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An Overview of Electrokinetic-Enhanced Oil Recovery: Recent Advances and Prospect

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Abstract

Electrokinetic-Enhanced Oil Recovery (EK-EOR) is a novel technique aimed at improving oil recovery in conventional and unconventional reservoirs. This paper provides a comprehensive overview of recent advances in EK-EOR, evaluating its effectiveness, methodologies, and economic viability. Through a systematic literature review, data from multiple studies were analyzed to assess the impact of EK-EOR on oil recovery rates, particularly for viscous oils. Results show that EK-EOR significantly enhances oil recovery, with sandstone reservoirs exhibiting higher recovery rates than carbonate reservoirs. Various EK-EOR methods, including thermal techniques and hybrid approaches such as EK-assisted smart water, surfactant, and nano flooding, were found to be effective. Economic analysis indicates that EK-EOR is cost-efficient, offering a favorable return on investment. The paper concludes with recommendations for further research, optimization of EK-EOR techniques, detailed reservoir characterization, economic feasibility assessments, and increased industry collaboration to facilitate the broader adoption of EK-EOR in the oil and gas sector

1. Introduction

Enhanced Oil Recovery (EOR) technologies have significantly evolved over the past few decades, driven by the persistent challenge of maximizing oil extraction from reservoirs. Despite the implementation of primary, secondary, and tertiary recovery methods, a substantial portion of the original oil in place (OOIP) remains untapped [1]. Recent advancements in recovery techniques, particularly Electrokinetic-Enhanced Oil Recovery (EK-EOR), have garnered attention due to their potential to improve recovery efficiency, especially in challenging reservoir conditions [2].

Primary recovery methods utilize the natural pressure within the reservoir to bring oil to the surface. These methods typically recover only about 10-20% of the OOIP, as the reservoir pressure decreases rapidly [3]. Secondary recovery methods, such as water flooding and gas injection, are employed to maintain reservoir pressure and improve oil displacement, resulting in the recovery of an additional 20-40% of the OOIP [4]. However, both primary and secondary recovery methods leave a significant amount of oil in the reservoir, necessitating the development of more advanced techniques to maximize recovery.

The global demand for oil continues to rise, with projections indicating significant increases in energy consumption over the coming decades [5]. This demand, coupled with the depletion of easily accessible oil reserves, necessitates the development of more efficient and sustainable recovery methods. Traditional EOR methods, such as thermal recovery, chemical flooding, and gas injection, have their respective advantages but also face limitations, particularly in reservoirs with low permeability and high viscosity oil [6].

Electrokinetic-Enhanced Oil Recovery (EK-EOR) represents a promising advancement in this field. EK-EOR utilizes direct current (DC) to improve oil recovery by altering the physical and chemical properties of the reservoir rock and fluids. This technique enhances oil mobility and reduces residual oil saturation by leveraging electrokinetic phenomena such as electroosmosis, electrophoresis, and electrolysis [7][8][9]. The application of EK-EOR is particularly advantageous in tight formations where traditional methods struggle to achieve satisfactory recovery rates.

Environmental sustainability is a critical consideration in the development and implementation of new EOR technologies. Conventional methods often involve significant environmental risks, including water contamination, greenhouse gas emissions, and chemical pollution . In contrast, EK-EOR offers a more environmentally friendly alternative by reducing the need for chemical additives and minimizing the generation of harmful by-products. [10][11][12][13].

The economic feasibility of EK-EOR is also an important factor driving its adoption. The technique has shown potential for reducing operational costs and improving the net present value (NPV) of oil recovery projects. By enhancing oil recovery rates and extending the productive life of reservoirs, EK-EOR can provide significant economic benefits to the oil and gas industry[14][15][16][17][18]
.

This paper aims to provide a comprehensive overview of Electrokinetic-Enhanced Oil Recovery, examining recent advances and future prospects. It will explore the underlying mechanisms of EK-EOR, its practical applications, and its potential to address the limitations of conventional EOR methods[20][21][22]. By synthesizing current research and field data, this review seeks to highlight the feasibility, effectiveness, and economic viability of EK-EOR as a sustainable solution for enhanced oil recovery[23][24][25].

2. Methodology

2.1 Research Approach

This study utilizes a qualitative research approach, employing a systematic literature review (SLR) to evaluate the feasibility, trends, and prospects of Electrokinetic-Enhanced Oil Recovery (EK-EOR) in the oil and gas industry. The SLR method is effective in gathering, analyzing, and synthesizing existing research, thus minimizing bias and ensuring comprehensive coverage of the topic.

The study follows the SALSA framework—Search, Appraisal, Synthesis, and Analysis—to systematically address the research questions:

1. What is the relevance of EK-EOR?
2. Which types or hybrid forms of EK-EOR are most and least studied?
3. What are the existing gaps and developments over the years?
4. What challenges hinder further research on EK-EOR?
5. How economical is EK-EOR?
6. What is the future of EK-EOR and its hybrids in field applications?

2.2 Search Stage

A comprehensive search strategy was defined to identify relevant literature. The search was conducted across three major databases: ScienceDirect, OnePetro, and Google Scholar. OnePetro was particularly targeted due to its extensive coverage of oil and gas research, while ScienceDirect and Google Scholar provided additional breadth.

Table 1. Adopted search terms/strings and compiled publications from each database.

Search strings/Terms	Publications per Database (2013-2023)		
Population			
	Science Direct	Google Scholar	One Petro
"Hydrocarbon reserves" OR "Oil reservoir" OR "Hydrocarbon reservoir" OR "Sandstone reservoir" OR "Carbonate reservoir" OR "Gas condensate reservoir" OR "Gas Reservoir"	34,643	17,800	14,731
Intervention			
"Electrokinetic" OR "Electric current" OR "Direct current" OR "Potential gradient" OR "Zeta Potential"	224,589	18,200	95,226
Outcome			
"Oil recovery" OR "Oil recovery factor" OR "Recovery factor" OR "Residual oil saturation" OR "Oil displacement efficiency" OR "Oil production" OR "Oil and gas production"	61,982	18,000	32,386

The initial search yielded a total of 67,174 articles in the Population category as shown in Table 1, 338,015 articles in the Intervention category, and 112,368 articles in the Outcome category as shown in Table 1. Using the "AND" Boolean operator, the search terms combined resulted in 1,574 items. This set was further refined to eliminate irrelevant or redundant articles.

2.3 Inclusion Criteria:

1. Papers published between 2013 and 2023.
2. Keywords present in the full text, title, or abstract.
3. Publications in English.
4. Studies with documented experiments, simulations, and laboratory works.
5. Peer-reviewed journals.

2.4 Exclusion Criteria:

1. Articles outside the relevant subject area.
2. Articles not containing relevant keywords in the title and abstract.

Applying these criteria, the initial set was reduced from 1,574 to 1,273 articles based on subject area and further narrowed to 57 articles by focusing on those with relevant titles and abstracts.

2.5 Appraisal Stage

A critical and methodical review of the selected literature was conducted, focusing on trends, results, and insights from experiments, laboratories, and simulations. The review encompassed a wide range of sources, including patents, conference papers, journal articles, periodicals, textbooks, and online materials, from the earliest research on electrokinetic mechanisms in EOR to the latest studies up to 2023.

2.6 Analysis Stage

The analysis compared the impact of EK-EOR on oil recovery in carbonate and sandstone reservoirs. Key metrics, such as oil recovery factors and displacement efficiency, were extracted and synthesized from the literature. The study's objectives and search criteria determined the final sample size. Access limitations to non-open-source articles also influenced the number of articles analyzed.

3. RESULTS AND DISCUSSION

3.1 Results

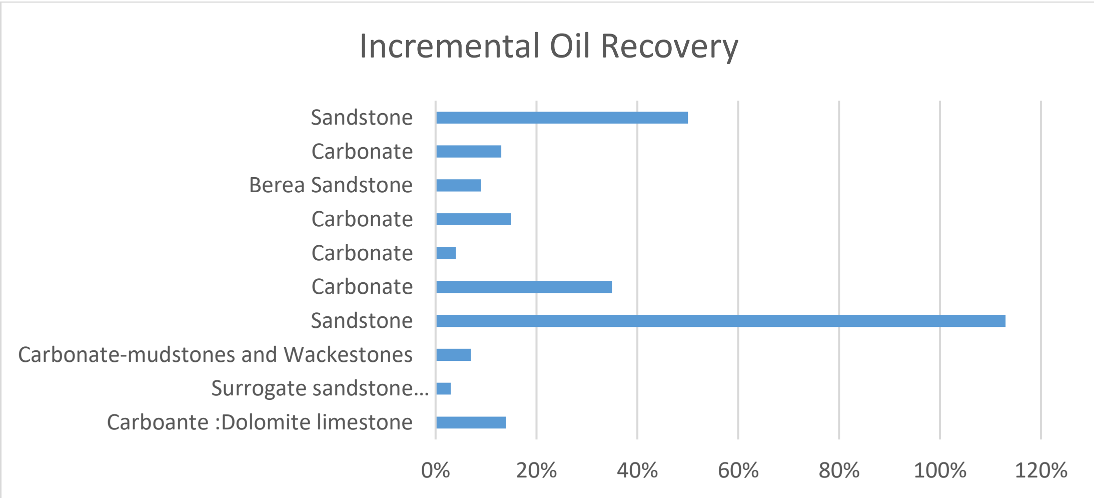

Figure 1 A plot of Cores vs Incremental Oil recovery (Data sourced from Ikpeka *et. al.*, 2022)

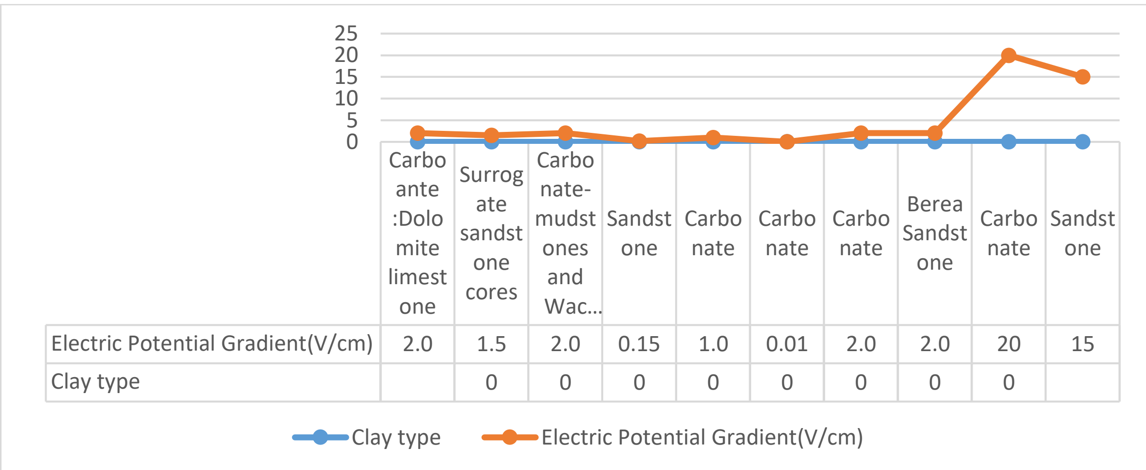

Figure 2 A plot of Clay type effect on Electric potential gradient (Data sourced from Ikpeka *et. al.*, 2022)

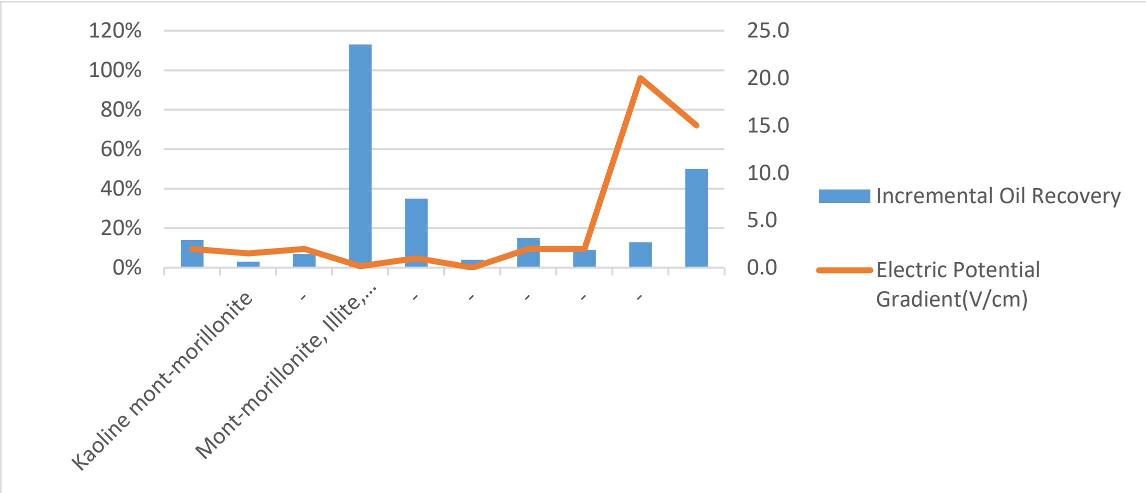

Figure 3 Clay type and electric potential gradient effect on Oil recovery (Data sourced from Ikpeka *et. al.*, 2022)

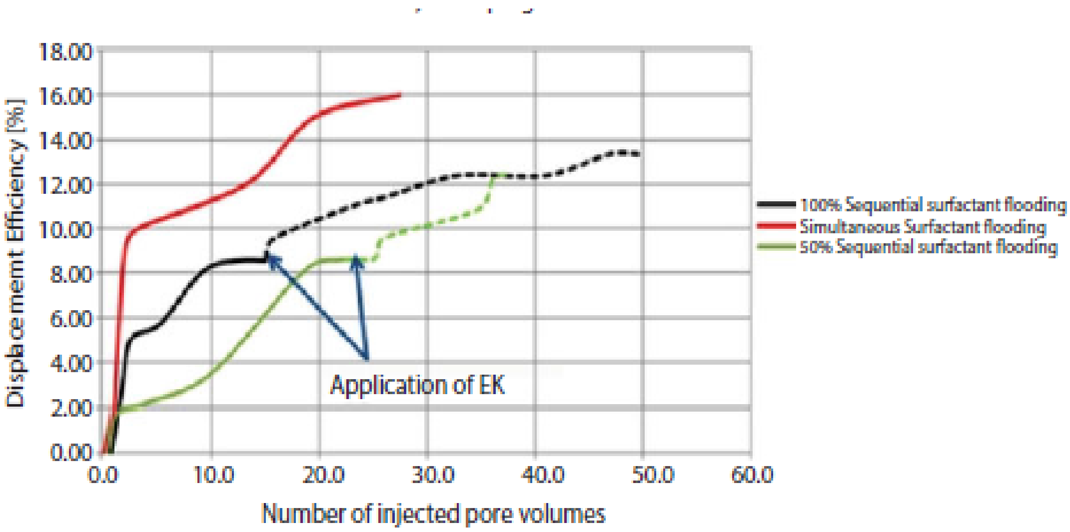

Figure 4 Plot of Displacement efficiency against Number of injected volumes (Chilingar *et. al.*, 2014)

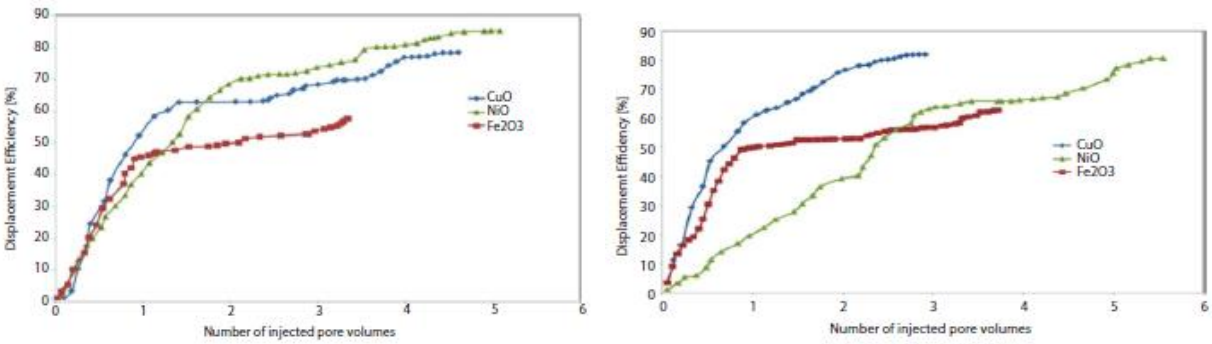

Figure 5 Sequential and Simultaneous comparism approach to EK-Nano EOR.(Chilingar *et. al.*, 2014)

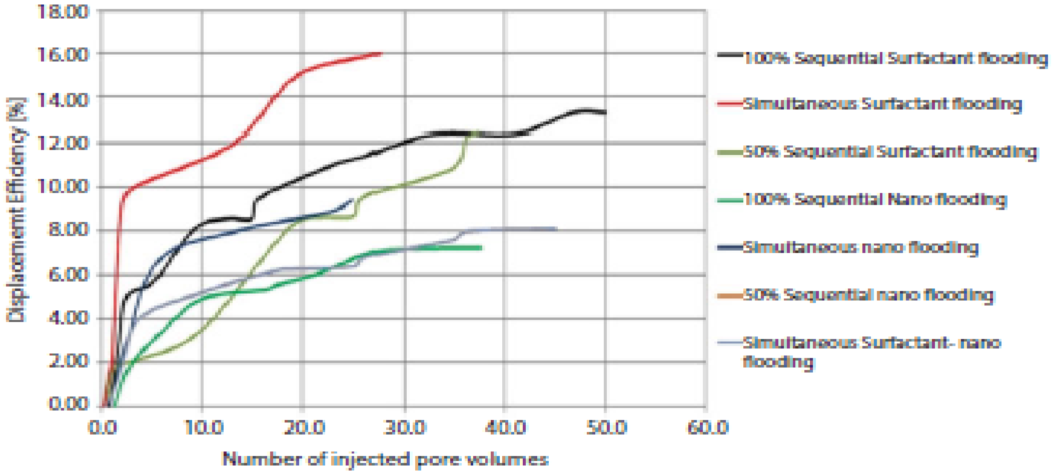

Figure 6. Comparison between EK-assisted nano-flooding and EK-assisted surfactant flooding. (Haroun et al., 2012)

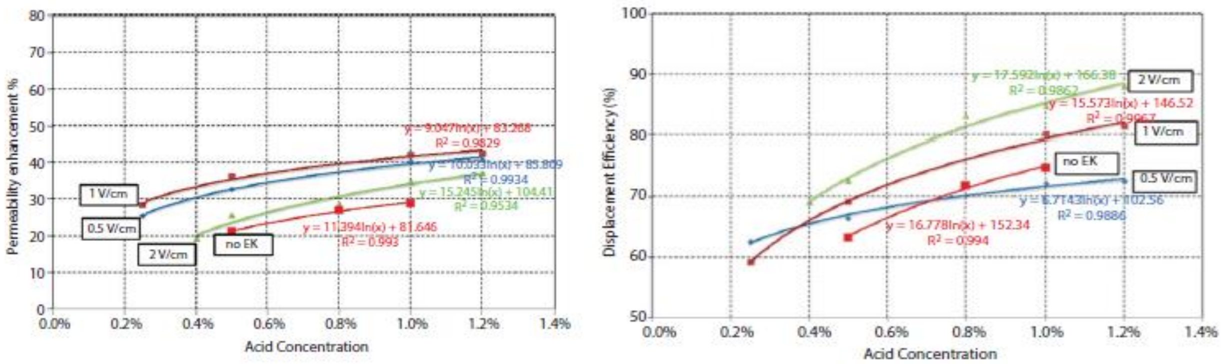

Figure 7 Effect of Applying low acid concentration on permeability enhancement and oil displacement efficiency (Chilingar, et al.,2014)

1. Overall EK-EOR Performance:

EK-EOR enhances oil recovery in both conventional and unconventional reservoirs

EK-EOR techniques have shown an additional oil recovery of 5% with a probability of 45%, and over 50% oil recovery with a probability of 27%

Sandstone reservoirs demonstrated a higher average incremental oil recovery (22.67%) compared to carbonate reservoirs (12.83%) as shown in Figure 1.

2. Techniques of Thermal EK-EOR:

Induction heating and low-frequency heating are found to be more effective than microwave heating due to fewer deficiencies.

3. **Impact of Reservoir Properties**:

Change in water composition is proportional to changes in rock surface structure.

Oil recovery is influenced by the clay content in the rock matrix, with sandstone yielding higher recovery rates than carbonates (Figure 2 and Figure 3).

4. **Wettability Impact:**
    - EK-EOR processes alter rock wettability to water-wet through the formation of acidic regions, improving oil displacement.
    - Increased electroosmotic flow correlates with increased direct current up to a threshold, enhancing oil recovery rates.

5. **EK-Assisted EOR Methods:**

- EK-Formation Water Flooding: Achieved an additional displacement efficiency of 67%, with a recovery factor of 40%.
- EK-Assisted Smart Water: Enhanced oil recovery by 10% with the use of SO42-depleted smart water at 90°C.
- EK-Assisted Surfactant Flooding: Simultaneous surfactant flooding showed a 2.1% reduction in displacement efficiency compared to sequential flooding but used 55% of the surfactant/water consumption (Figure 4).
- Electrokinetic-Assisted Surfactant Flooding on Mixed to Oil-Wet Core Plugs:
  A displacement efficiency of 87% was achieved, and at the point of concurrent surfactant flooding, 55% surfactant/water consumption reduction yielded 2.1% greater displacement efficiency than sequential surfactant flooding. (Haroun et al., 2014) There was an achieved oil recovery factor of 0.52 at a power consumption equivalent to a 15A/m2 current density. [22].
- EK-Assisted Nano Flooding: Sequential nano flooding yielded an 85% displacement efficiency using Nickel (II) Oxide (Figure 5).
- The application of nanoparticles modifies oil characteristics in order to facilitate the release of trapped oil. A particle size of 1-100nm and the use of Al_20_3 has been considered an optimal material for this process. Nano EOR flooding has however shown encouraging results in carbonate reservoirs, where it increases oil recovery by changing the viscosity of the displacing fluid. The comparison between EK-aided nano-flooding and EK-aided surfactant flooding as shown in Figure 6
- EK-EOR with Low-concentration Acid (HCl): Demonstrated that low HCl concentration improves permeability, although higher concentrations can cause pore blockage due to increased clay and sand production (Figure 7).
- Electrokinetic-assisted waterflooding with Low Concentration of Hydrochloric Acid HCl
  The injection of HCl causes a rock sample to develop pores, particularly in cores with high permeability contrast, which allows oil to pass through. Initiation of the electrokinetic process concurrently influenced fluid flow in the newly formed pore spaces. However, a key concern is the precipitation of heavy metals in the cathode. [24]

6. **Economic Feasibility:**
    - There are very limited publications that highlight the economic aspect of adopting EK-EOR. However, a publication published that the estimated power consumption for EK-EOR is 5.57 kW per well, costing approximately $7.89 per day [23].Total daily cost per well is $57.89, including labor and electricity.
    - Annual profit per well estimated at $357,229.15, yielding $33.7 return per dollar invested

3.2 Discussion

The data highlights EK-EOR's potential to significantly boost oil recovery rates, particularly in reservoirs with higher viscosity oils. The probability metrics indicate substantial improvements in yield, making EK-EOR a promising technique for enhancing oil recovery. Among thermal methods, induction and low-frequency heating are more efficient and have fewer operational issues compared to microwave heating, suggesting a preference for these techniques in practical applications. The relationship between water composition and rock surface structure, as well as the influence of clay content, underscores the importance of reservoir characterization in optimizing EK-EOR processes. Sandstone reservoirs, due to their higher clay content, show better recovery rates compared to carbonates.

The alteration of rock wettability to water-wet conditions through electrokinetic processes is crucial for enhancing oil recovery. The observed increase in electroosmotic flow and oil flow rate with higher electrical potential gradients indicates a direct benefit of applying these techniques.
Various EK-assisted methods show substantial improvements in oil recovery. The effectiveness of formation water flooding, smart water EOR, surfactant flooding, and nano flooding illustrates the versatility and adaptability of EK-EOR techniques to different reservoir conditions.

The economic analysis confirms that EK-EOR is not only technically viable but also economically feasible. The substantial return on investment suggests that EK-EOR can be a profitable enhancement method for oil recovery, particularly in challenging reservoirs.
The integration of EK-EOR techniques shows significant promise in improving oil recovery rates and presents a viable economic option for the oil and gas industry. Further research and field trials will help refine these techniques and optimize their application in various reservoir conditions

4. Conclusion and Recommendation

4.1 Conclusion

From the comprehensive literature review and analysis of various publications on Electrokinetic-Enhanced Oil Recovery (EK-EOR), it is evident that while EK-EOR shows significant promise, it is often insufficient as a standalone tertiary recovery method. The adoption of hybrid methods enhances its effectiveness. Several factors influencing the feasibility of EK-EOR include:

1. Reservoir Type and Chemistry: The type of reservoir plays a crucial role in the effectiveness of EK-EOR. Experimental results indicate that carbonate reservoirs yield lower oil recovery rates compared to sandstone reservoirs. Specifically, carbonate reservoirs show an incremental yield of 12.83% while sandstone reservoirs achieve 35.5%.
2. Clay Type and Volume: The type and volume of clay in the reservoir significantly impact EK-EOR efficiency. For instance, Kaolinite and illite clays result in lower recovery rates compared to montmorillonite clays.
3. Reservoir Permeability: EK-EOR is particularly effective in tight reservoirs with low permeability, where traditional methods might struggle.
4. Hybrid Methods: Analysis and comparison of various EK-EOR hybrid methods reveal a trend in environmental and economic impacts:

EK-Low Concentration Acid EOR > EK-Nano EOR > EK-Surfactant EOR > EK-WF EOR

EK-low concentration acid EOR consistently shows the highest displacement efficiency across all reviewed studies.

5. Economic and Environmental Benefits: EK-EOR is not only efficient but also economical and environmentally friendly compared to other conventional EOR methods. Economic calculations indicate that EK-EOR techniques provide a favorable return on investment, making them a worthwhile pursuit.

3.2 Recommendations

1. Expanded Research and Publications: Despite a substantial body of research on EK-EOR over the past decade, more studies are needed from diverse geographic locations beyond the well-studied basins in California, Alberta, and Santa Cruz. This will provide broader insights into the sustainability of EK-EOR.

2. Hybrid Method Modeling: Given the established effectiveness of EK-EOR hybrid methods, future research should focus on developing models that accurately quantify the incremental recovery produced by each hybrid combination.

3. Increased Funding for Research: More funding is essential to develop and refine EK-EOR techniques. This will enable further exploration of innovative methods and their practical applications.

4. Advanced Technologies: Incorporating advanced technologies such as machine learning and artificial intelligence into EK-EOR research could significantly enhance the prediction and optimization of recovery processes. This technological integration will be crucial for future advancements and practical applications in the field.

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