

Chapter

Innovation Technique for Enhanced Oil Recovery: Sustainable Approaches and Environmental Considerations

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Abstract

Enhance oil recovery development is under the intervention of rapid change in the increase of sustainability efforts and technological innovation. Data analytics and nanotechnology are being used to optimize enhanced oil recovery (EOR) processes, enhancing recovery efficiency and resource efficiency. Renewable energy sources, such as solar thermal, are being integrated into EOR operations, complementing global decarbonization efforts. The policy and regulatory support are also important for sustainable EOR, including water treatment and emission reductions. While innovation is ongoing, EOR could also bridge conventional fossil fuel production and clean energy sources.

Keywords: enhance, oil, recovery, sustainability, environmental

1. Introduction

Advanced extraction method applied to recover oil that cannot be retrieved through primary and secondary recovery processes, but tertiary recovery is called enhanced oil recovery (EOR) [1]. EOR has become a foundation of the global oil industry, driven by its capacity to meet rising energy demands in the face of reducing conventional resources. While traditional extraction methods leverage natural reservoir pressure and water injection to push oil to the surface, EOR techniques aim to maximize oil extraction by altering the properties of the reservoir fluid. Utilizing advanced recovery techniques, EOR can boost oil recovery rates by up to 30–60%, making it an essential tool for stabilizing supply in a competitive and fluctuating energy market [2].

The risks of natural ecosystems that are linked to standard EOR methods, which result in environmental impacts, such as elevated carbon emissions, increased water consumption, and the risk of chemical contamination, need consideration [3]. The noted challenges require sustainable and environmentally friendly methods that can balance a long-term oil recovery with long-term ecological stability. Low-carbon thermal recovery, biodegradable chemical injections, and renewable energy aim to minimize environmental impact and reduce greenhouse emission while maintaining

EOR extraction methods [4]. The development of minimizing environmental impact is important for also compliance, cost reduction, and feasibility of oil production [5]. This chapter examines recent advancements in enhanced oil recovery (EOR), focusing on sustainable methods and environmental factors crucial for reducing impact while addressing global energy requirements.

1.1 Background

Reducing oil viscosity and interfacial tension after primary and secondary recovery stages, while improving oil efficiency is what enhanced oil recovery (EOR) intends to achieve [6]. EOR research has developed over the years with advanced process that requires compliance standards due to population growth. Forty years ago, carbon dioxide EOR was developed to increase the percentage of oil that's within the reservoir [7]. Nonetheless, the 1950s witnessed notable developments in chemical injection and thermal recovery, establishing the groundwork for modern OER, aimed at maximizing recovery and managing declining production rates [8].

1.2 Fundamentals of enhanced oil recovery

The following summarizes the stages of oil production that lead to improved oil recovery [9]:

- a. Initial recovery: this is the first phase of oil production from a reservoir, during which natural processes such as drainage, water migration, gas expansion, and oil expansion push oil to the surface [10].
- b. Secondary recovery: recovers up to 40% of oil by employing surface and submerged pumps to mechanically lift fluids in the reservoir, as well as water injection, natural gas reinjection, and gas lift [10].
- c. Third recovery, also known as improved oil recovery, is a method of boosting production and field life by injecting CO₂ into exhausted oil or gas reservoirs. Accordingly, the recovery is increased to 30–60% [11].

When enhanced oil recovery (EOR) techniques are used to increase both the amount of oil recovered and the pace of recovery, two parts can be identified (**Figure 1**): both traditional and non-traditional [13].

1.3 Conventional

Conventional oil recovery involves natural flow, artificial lift, water floods, and pressure maintenance, as illustrated in **Figure 1** [12]. Traditional conventional oil recovery often utilizes well drilling in those fields where a gas drive mechanism pushes the oil into production wells. However, the problem of pressure depletion can easily arise much earlier in the life of such a reservoir. In order to delay this process, reservoir engineers generally reinject the produced gas to maintain pressure.

According to Geologist skills [14], when a strong water drive exists, water flooding is commonly used once oil production slows. The objective is to push the remaining oil into production wells. Dry gas injection is done into the same types of porous (**Figure 2**).

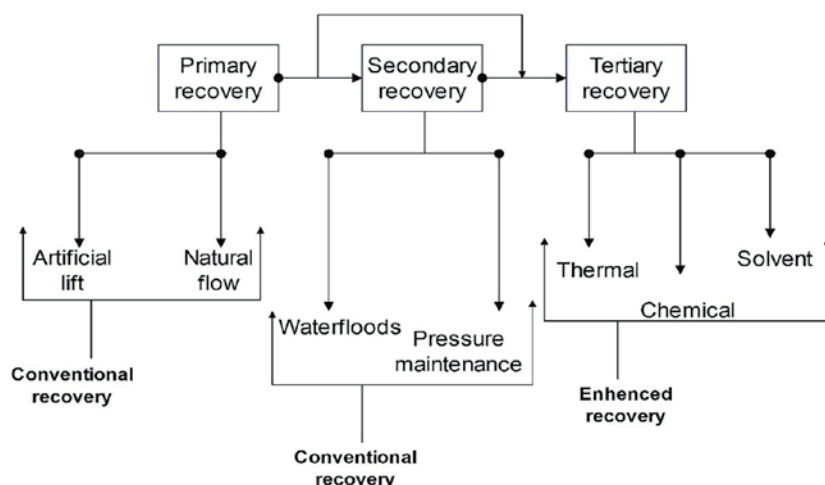


Figure 1.
 Fundamental of recovery [12].

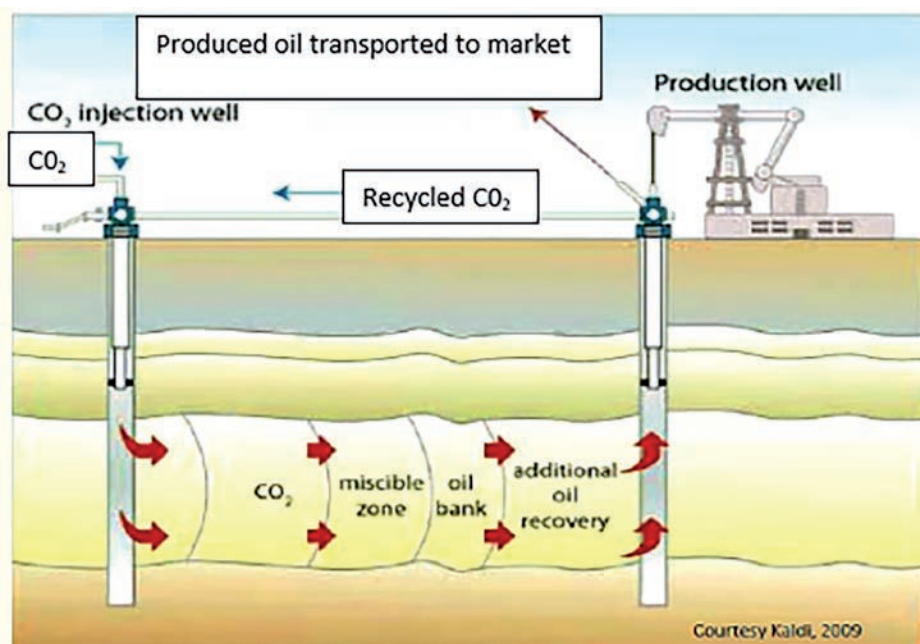


Figure 2.
 Traditional conventional oil recovery [15].

Conventional EOR methods can be categorized into the following groups:

Thermal EOR: By heating the reservoir, the oil's viscosity is decreased, and its flow is enhanced with two popular techniques, which are combustion and steam injection [16].

Gas Injection EOR: Gases used in this process include CO₂, nitrogen, or natural gas, which can either maintain reservoir pressure or reduce oil viscosity, facilitating improved recovery [8].

1.4 Unconventional EOR

Unconventional EOR methods are those using innovative technologies and sustainability-driven approaches to extract oil more effectively. Examples include low-salinity water flooding, which lowers the interfacial tension between water and oil; nanotechnology-based EOR, in which nanoparticles change the ability to absorb water within the rock elements; and microbial EOR, which uses bacteria to improve oil recovery by producing surfactants or gases [17]. In recent years, such unconventional approaches have found wider application as sustainable and potentially cost-effective methods, especially in environmentally sensitive or complex reservoirs [18].

2. Economic and technical challenges in EOR

EOR presents great economic and technical challenges, along with its potential. This is due to most of the EOR projects are capital-intensive, they requiring huge upfront costs in deploying technology, chemicals, and infrastructure, which may not be economically viable in a low oil price environment. In addition, EOR is usually energy-intensive, with thermal methods such as steam injection requiring huge amounts of fuel, which contributes to greenhouse gas emissions and increases operational costs.

Technically, the different EOR techniques need to be tailored with care for a reservoir whose temperature, pressure, rock composition, and fluid properties may be different from each other. This requires thorough reservoir characterization and modeling. The main reasons are therefore complexity and high implementation cost. Additionally, the majority of EOR compounds are vulnerable to harsh tank conditions like high salt levels or elevated temperatures, which could limit their use and necessitate a sophisticated formulation [8, 19].

In general, EOR is one of the necessary means in the process of increasing production from mature and complex reservoirs; it has constant needs for innovation to mitigate economic and technical difficulties. Developments in sustainable EOR methods are needed to mitigate environmental impact and minimize costs for the long-term sustainability of oil fields worldwide.

2.1 Innovative methods of enhanced oil recovery

The need to produce more oil with fewer environmental impacts has resulted in a significant development of EOR technology over the years. These methods are very important in recovering more oil in mature or problematic reservoirs and include a wide range of approaches tailored to specific reservoir conditions. This section highlights the latest innovations across chemical, thermal, gas injection, and microbial EOR techniques, with a focus on sustainable and eco-friendly practices.

2.2 Chemical EOR techniques

To improve the process of oil movement or recovery, fluids containing active agents are injected into the formation using physical and chemical EOR techniques. Surfactants, polymers, alkalis, sulfuric acid, carbon dioxide, and micellar solutions

are examples of active agents [20]. However, solvents improve mobility by lowering the interfacial tension between water and oil. Polymers improve the flooding process's sweep efficiency by making water more viscous [18].

While carbon dioxide dissolves in the oil, decreasing its viscosity and causing it to swell for easier recovery, alkaline agents react with some crudes to create *in situ* surfactants [19]. Micellar solutions blend surfactants and co-surfactants to make microemulsions that displace trapped oil with high efficiency [21]. These methods are tailored to the reservoir characteristics in order to maximize recovery.

2.3 Flooding with polymers

In order to improve the efficiency of oil displacement by decreasing the mobility ratio between water and oil, polymer flooding involves injecting water-soluble polymers, usually polyacrylamides, which raise the viscosity of the injected water [8]. Although polymers increase the viscosity of injected water, they improve sweep efficiency and decrease water channeling, which promotes the mobilization and recovery of oil that would otherwise be trapped (Figure 3) [21].

The reason for the addition of polymers in water is to increase viscosity, reducing permeability due to mechanical entrapment, which will result in decreased mobility in water [22]. Recently, there has been progress in developing high levels of salt alongside elevated heat-resistant polymers in addressing challenging reservoir conditions [18].

2.3.1 Surfactant and alkaline flooding

According to references [23, 24], surfactant and alkaline flooding is the method of delivering alkali, surfactant, and polymer onto the same drum. Surfactants improve the mobilization of oil droplets by reducing the interfacial tension between water and oil [25].

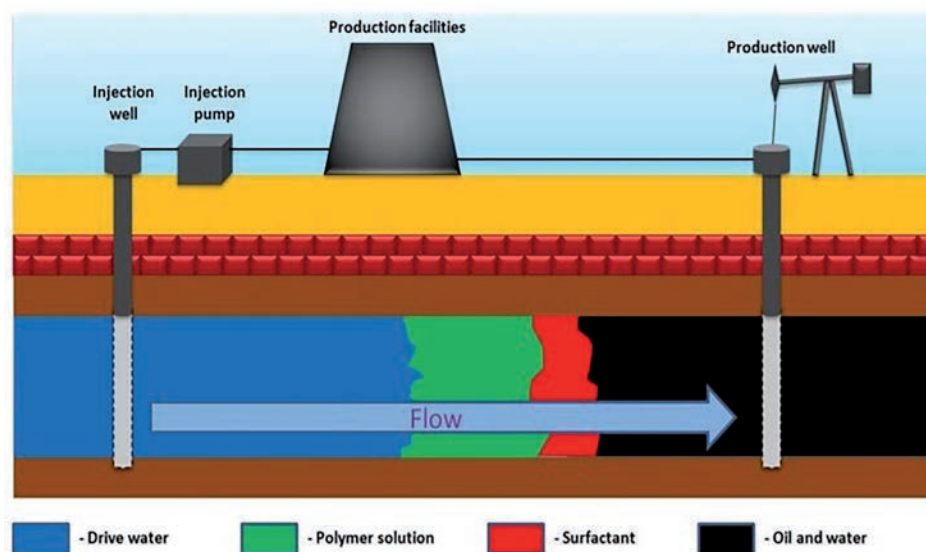


Figure 3.
 Polymer flooding [22].

According to reference [8], this combination can greatly improve oil recovery, especially in reservoirs with highly salinized water.

To address environmental concerns, much research has been conducted on the development of biodegradable and eco-friendly surfactants and polymers from natural sources, such as lignin, cellulose, and starch-based materials [26]. These green chemicals aim to reduce the environmental footprint of chemical EOR and lower the risk of contamination of water sources [18].

2.3.2 Thermal EOR techniques

Conventional thermal methods, such as ordinary steam injection, do not apply for outsized oils from underground storage with a light coat [27]. To address this challenge, the following we looked into expect were looked into details:

2.3.2.1 Steam injection and its environmental impact

One of the most often used thermal EOR techniques is vapor infusion, primarily in the form of cyclic vapor stimulation and steam flooding [28]. In order to heat the reservoir and, as a result, reduce the viscosity of the oil for easier flow toward the production wells, steam at high temperatures is introduced into it [29]. Active agents and gases have been put in place to strategize how the optimization of steam injection can be improved; various works have explored the use of steam in combination with carbonate minerals as catalysts in improving combustion processes for improved recovery rates of heavy oil [30].

Steam injection may be a good way, but it does need massive energy investments and gives rise to carbon emissions during the combustion process for steam generation, thereby posing colossal environmental concerns [19]. Thus, in response to the environmental challenges of steam injection, microwave-assisted and electrical heating techniques have certainly emerged as possible alternatives [31]. Microwave heating produces heat right within the reservoir, thus reducing the energy required to achieve target temperatures and improving efficiency, while it has a major role in low-permeability formations [32]. Electrical heating, on the other hand, operates on resistive heating, thereby raising the temperature of the reservoir and enhancing oil flow, with minimum surface emissions [33].

Innovative thermal-enhanced oil recovery solutions for emission reduction consist of incorporating renewable energy sources such as solar steam generation, where solar energy is used to produce steam for injection [34]. Solar-assisted EOR has shown promise in reducing carbon footprints from steam injection, especially with respect to sunny areas while providing cheaper fuel use [4].

2.3.2.2 Gas injection EOR techniques

In particular, the three main gas injection techniques, CO₂, nitrogen, and hydrocarbon gas injection, have revolutionized the oil business by increasing the recovery rate and production life cycle [35]. According to reference [36], carbon dioxide (CO₂) is a renewable, inexpensive, abundant, and harmless material used in organic synthesis. Coinjection is the term used in the context of enhanced oil recovery (EOR) to describe the injection of CO₂ along with certain additives that create new ways to maximize recovery, reduce costs, and increase environmental benefits by utilizing the agents' synergies [17].

2.3.2.2.1 Water-substituting gas infusion using CO₂

Substituting gas infusion is a popular EOR technique that uses alternate gas and water injection to increase oil recovery and sweep efficiency (**Figure 4**) [38]:

- *Benefits:* Combining the advantages of water-substituting gas infusion with CO₂ helps regulate movement and reduces the influence of viscosity, increasing the extraction of oil [38].
- *Innovation:* The optimum well controls the ratios of CO₂ and water injection [39].
- *Studies:* An investigation titled water-alternating-gas injection with chemical assistance for increased sweep efficiency in CO₂-EOR was performed by Fang et al. [37]. Chemical-assisted CO₂-WAG has various advantages relative to conventional methods, including an enhanced mobility ratio, sealing off fractures that may otherwise extend the production life in some cases, and easier access to production zones tightly connected by permeable channels. The technologies are shown to be critical in developing heterogeneous reservoirs economically, as proven by the recovery factors above 5% beyond conventional methods.

2.3.2.2.2 CO₂-polymer coinjection

The use of CO₂ and polymers for coinjection into the reservoir was recently developed as an EOR alternative that involves using CO₂ with polymers for mobility control of CO₂ to enhance the sweep efficiency and maximize the recovery [40].

- *Benefits:* The CO₂-polymer coinjection has several advantages, which include good operational performance, good behavior of the esthetic, cost-effective, inclusion of other types of polymers with unique characteristics, enhanced

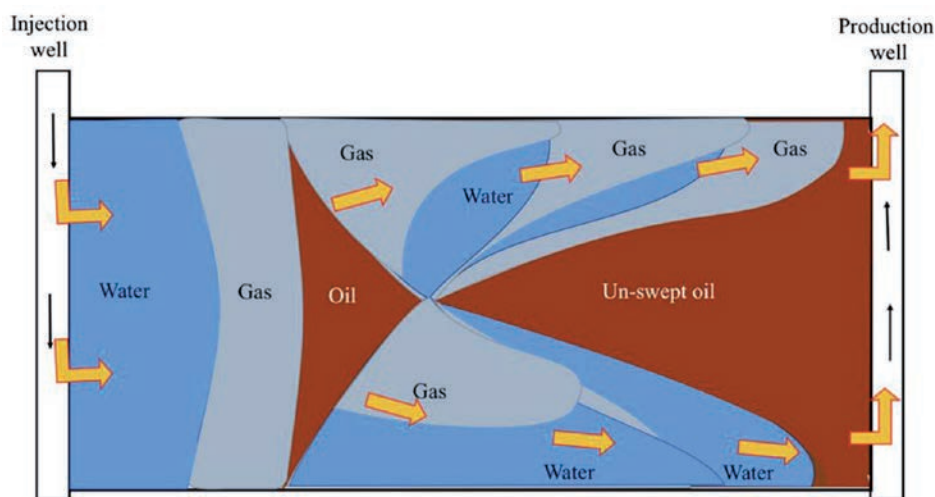


Figure 4.
 Water injection to increase oil recovery [37].

control over mobility and volumetric sweep efficiency, and advances in special physical development properties, according to reference [41].

- **Innovation:** Introduction of environmentally friendly polymers and Nano polymers. Running along is the rising tide of CO₂-based polymerization of CO₂/olefins, CO₂/alkyne, CO₂/isocyanides, and CO₂/FLP polymerizations [17].
- **Studies:** Oil recovery enhancement by about 30% has been shown by laboratory tests in the case of CO₂-only injection (**Table 1**) [18].

2.3.2.2.3 Coinjection of CO₂-nitrogen (N₂)

The method for recovering methane from hydrate structures is coinjection of CO₂-nitrogen (N₂) [42].

- **Benefits:** Reduction of CO₂ in coal seams, improved gas drainage efficiency, improved geological underground storage of CO₂, improved restoration, and increased CH₄ diffusion [43–46].

Year of study	Research and findings
2008	Thomas [19], conducted a study using a mechanism of reduced oil viscosity by injecting CO₂, which expanded the oil recovery. • Polymer improves mobility control by increasing water viscosity and reducing fingering. The findings were as follows: • Polymer improves mobility control by increasing water viscosity and reducing fingering, with a range of concentration of polymers within 500 to 2000 ppm. • CO₂ injection rates: 0.5–1.5 MSCF/day.
2010	Research to study the improvement of oil recovery by integrating CO₂ injection with polymer flooding in order to enhance the sweeping efficiency while reducing the mobility of CO₂ was conducted by Alvarado and Manrique [17]. Some of the following results were found: • increase in oil recovery of 10–20% and • Reduction in the mobility of CO₂ by 30–60%. Alvarado and Manrique [17], also performed an experiment that proved that the use of the introduction of environmentally friendly polymer Reduced CO₂ recycling costs. Cost-saving contribution in operational efficiency at 15–30%.
2014	A discovery was made by Sheng [18] that while the area of polymers has been one of the most interesting research fields in the years, there are challenges yet associated with the degrading of polymers at high temperatures, compatibility of the polymer with reservoir conditions, salinity, hardness. It was found that hydrolyzed polyacrylamides were susceptible to degradation under harsh conditions; therefore, much effort has been done toward developing sulfonated and thermally stable polymers [18]. Advancement in cross-linked and modified polymers enhanced performance in saline reservoirs and achieved 10–15% incremental oil recovery [18].

Table 1.
Summarized work done on CO₂-polymer coinjection.

- **Innovation:** Gas mixtures can be optimized for particular reservoir conditions by real-time monitoring and simulation [47].
- **Studies:** McLaughlin et al. [41] conducted an investigation on the recovery of methane from hydrate structures using a binary CO_2/N_2 gaseous mixture, where they compared to pure carbon dioxide, and the proportion of methane recovered was low, staying below 26%, the mixture, which is 50/50 volume % carbon dioxide and nitrogen, was found to be less expensive.

2.3.2.2.4 CO_2 with surfactants

The choice of the CO_2 -foam descending method depends on the selection of surfactant, which should have low adsorption, low oil phase partitioning, low adsorption, poor sodium tolerance, and low heat stability (**Figures 5 and 6**) [50].

- **Benefits:** EOR efficiency is increased by mixing carbonated water with chemical additions like surfactants and nanoparticles [51]. There are some open issues regarding early breakout problems, limited mobility control and gravity segregation that were reported by Peach and Eastoe [52]. Many surfactants with higher partition coefficients are much more efficient at improving oil recovery [53]. Although mobility control is an issue still to be overcome, CO_2 injection projects can contribute to climate change mitigation efforts through underground CO_2 storage [47].
- **Innovation:** Recent advancements in surfactant compositions, foam fluid movement, fluid imaging, modeling tools, process design, and reservoir performance

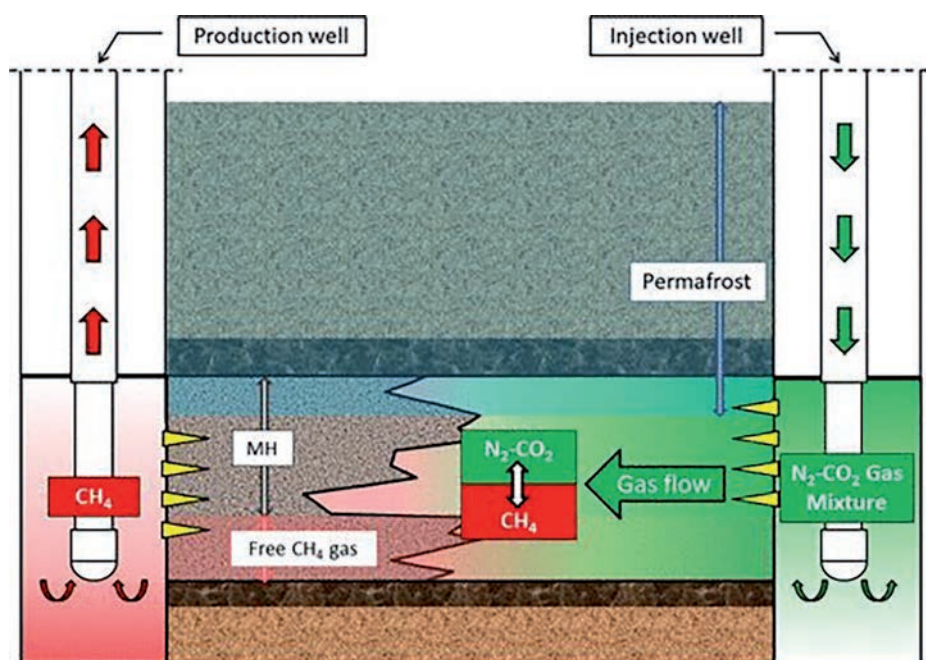


Figure 5.
 Representation of CO_2 -nitrogen (N_2) to improved restoration, and increased CH_4 diffusion [48].

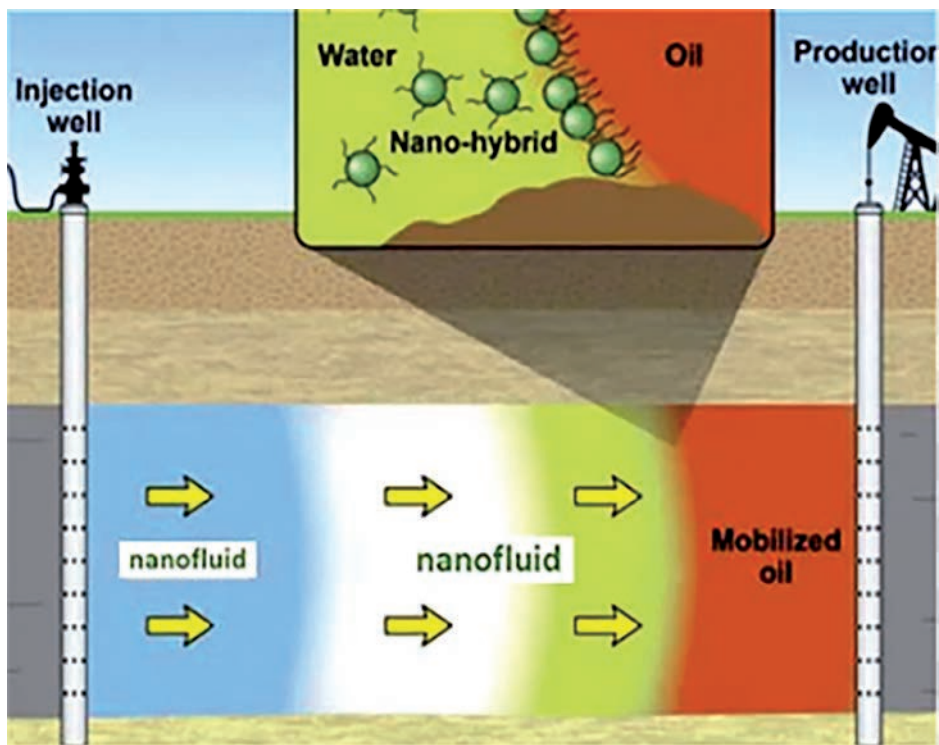


Figure 6.
Addition of nanoparticles to mobilized oil [49].

evaluation issues are all explored, along with preliminary experiments including the deployment of CO₂ foam in carbonate reservoirs [47].

- *Studies:* Zhang et al. [53], assessed surfactants and nanoparticles in oil recovery foam. Their main focus was to find conditions under which the process had increased stability and strength for difficult reservoir conditions. Oil recovery addition increased nanoparticle addition substantially; the addition may act in ways that could stabilize CO₂/Brine foam.

3. Impact on the environment and risk reduction

On the other hand, although these techniques are viewed as enhancing the oil recovery rates, they have adverse effects on the environment with emissions, water usage, and land disturbance. Thus, effective risk management techniques are significantly needed, in order to weed these out [18]. Thermal and other such EOR techniques warrant monitoring and management for their polluting nature-emissions due to fuel burning, local water bodies withering away, and land subsidence [19].

This is why a complex regulatory framework – prescripts regarding emissions, water usage, and disposal of waste – must be established for any given EOR project to manage these matters, to ensure compliance with environmental standards, and, at the same time, reduce ecological harm. For example, CO₂ injection for EOR must conform to CO₂ storage regulations to prevent leaks and protect groundwater quality [3]. The sequential order of effective risk management involves the assessing of risks, which

aptly fall within the frames of certain EOR methodologies. Hence, reservoir characterization, environmental impact analyses, and groundwater modeling become vital instruments for understanding probable hazards and formulating mitigation plans.

Gbadamosi et al. [5] mentioned that such evaluations assist operators in predicting the possible effects of EOR operations on the ecosystem and community resources. Operators can often employ best practices in monitoring and clean-up so as to minimize environmental issues. Environmental concerns can be ameliorated in EOR projects through timely remediation and routine monitoring of emissions and water characteristics. Environmental condition-monitoring technologies include automated leak detection systems and real-time monitoring systems to ensure that any problem becomes an issue of the past [19].

4. Conclusion

EOR development has reached an important turning point as rising sustainability efforts are becoming part of technological innovations and an even stronger commitment to environmental responsibility. Insights from renewable energy integration always suggest that EOR remains one of the best solutions to meet the global energy demand and avoid threatening the environment.

4.1 An overview of the main conclusions

- Technology innovations: Uses of data analytics for optimizing the EOR process will contribute to online decision-making that enhances recovery efficiency while using fewer resources and nanotechnology to enhance mobility that makes recovery viable in low-permeability formations, especially when mixing eco-friendly and biodegradable materials.
- The environmental benefits of renewable energy and CO₂-EOR: The incorporation of renewable energy sources like solar thermal into EOR operations allows them to become greener and complement global decarbonization efforts. CO₂-EOR fits into dual-stage procedures: stimulating oil production and sequestration of CO₂ as a very strong enabling technique for sustainable energy production. 2.
- Policy and regulatory support: These include regulations around water treatment and emission reductions, which are examples of how regulation is among initiatives that the realization of sustainable EOR will need. Such support will thus ensure environmental compliance as well as cheap and resource-efficient recovery.
- As innovation progresses, EOR could serve as a go-between for traditional fossil fuel production on one hand and clean energy sources on the other. The future of EOR will begin tagging along with its responsiveness, as it gradually turns into an active technique of recovery into a New World that is bound to be carbon-conscious.

4.2 Recommendation

- Environmentally-safe materials: Develop environmentally safe materials that would minimize environmental pollution while meeting environmental sustainability standards. Utilizing renewable energy for thermal EOR, instead of using

steam injection techniques, the technique would apply solar-assisted steam generation. These developments, especially in very dry regions, would reduce the energy used and carbon emitted per barrel of oil while enhancing the recovery efficiency.

- Apply advanced techniques of CO₂ injection with chemical assistance, and this could enhance recovery by improving the efficiency of techniques to increase oil recovery. Regarding certain reservoirs, both simulation and real-time optimization would identify the gas-to-water ratio.
- Enhancing gas injection methodology by the use of nanotechnology. This would also improve foam stability, mobility control, and oil recovery in challenging reservoir conditions, as well as assist in carbon separation.
- Improve the level of risk mitigation and environmental monitoring through the development of comprehensive regulatory frameworks and the deployment of technologies such as real-time monitoring and automatic leak detection. Conduct detailed reservoir characterization, environmental impact studies, and ground-water modeling in order to reduce potential risks and ensure sustainability.

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