery methods [5].

The data were organized according to EOR category, recovery mechanism, target reservoir condition, reported oil recovery, and major operational limitation. The comparison focuses on reported recovery as percentage of original oil in place, incremental recovery over water flooding, interfacial tension reduction, viscosity retention, minimum miscibility pressure, and wettability alteration where available.

Experimental Data

The attached article reports a wide range of experimental and field-scale results. Table 1 summarizes representative data used in this paper.

EOR method	Experimental or field condition	Reported result	Main mechanism
Steam flooding	Heavy oil reservoirs	50–60% OOIP recovery	Viscosity reduction
SAGD	Heavy oil and bitumen reservoirs	70–80% OOIP recovery	Thermal viscosity reduction and gravity drainage
In-situ combustion	Heavy oil reservoirs	40–50% OOIP recovery	Heat generation and oil upgrading
Polymer flooding	Sandstone reservoirs, moderate temperature	5–15% incremental OOIP	Mobility control
Surfactant flooding	Medium-light oil reservoirs	15–25% incremental OOIP	Interfacial tension reduction
Alkaline flooding / ASP	Sandstone and carbonate cases	15–30% incremental OOIP	In-situ soap generation, IFT reduction, mobility control
Miscible CO_2 flooding	Light and medium oil reservoirs above MMP	10–20% incremental OOIP	Miscible displacement and oil swelling
Nitrogen flooding	Deep, high-pressure reservoirs	5–12% incremental OOIP	Pressure maintenance and gas drive
Microbial EOR	Low-temperature reservoirs	5–15% incremental OOIP	Biosurfactant, gas, and biopolymer generation
Nanofluid EOR	Laboratory core-flooding studies	Variable; strong lab-scale improvement	Wettability alteration and IFT reduction

The article also reports specific experimental examples. TiO_2 nanoparticles shifted oil-wet sandstone toward more water-wet conditions and increased total oil recovery from 49% to 80% OOIP in a laboratory core-flooding study [6]. In polymer studies, scleroglucan retained more than 80% of its original viscosity after 90

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days at 90 °C and 100,000 mg/L total dissolved solids, indicating strong potential for high-temperature, high-salinity reservoirs [7]. In CO_2-EOR, adding 5% pentane reduced the minimum miscibility pressure from 18.04 MPa to 16.16 MPa and improved oil recovery by approximately 19.94% [8].

RESULTS AND DISCUSSION

Thermal EOR Performance

Thermal EOR is the most commercially mature option for heavy oil and bitumen reservoirs. Its main mechanism is viscosity reduction. Heavy oils can have viscosities above 10,000 cP, making them difficult to mobilize using conventional water flooding. Heating the reservoir lowers viscosity and improves oil mobility [9].

Steam flooding can recover approximately 50–60% OOIP, while SAGD can reach 70–80% OOIP in suitable reservoirs. SAGD is especially effective because steam heats the oil, and gravity drains the mobilized oil toward the production well. However, thermal EOR requires high energy input, large water volumes, and expensive surface facilities. It also produces greenhouse gas emissions from steam generation [10].

In-situ combustion provides another thermal pathway by burning part of the reservoir oil to generate heat underground. Reported recovery ranges from 40–50% OOIP, and some wet combustion and hybrid combustion studies report even higher recovery. However, combustion-front control, reservoir damage, and operational safety remain major challenges [13].

Chemical EOR Performance

Chemical EOR improves recovery mainly by reducing interfacial tension, altering wettability, and improving mobility control. Polymer flooding is one of the most widely used chemical methods because it increases injected water viscosity and reduces viscous fingering. Reported incremental recovery commonly ranges from 5–15% OOIP [12].

Polymer selection is highly dependent on reservoir temperature and salinity. HPAM is widely used in moderate conditions, but it degrades under high temperature and high salinity. More stable polymers such as sulfonated polyacrylamide and biopolymers such as scleroglucan are more suitable for harsh reservoirs. The reported viscosity retention of scleroglucan above 80% after 90 days at 90 °C and 100,000 mg/L salinity shows its value for high-temperature, high-salinity applications [7, 12].

Surfactant flooding reduces oil-water interfacial tension and mobilizes trapped residual oil. Reported incremental recovery ranges from 15–25% OOIP. However, surfactant adsorption, high cost, salinity sensitivity, and formulation complexity limit large-scale application. Alkaline-surfactant-polymer flooding combines alkali, surfactant, and polymer to reduce interfacial tension, generate in-situ soap, and improve sweep efficiency. ASP systems can recover 15–30% incremental OOIP and, in some reported cases, recover more than 90% of remaining oil after water flooding [3, 15].

Gas Injection EOR Performance

Gas injection EOR includes CO_2, nitrogen, and hydrocarbon gas injection. CO_2 flooding is especially important because it can increase oil recovery and support carbon storage objectives. CO_2 dissolves in crude oil, reduces viscosity, causes oil swelling, and can achieve miscibility above the minimum miscibility pressure [13].

Miscible CO_2 flooding typically provides 10–20% incremental OOIP. Under miscible conditions, interfacial tension between oil and gas can approach zero, allowing high microscopic displacement efficiency. However, field-scale recovery is limited by sweep efficiency, gas channeling, gravity override, and early CO_2 breakthrough [14].

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The article reports that adding pentane to CO_2 reduced minimum miscibility pressure from 18.04 MPa to 16.16 MPa and improved recovery by 19.94%. This shows that gas composition can strongly influence CO_2-EOR performance. Foam-assisted CO_2 injection and water-alternating-gas methods can improve sweep efficiency by reducing gas mobility, but foam stability and chemical cost remain limitations [14, 6].

Nitrogen injection is less expensive and widely available, but it requires higher pressure to achieve miscibility. It is more suitable for deep, high-pressure reservoirs. Hydrocarbon gas injection can be effective for light oil reservoirs because intermediate hydrocarbon components improve miscibility, but cost and gas availability may limit application [15, 7].

Nanofluid EOR Performance

Nanofluid EOR is an emerging technology that uses nanoparticles such as SiO_2, Al_2O_3, TiO_2, ZnO, MgO, and Fe_3O_4 to improve oil recovery. The main mechanisms include interfacial tension reduction, wettability alteration, emulsion stabilization, foam stabilization, and sometimes asphaltene control [2, 17].

The strongest reported laboratory example in the article is TiO_2 nanoparticle flooding, which increased recovery from 49% to 80% OOIP in an oil-wet sandstone core. This result was mainly attributed to wettability alteration from oil-wet toward water-wet conditions [4, 7].

Despite promising laboratory results, nanofluid EOR faces significant field-scale challenges. Nanoparticles can aggregate, adsorb onto pore surfaces, block pore throats, or lose stability in high-salinity brines. Their cost and long-term environmental behavior also require further evaluation before widespread deployment [13, 9].

Microbial EOR Performance

Microbial EOR uses microorganisms or microbial products to improve oil recovery. Microbes can generate biosurfactants, biopolymers, gases, acids, and solvents inside the reservoir. These products can reduce interfacial tension, alter wettability, increase pressure, and improve mobility control [12, 7].

Reported microbial EOR recovery commonly ranges from 5–15% incremental OOIP, although some laboratory and field studies report higher values under favorable conditions. MEOR is attractive because it can use low-cost nutrients and biodegradable microbial products. However, its performance is difficult to predict because microbial growth depends on reservoir temperature, salinity, pH, nutrient distribution, and competition with native microbial communities [16, 11].

Hybrid EOR Performance

Hybrid EOR methods combine multiple recovery mechanisms and therefore often outperform single-method approaches. Examples include ASP flooding, surfactant-polymer flooding, polymer-alternating-gas injection, surfactant-alternating-gas injection, and low-salinity polymer flooding [12, 10].

ASP flooding is one of the most effective hybrid chemical methods because alkali generates in-situ surfactant, surfactant reduces interfacial tension, and polymer improves mobility control. Polymer-alternating-gas combines gas miscibility with polymer mobility control, reducing gas channeling and improving sweep efficiency. Hybrid EOR methods can achieve 20–40% incremental recovery in favorable reservoirs, but they are more complex to design and operate [6, 15].

Role of Artificial Intelligence in EOR

Artificial intelligence and machine learning are increasingly used for EOR screening, performance prediction, minimum miscibility pressure estimation, injection optimization, and uncertainty analysis. The article reports that deep learning models have achieved up to 95% accuracy in EOR method selection, although validation accuracy may be lower and overfitting remains a concern [2, 12].

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AI models can reduce the time and cost of reservoir simulation by creating proxy models that estimate recovery performance under different injection scenarios. However, AI models depend heavily on high-quality data and may not generalize well outside their training conditions. Future AI-assisted EOR should focus on physics-informed models, explainable AI, uncertainty quantification, and validation against independent field data [3, 13].

KEY FINDINGS

The results show that each EOR method has a distinct operating window. Thermal EOR is most effective for heavy oil reservoirs, especially when oil viscosity is the main limitation. Chemical EOR is effective in reservoirs where mobility control and interfacial tension reduction are needed, but chemical stability and adsorption must be managed. Gas injection is highly effective in deep, light-to-medium oil reservoirs where miscibility can be achieved. Nanofluid EOR is promising for wettability alteration, especially in oil-wet carbonates and sandstones, but it remains field-limited. Microbial EOR is environmentally attractive but difficult to control. Hybrid EOR provides the best recovery potential because it combines complementary mechanisms.

The most important technical challenge across all methods is reservoir heterogeneity. Even if microscopic displacement efficiency is high, poor sweep efficiency can leave large volumes of oil uncontacted. Therefore, future EOR projects should not focus only on reducing residual oil saturation at the pore scale but should also improve macroscopic sweep efficiency through mobility control, conformance improvement, and reservoir-specific design.

CONCLUSION

Enhanced oil recovery remains essential for increasing production from mature and partially depleted oil fields. Based on the experimental and field data reviewed in the attached article, thermal EOR provides the highest recovery for heavy oil, chemical EOR improves sweep and displacement efficiency, gas injection offers both recovery and carbon-management benefits, and nanofluid and microbial EOR provide promising but still developing alternatives.

The most effective future direction is hybrid EOR, where multiple mechanisms are combined to address both microscopic trapping and macroscopic sweep limitations. ASP flooding, polymer-alternating-gas, surfactant-alternating-gas, and nanofluid-assisted chemical systems show strong potential because they integrate interfacial tension reduction, wettability alteration, miscible displacement, and mobility control.

However, the commercial success of EOR depends on reservoir-specific design, economic feasibility, environmental safety, and field-scale validation. Future research should focus on stable chemicals for high-temperature and high-salinity reservoirs, environmentally friendly surfactants and polymers, scalable nanofluids, improved CO_2-EOR/CCUS integration, and physics-informed AI models for real-time optimization. Overall, EOR will remain a critical technology for maximizing recovery from existing oil fields while supporting more efficient and sustainable reservoir management.

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