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Original Article

Reservoir Simulation of Enhanced Oil Recovery Using Palm Oil–Based Surfactants

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Abstract: The oil and gas industry faces persistent challenges in recovering residual hydrocarbons from mature reservoirs, where conventional primary and secondary recovery methods leave a significant portion of oil trapped due to capillary forces and unfavorable fluid–rock interactions. Chemical Enhanced Oil Recovery (EOR), particularly surfactant flooding, has emerged as a viable solution, with growing interest in sustainable alternatives such as palm oil–based methyl ester sulfonate (MES). However, existing studies often examine surfactant performance in isolation, with limited integration between laboratory experiments and reservoir simulation, and insufficient analysis of the combined effects of surfactant concentration and oil properties such as API gravity. This study addresses these gaps by developing a reservoir simulation model validated against laboratory core data to evaluate MES surfactant performance. The methodology involves constructing a radial grid-based reservoir model, incorporating rock and fluid properties, and simulating surfactant injection at varying concentrations and oil API conditions. The results show strong agreement between laboratory and simulation outputs, with minimal error in oil-in-place and recovery factor. Surfactant flooding significantly improves recovery compared to waterflooding, achieving recovery factors above 65%. The analysis identifies an optimal surfactant concentration range of approximately 1.8% to 2.0%, beyond which performance stabilizes or slightly declines. Furthermore, oil specific gravity strongly influences recovery, with higher API oils achieving substantially higher recovery factors. These findings confirm that MES surfactant is effective in enhancing oil recovery when properly optimized. The study concludes that integrating laboratory validation with reservoir simulation provides a reliable framework for optimizing sustainable surfactant-based EOR strategies in mature reservoirs.

Keywords: Enhanced Oil Recovery; Surfactant Flooding; Methyl Ester Sulfonate; Reservoir Simulation; Oil Recovery Factor.

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1. Introduction

The oil and gas industry continues to play a central role in meeting global energy demand. Despite technological progress, a substantial proportion of hydrocarbons remains unrecovered in mature reservoirs due to complex pore structures, capillary forces, and unfavorable fluid–rock interactions. Conventional recovery processes are generally classified into three stages. Primary recovery depends on the reservoir's natural energy and typically extracts only a limited fraction of the original oil in place. Secondary recovery, commonly through water or gas injection, improves pressure maintenance and displacement efficiency but still leaves a significant volume of residual oil. Consequently, tertiary recovery or Enhanced Oil Recovery (EOR) has become essential for maximizing hydrocarbon extraction in aging reservoirs (Sheng, 2010; Thomas, 2008).

Among various EOR techniques, chemical methods, particularly surfactant flooding, have gained increasing attention due to their ability to reduce interfacial tension, alter wettability, and mobilize trapped oil. Surfactants function by adsorbing at the oil–water interface, lowering capillary forces and improving displacement efficiency within porous media (Narukulla et al., 2024). Recent studies emphasize that the effectiveness of surfactant flooding depends on multiple interacting parameters, including surfactant concentration, salinity, reservoir temperature, and crude oil properties (Charoentanaworakun et al., 2023; Hakiki et al., 2025). Furthermore, advances in molecular and experimental research confirm that surfactants enhance oil recovery by forming micelles, emulsifying oil, and increasing capillary number, thereby facilitating residual oil mobilization (Mahfud, 2024; Pu et al., 2026).

In recent years, the industry has shifted toward sustainable, environmentally friendly EOR solutions. Biosurfactants derived from renewable resources, particularly palm oil–based methyl ester sulfonate (MES), have emerged as promising alternatives to petroleum-based surfactants. These materials exhibit strong interfacial activity, biodegradability, and competitive economic performance (Charoentanaworakun et al., 2023; Zhuniskenov et al., 2023). Laboratory and simulation studies demonstrate that MES can significantly improve recovery factors by reducing interfacial tension and enhancing microscopic sweep efficiency (Ridaliani et al., 2025; Meidya Buana et al., 2025). In addition, plant-based surfactants have demonstrated compatibility with light crude oil systems and the ability to form stable emulsions, thereby further improving recovery (Setiati et al., 2025).

Parallel developments in chemical EOR include hybrid systems such as surfactant–polymer flooding and nanoparticle-assisted surfactant injection. These approaches aim to overcome limitations such as surfactant adsorption and instability under harsh reservoir conditions (Tang et al., 2023; Dampang et al., 2024). Similarly, alternative green injectants, such as date palm ash solutions, have demonstrated potential in enhancing oil recovery while maintaining environmental sustainability (Alade et al., 2025). Nanoemulsion-based systems and advanced surfactant formulations also provide improved stability and interfacial properties, contributing to more efficient oil displacement (Aladin et al., 2024). These innovations indicate a broader transition toward integrated, sustainable, and cost-effective EOR strategies.

However, several critical issues remain unresolved. First, many EOR studies focus primarily on laboratory experiments, with insufficient integration with reservoir-scale simulation, limiting their applicability for field implementation. Second, while surfactant concentration is recognized as a key parameter, its optimal range under varying reservoir conditions is not consistently defined across studies. Third, the influence of crude oil properties, particularly API gravity, on surfactant performance has not been systematically quantified in combination with concentration effects. Fourth, although biosurfactants such as MES are environmentally favorable, their performance under different operational scenarios requires further validation through combined experimental and numerical approaches (Hakiki et al., 2025; Suleimanov & Veliyev, 2025).

Existing literature provides important insights but also reveals clear research gaps. Many studies examine either experimental core flooding or numerical modeling independently, with limited efforts to validate simulation models against laboratory data. For instance, simulation-based optimization of MES concentration has been explored (Meidya Buana et al., 2025), while laboratory-scale evaluations confirm its effectiveness in improving recovery (Ridaliani et al., 2025). However, integrated validation between these approaches remains limited. Additionally, previous research often evaluates surfactant performance under fixed oil properties, neglecting the interaction between surfactant concentration and oil API gravity. This limits the generalizability of findings for different reservoir types. Moreover, while natural and green surfactants have been widely studied, comparative assessments of their performance across concentration gradients and fluid properties are still insufficient (Zhuniskenov et al., 2023; Setiati et al., 2025).

Therefore, this study addresses these gaps by integrating laboratory-based surfactant injection data with reservoir simulation modeling to provide a more comprehensive evaluation of palm oil–based MES performance. The research focuses on quantifying the relationship between surfactant concentration and recovery factor, as well as analyzing the influence of oil specific gravity (API) on recovery efficiency. By combining validated simulation with empirical data, the study aims to improve the reliability of EOR modeling and support the optimization of surfactant flooding strategies. Accordingly, the objectives of this research are: (1) to develop and validate a reservoir simulation model for laboratory-scale surfactant injection using palm oil–based MES, (2) to analyze the effect of surfactant concentration on the recovery factor, and (3) to evaluate the influence of oil specific gravity (API) on the efficiency of enhanced oil recovery.

2. Literature Review

Enhanced Oil Recovery (EOR) has been widely recognized as a critical strategy to improve hydrocarbon extraction from mature reservoirs where conventional methods fail to achieve optimal recovery. Empirical evidence indicates that primary and secondary recovery techniques typically leave more than 60% of the original oil in place due to capillary trapping and high interfacial tension between oil and reservoir rock (Habib et al., 2024). Classical EOR frameworks classify recovery methods into thermal, gas, and chemical processes, with chemical EOR, particularly surfactant flooding, demonstrating strong potential to enhance microscopic displacement efficiency (Sheng, 2010; Thomas, 2008). Surfactant flooding operates through well-established physicochemical mechanisms. Surfactant molecules adsorb at the oil–water interface, reduce interfacial tension, alter wettability, and increase the capillary number, which facilitates the mobilization of residual oil (Narukulla et al., 2024). Experimental and molecular-level studies confirm that emulsification, micelle formation, and interfacial film stabilization are key processes that enhance recovery (Mahfud, 2024; Pu et al., 2026).

However, these mechanisms are highly sensitive to reservoir conditions such as salinity, temperature, and mineral composition. For instance, Charoentanaworakun et al. (2023) show that surfactant performance varies significantly with salinity levels, which can either enhance or inhibit interfacial tension reduction depending on ionic interactions. This indicates that surfactant effectiveness cannot be generalized across reservoir types and requires tailored optimization. Recent literature emphasizes the transition toward sustainable and bio-based surfactants. Natural surfactants derived from renewable resources, particularly methyl ester sulfonate (MES), have gained increasing attention due to their biodegradability, low toxicity, and favorable interfacial properties (Hama et al., 2023). MES demonstrates strong capability to reduce interfacial tension and improve oil recovery across a wide range of reservoir conditions (Hakiki et al., 2025; Ridaliani et al., 2025). In addition, MES maintains stability in high-salinity and elevated-temperature environments, which are typical of many mature reservoirs (Hakiki et al., 2025). Simulation-based studies further indicate that optimizing surfactant concentration is essential to achieving maximum recovery efficiency, as both insufficient and excessive concentrations reduce effectiveness (Meidya Buana et al., 2025).

Despite these advantages, critical evaluation of the literature reveals several inconsistencies. First, many studies isolate key variables such as surfactant concentration, salinity, or temperature without examining their combined effects. This reductionist approach limits the ability to understand interactions between parameters that influence recovery performance. For example, while concentration optimization is frequently reported, its interaction with crude oil properties, particularly API gravity, remains underexplored. Evidence suggests that lighter oils respond more effectively to surfactant flooding due to lower viscosity and improved flow behavior (Setiati et al., 2025). However, most studies do not integrate oil properties into concentration-based analyses, resulting in fragmented findings. Second, the methodological divide between laboratory experiments and numerical simulation remains a significant limitation. Laboratory core flooding experiments provide detailed insights into pore-scale displacement mechanisms but often fail to represent reservoir-scale heterogeneity.

In contrast, numerical simulations offer broader system-level analysis but frequently lack validation against empirical data. Zhuniskenov et al. (2023) demonstrate that, while numerical models can approximate experimental outcomes, discrepancies persist due to simplifications in modeling complex physicochemical interactions. Chen et al. (2024) highlight that current simulation frameworks struggle to accurately capture surfactant behavior in unconventional reservoirs, particularly in tight and shale formations. This indicates a need for integrated approaches that combine experimental validation with robust simulation modeling. Third, hybrid and advanced EOR methods introduce additional complexity. Surfactant–polymer systems and nanoparticle-assisted surfactants have shown improved recovery performance by enhancing sweep efficiency and reducing adsorption losses (Tang et al., 2023; Dampang et al., 2024). However, these systems require precise formulation control and increase operational costs, which may limit their field applicability. Similarly, alternative green injectants, such as biomass-derived alkaline solutions, show promising results but lack sufficient validation across diverse reservoir conditions (Alade et al., 2025). These limitations suggest that while advanced methods improve performance, they also introduce trade-offs between efficiency, cost, and operational feasibility.

Fourth, the literature on bio-based surfactants often emphasizes sustainability benefits but fails to adequately address performance constraints. Although MES and similar surfactants are environmentally advantageous and cost-competitive, issues such as adsorption to rock surfaces, chemical degradation, and reduced effectiveness at high salinity remain significant challenges (Habib et al., 2024). These factors can reduce the effective surfactant concentration in the reservoir, thereby limiting recovery efficiency. As a result, the assumption that bio-based surfactants can universally replace synthetic alternatives requires further empirical validation. A synthesis of existing studies indicates that surfactant-based EOR has advanced significantly, yet several research gaps persist. There is limited integration between laboratory-scale experiments and reservoir-scale simulations, leading to gaps in model validation. The interaction between surfactant concentration and oil properties, particularly API gravity, remains insufficiently analyzed.

Furthermore, there is a lack of standardized frameworks for evaluating bio-based surfactants under varying reservoir conditions. These gaps reduce the reliability and generalizability of existing findings. Therefore, the current study addresses these limitations by adopting an integrated analytical framework that combines laboratory data with reservoir simulation to evaluate palm oil–based MES surfactant injection. The study systematically analyzes the effect of surfactant concentration on the recovery factor, incorporating oil specific gravity as a key variable. By linking empirical validation with numerical modeling, this research provides a more comprehensive understanding of surfactant performance and contributes to the development of more reliable and sustainable EOR strategies.

3. Materials and Methods

3.1 Research Design

This study applies a quantitative modeling approach to evaluate the performance of palm oil–based methyl ester sulfonate (MES) surfactant in enhanced oil recovery. The methodology integrates laboratory-scale core data with reservoir simulation to ensure consistency between empirical observations and numerical modeling. The design aligns with the research objectives, which focus on three aspects: model development and validation, analysis of surfactant concentration effects on recovery factor, and evaluation of oil specific gravity (API) influence on recovery efficiency.

3.2. Materials

The materials used in this study consist of core rock samples, reservoir fluid properties, and surfactant formulations. Core samples represent porous media with defined physical properties, including porosity, permeability, and bulk volume. Fluid components include crude oil with varying API gravity, formation water, and gas properties. The injected chemical agent is a palm oil–based MES surfactant, prepared at varying concentrations to assess its impact on oil recovery performance. Reservoir and fluid parameters are defined based on standard petroleum engineering inputs. These include oil density, gas density, water density, reservoir pressure, reservoir temperature, oil bubble point pressure, oil compressibility, and water compressibility. Rock–fluid interaction parameters include relative permeability curves, connate water saturation, critical water saturation, and residual oil saturation. These inputs form the basis for simulating multiphase flow behavior during surfactant flooding.

3.3. Reservoir Model Construction

The reservoir model is constructed using a radial grid system to represent the core sample's geometry. The radial configuration allows accurate simulation of fluid flow from the injection point through the porous medium. Core dimensions, including diameter, length, and bulk volume, are used to define the grid structure. Grid properties such as top depth and thickness are specified to ensure accurate spatial representation. Rock properties are then assigned to the grid, including porosity and permeability. These parameters determine the model's fluid storage capacity and flow characteristics. Fluid properties are subsequently defined to represent the multiphase system, including oil, water, and gas phases. The model incorporates variations in oil API gravity to evaluate their effect on recovery performance. Rock–fluid interaction properties are integrated into the model through relative permeability functions and saturation parameters. These include connate water saturation, critical water saturation, and residual oil saturation. These parameters are essential for simulating displacement efficiency and fluid mobility during surfactant injection.

3.3.1. Initial and Boundary Conditions

Initial reservoir conditions are specified to establish equilibrium before the simulation. These include reference pressure, reference depth, and water–oil contact. These parameters define the initial distribution of fluids within the porous medium. Numerical settings are then configured to control the simulation process. Time-stepping parameters are defined to ensure computational stability and accuracy. The simulation start time and duration are set based on the injection schedule and production period.

3.3.2. Well Configuration and Injection Scheme

The model includes both injection and production well configurations to simulate fluid displacement processes. However, since the study focuses on laboratory-scale core analysis, the simulation emphasizes injection well behavior. The injection well is defined by specifying operational constraints, including surface water rate, injection timing, injected fluid composition, and temperature. The injected fluid consists of water and MES surfactant at varying concentrations. The well is perforated across the grid to allow uniform fluid distribution within the core model. Production well parameters are defined to simulate oil recovery from the system. These include bottom hole pressure constraints and perforation settings. The production well enables measurement of oil output and recovery factor during the simulation.

3.4. Simulation Scenarios

To address the research objectives, multiple simulation scenarios are conducted. First, model validation is performed by comparing simulation results with laboratory data, particularly oil-in-place and recovery factor values. This step ensures that the model accurately represents physical processes. Second, surfactant concentration is varied systematically across predefined levels to evaluate its effect on the recovery factor. Each concentration scenario is simulated under identical reservoir conditions to isolate the impact of concentration on performance. Third, oil specific gravity (API) is varied to assess its influence on recovery efficiency. Different API values are assigned while maintaining consistent surfactant concentration and reservoir conditions. This allows for analysis of the interaction between fluid properties and surfactant performance.

3.5. Data Analysis

The primary performance indicator in this study is the recovery factor, defined as the percentage of oil recovered relative to the original oil in place. Simulation outputs are analyzed to determine the relationship between surfactant concentration and recovery factor, as well as the effect of API gravity on recovery efficiency. Comparative analysis is conducted between laboratory and simulation results to evaluate model accuracy. Sensitivity analysis is applied to identify optimal surfactant concentration and to quantify the influence of oil properties on recovery performance.

4. Results

4.1. Model Validation (Laboratory vs. Reservoir Simulation)

Table 1 presents the validation results comparing laboratory measurements and reservoir simulation outputs. The comparison focuses on key parameters, namely Original Oil in Place (OOIP) and Water Injected in Place (WIIP), along with their corresponding error values.

Table 1. Results of Model Validation (Laboratory vs. Reservoir Simulation)

Parameter	Laboratory (cc)	Simulator (cc)	Error (%)
OOIP	1.6	1.56	4%
WIIP	0.35	0.34	1%

The results indicate a strong agreement between laboratory data and simulation outputs. The OOIP shows a minor deviation of 4%, while the WIIP shows a smaller deviation of 1%. These low error margins confirm that the reservoir simulation model reliably represents the physical behavior observed in laboratory experiments. The consistency between both datasets demonstrates that the model is sufficiently accurate for further analysis, including evaluating the effects of surfactant concentration and oil API gravity on recovery performance.

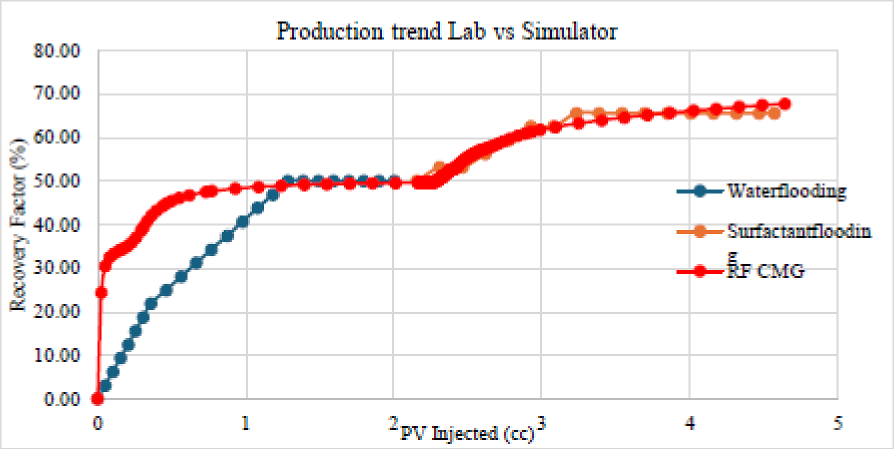

Figure 1. Result of the comparative production trend between laboratory results and reservoir simulation

Figure 1 presents the comparative production trends between laboratory results and reservoir simulation for both waterflooding and surfactant flooding. The horizontal axis represents the injected pore volume (PV), while the vertical axis shows the recovery factor as a percentage. The figure illustrates three curves: waterflooding (blue), surfactant flooding (orange), and reservoir simulation output (red). At the early stage of injection, waterflooding demonstrates a gradual increase in recovery factor. The recovery rises steadily from near zero to approximately 45–50% at around 1 PV injected. This trend indicates that waterflooding improves macroscopic sweep efficiency by displacing movable oil. However, the curve plateaus after this point, suggesting that waterflooding alone cannot effectively mobilize residual oil held by capillary forces. In contrast, surfactant flooding shows a significantly different behavior. The recovery factor increases more rapidly during the initial stage, reaching approximately 45% at a lower injected volume than in waterflooding. This indicates that surfactants reduce interfacial tension early in the injection process, allowing trapped oil to become mobile more quickly. As injection continues beyond 2 PV, the recovery factor continues to increase, reaching values above 65%. This improvement reflects enhanced microscopic displacement efficiency resulting from altered wettability and emulsification effects.

The reservoir simulation results closely follow the surfactant flooding trend. The red curve aligns well with the experimental surfactant flooding data, particularly after the transition from waterflooding to surfactant injection. The recovery factor from simulation is approximately 68%, consistent with laboratory observations. This agreement confirms the simulation model's reliability in capturing the dynamic behavior of surfactant flooding. A critical observation from the figure is the transition phase around 2 PV injected. At this stage, the recovery curve shifts from a relatively stable plateau to a sharp increase. This transition corresponds to the onset of surfactant effectiveness, during which interfacial tension reduction and altered wettability significantly enhance oil mobilization. The delayed response suggests that a certain injection volume is required for the surfactant to propagate through the porous medium and interact effectively with trapped oil. Furthermore, the difference between waterflooding and surfactant flooding becomes more pronounced at higher injected volumes. While waterflooding stabilizes below 50% recovery, surfactant flooding continues to improve recovery up to approximately 68%. This indicates that surfactant injection contributes primarily to incremental oil recovery beyond the limits of conventional secondary recovery methods.

4.2. Effect of Surfactant Concentration on Recovery Factor

Figure 2 illustrates the relationship between surfactant concentration and recovery factor, highlighting the sensitivity of oil recovery performance to variations in methyl ester sulfonate (MES) concentration. The horizontal axis represents surfactant concentration from 1.00% to 2.20%, while the vertical axis indicates the recovery factor. The trend shows a clear positive relationship between surfactant concentration and recovery factor at lower concentration levels. At 1.00%, the recovery factor is approximately 68.02%, which increases steadily to around 68.12% at 1.20% and 68.14% at 1.40%. This gradual improvement indicates that increasing surfactant concentration enhances interfacial tension reduction and improves oil mobilization within the porous medium. A more pronounced increase is observed between 1.40% and 1.80%, where the recovery factor rises to approximately 68.22–68.23%. This phase represents the optimal interaction between surfactant molecules and the oil–water interface, where micelle formation and wettability alteration are most effective.

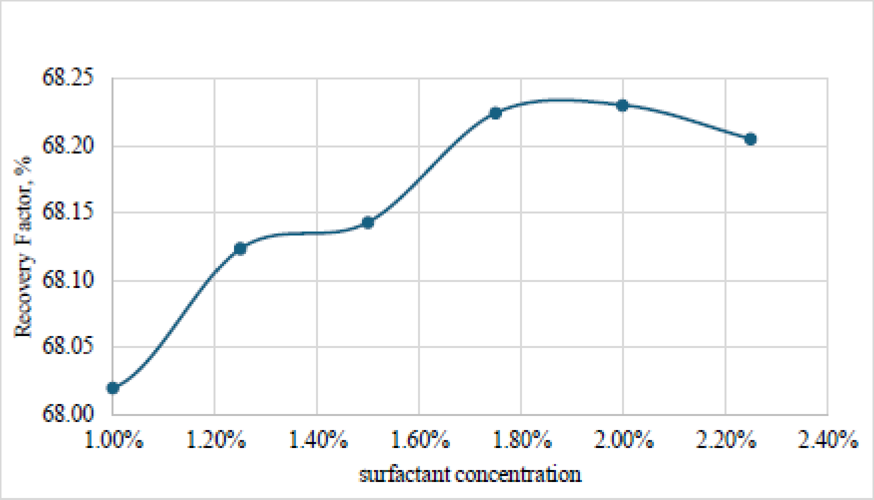

Figure 2. The Effect of Surfactant Concentration on Recovery Factor

The improvement in recovery efficiency during this range suggests that the surfactant concentration approaches the critical micelle concentration, where interfacial activity is maximized. However, beyond 1.80% to 2.00%, the recovery factor plateaus, with only marginal improvement. At 2.00%, the recovery factor stabilizes around 68.23%, indicating that additional surfactant does not significantly enhance oil displacement. This behavior suggests diminishing returns due to saturation of the interface and possible aggregation effects that do not further reduce interfacial tension. At higher concentrations, specifically 2.20%, a slight decline in recovery factor is observed, decreasing to approximately 68.20%. This decline may be attributed to increased surfactant adsorption on rock surfaces or to reduced efficiency due to excess chemical concentration, both of which can negatively affect flow dynamics and economic feasibility.

4.3. Effect of Oil Specific Gravity (API) on Recovery Factor

Table 2 presents the relationship between oil specific gravity (API) and recovery factor using palm oil–based surfactant injection. The results show a strong positive correlation between API gravity and recovery efficiency.

Table 2. Oil Gravity Effect on Recovery Factor Using Palm Oil Surfactant

Oil Specific Gravity (°API)	Recovery Factor (%)
15	35
30	57
45	68.11

The results indicate that oil with a lower API gravity, such as 15°, yields a significantly lower recovery factor of 35%. This reflects the high viscosity and poor mobility of heavier crude oil, which limits the effectiveness of surfactant flooding. In such conditions, capillary forces and flow resistance remain dominant, reducing the surfactant's ability to mobilize trapped oil. At moderate API gravity (30°), the recovery factor increases substantially to 57%. This improvement suggests that as oil becomes less viscous, surfactant injection becomes more effective in reducing interfacial tension and improving displacement efficiency. The mobility ratio improves, allowing better sweep and enhanced oil production. The highest recovery factor is observed at 45° API, reaching 68.11%. This indicates that lighter oils respond more effectively to surfactant flooding due to lower viscosity and higher fluid mobility. Under these conditions, surfactants can more efficiently alter wettability and form emulsions, thereby improving microscopic displacement and increasing overall recovery. The findings demonstrate that oil specific gravity is a critical factor influencing the success of surfactant-based EOR. Higher API gravity is associated with improved recovery performance, confirming that surfactant flooding is more effective in reservoirs containing lighter crude oil. This highlights the importance of considering fluid properties when designing and optimizing EOR strategies.

5. Discussion

The findings of this study confirm that a palm oil–based methyl ester sulfonate (MES) surfactant improves oil recovery when integrated into a validated reservoir simulation framework. The close agreement between laboratory and simulation results demonstrates that the modeling approach reliably represents multiphase flow behavior under surfactant flooding conditions. The observed error margins of 4% for OOIP and 1% for WIIP indicate strong model fidelity, consistent with prior studies emphasizing the importance of calibration between experimental data and numerical simulations to enhance predictive reliability (Zhuniskenov et al., 2023; Chen et al., 2024). This alignment supports the use of simulation as a decision-support tool for optimizing chemical EOR processes under controlled conditions.

The production trend analysis shows that surfactant flooding significantly outperforms waterflooding in terms of both early-stage and ultimate recovery. Waterflooding reaches a plateau at approximately 50% recovery, while surfactant flooding continues to increase recovery to above 65%. This pattern is consistent with established EOR theory, which states that waterflooding improves macroscopic sweep efficiency but fails to overcome capillary trapping at the pore scale (Sheng, 2010; Thomas, 2008). In contrast, surfactant injection reduces interfacial tension and alters wettability, thereby increasing the capillary number and mobilizing residual oil (Narukulla et al., 2024; Hakiki et al., 2025). The transition observed around 2 pore volumes injected indicates the time required for surfactant propagation and interaction with trapped oil, which aligns with experimental evidence on delayed surfactant effectiveness due to adsorption and dispersion processes within porous media (Mahfud, 2024).

The analysis of surfactant concentration reveals a nonlinear relationship between concentration and recovery factor. Recovery increases steadily with concentration up to an optimal range of approximately 1.8% to 2.0%, after which performance stabilizes and slightly declines. This result supports the concept of the critical micelle concentration, in which additional surfactant molecules no longer contribute to further reduction in interfacial tension (Pu et al., 2026). Similar findings have been reported in simulation and laboratory studies, showing that optimal surfactant concentration maximizes recovery efficiency while minimizing excessive chemical consumption (Meidya Buana et al., 2025). The slight decline at higher concentrations suggests the influence of adsorption and aggregation effects, which reduce effective surfactant availability and increase operational costs. This finding highlights the importance of concentration optimization for achieving both technical efficiency and economic feasibility.

The effect of oil specific gravity further demonstrates that fluid properties play a critical role in determining EOR performance. The recovery factor increases significantly from 35% at 15° API to 68.11% at 45° API, indicating that lighter oils respond more effectively to surfactant flooding. This trend reflects the lower viscosity and improved mobility of lighter crude, which facilitates displacement and reduces flow resistance. Previous studies confirm that surfactant efficiency is strongly influenced by oil viscosity and composition, with lighter oils exhibiting higher recovery due to better interaction with surfactant molecules (Setiati et al., 2025; Charoentanaworakun et al., 2023). These results reinforce the need to consider reservoir fluid characteristics when designing EOR strategies, as a single surfactant formulation may not be equally effective across different oil types.

From a sustainability perspective, the use of palm oil–based MES aligns with the growing emphasis on environmentally friendly EOR solutions. Bio-based surfactants offer advantages in terms of biodegradability and reduced toxicity while maintaining competitive performance compared to synthetic alternatives (Hama et al., 2023; Habib et al., 2024). The recovery improvements observed in this study support previous findings that MES can effectively reduce interfacial tension and enhance oil displacement under various reservoir conditions (Ridaliani et al., 2025; Hakiki et al., 2025). However, the results also indicate that performance optimization depends on operational parameters such as concentration and reservoir characteristics. This suggests that environmental benefits alone are insufficient without careful technical optimization.

The findings also provide insight into the limitations of more complex EOR approaches. While hybrid methods such as surfactant–polymer flooding and nanoparticle-assisted systems have demonstrated higher recovery in some studies, they introduce additional complexity in formulation and operational control (Tang et al., 2023; Dampang et al., 2024). In contrast, a single surfactant system, as demonstrated in this study, offers a more straightforward and potentially cost-effective solution when properly optimized. Similarly, alternative green injectants such as biomass-derived alkaline solutions have shown promise but require further validation across varying reservoir conditions (Alade et al., 2025).

Despite these contributions, the study has several limitations. The analysis is based on laboratory-scale core models that may not fully capture reservoir heterogeneity or large-scale flow dynamics. Although the simulation model is validated, it simplifies complex physicochemical interactions that occur in real reservoirs. Additionally, the study focuses on a limited range of surfactant concentrations and API values, which may not represent all reservoir scenarios. These limitations are consistent with challenges identified in previous literature, where scaling laboratory results to field applications remains a critical issue (Chen et al., 2024; Suleimanov & Veliyev, 2025).

6. Conclusions

This study evaluates the performance of a palm oil–based methyl ester sulfonate (MES) surfactant for enhanced oil recovery using an integrated laboratory and reservoir simulation approach. The findings confirm that the simulation model accurately represents physical processes, as indicated by the small deviation between laboratory and simulated values of oil in place and recovery factor. This validates the reliability of the modeling framework for analyzing surfactant flooding performance. The results demonstrate that surfactant flooding significantly improves oil recovery compared to conventional waterflooding. The recovery factor increases beyond the plateau observed in secondary recovery, confirming that MES effectively reduces interfacial tension and enhances microscopic displacement efficiency. The analysis further shows that surfactant concentration has a nonlinear effect on recovery. An optimal concentration range of approximately 1.8% to 2.0% yields the highest recovery, while higher concentrations do not provide additional benefits and may reduce efficiency.

Oil specific gravity also plays a critical role in determining recovery performance. Lighter oils with higher API gravity exhibit substantially higher recovery factors, indicating that fluid mobility and viscosity strongly influence the effectiveness of surfactant flooding. This highlights the importance of aligning surfactant design and injection strategies with reservoir fluid characteristics. The study contributes to advancing sustainable chemical EOR by demonstrating that a palm oil–based MES surfactant can serve as an effective, environmentally compatible alternative to conventional surfactants. The integration of experimental validation and numerical simulation provides a more comprehensive basis for optimizing surfactant flooding strategies in mature reservoirs.

6.1. Research Limitations

Several limitations should be acknowledged. First, the study is based on laboratory-scale core models, which do not fully represent reservoir heterogeneity, anisotropy, and large-scale flow dynamics. Second, the simulation model simplifies complex physicochemical interactions, such as surfactant adsorption, chemical degradation, and multiphase flow behavior under varying reservoir conditions. Third, the analysis is limited to a specific range of surfactant concentrations and oil API values, which may restrict the generalizability of the findings to other reservoir types. Fourth, economic evaluation and field-scale feasibility are not explicitly assessed, which limits the practical applicability of the results for large-scale implementation.

6.2. Policy Implications

The findings have several implications for energy policy and resource management. First, the demonstrated effectiveness of palm oil–based MES supports the adoption of bio-based surfactants in EOR operations, aligning with sustainability goals and reducing dependence on petroleum-derived chemicals. Policymakers can encourage the development and utilization of renewable chemical inputs in the oil and gas sector through targeted incentives and regulatory frameworks. Second, the identification of optimal surfactant concentration highlights the importance of efficiency-driven resource utilization. Policies that promote optimization of chemical usage can reduce operational costs and minimize environmental impact. This is particularly relevant for mature oil-producing regions where cost efficiency and environmental compliance are critical. Third, the strong influence of oil properties on recovery performance suggests the need for reservoir-specific EOR strategies. Regulatory bodies and industry stakeholders should support data-driven reservoir characterization and technology selection to ensure that EOR methods are applied effectively. Finally, the integration of simulation and experimental validation underscores the importance of technological innovation in the energy sector. Investment in research and development, particularly in digital reservoir modeling and sustainable EOR technologies, can enhance recovery efficiency while supporting long-term energy security.

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