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Effects of Palm-Oil-Based Methyl Ester Sulfonate (MES) in Laboratory-Scale Enhanced Oil Recovery Process

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ABSTRACT - Natural Declining oil production is often caused by reduced natural driving forces within reservoirs. To address this limitation, enhanced oil recovery (EOR) technology introduces external energy or chemical agents to mobilize residual oil. This study evaluated the performance of palm-oil-based methyl ester sulfonate (MES) an anionic and biodegradable surfactant synthesized from renewable feedstock for improving recovery efficiency under laboratory-scale conditions. Core-flood experiments were performed using Berea sandstone cores, intermediate 33°API crude oil, low salinity of 10,000 ppm, synthetic brine at 60 °C. The testing sequence included screening test of palm-oil-based MES, brine saturation, oil saturation, waterflooding, and subsequent surfactant flooding with 1.5% MES solution. During waterflooding, the recovery factor reached 62.8 %, leaving 31.29 % residual oil saturation. Injection of 1.5 wt % MES increased the recovery factor to 68.8 % and reduced residual oil saturation to 26.25 %, indicating enhanced displacement and improved microscopic sweep efficiency. The results confirmed that palm-oil-derived MES effectively mobilizes trapped oil and demonstrates strong potential as an environmentally friendly and locally available surfactant for chemical EOR applications in the reservoirs.

Keywords: enhanced oil recovery (EOR), chemical injection, surfactant, methyl ester sulfonate (MES)

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INTRODUCTION

A decline in oil production from mature reservoirs is primarily caused by reduction in natural energy that drives reservoir fluids toward a production well. Conventional primary and secondary recovery methods typically produce less than half of the original oil in place, leaving significant residual oil trapped by capillary forces and strong rock–fluid interactions. To overcome this limitation, enhanced oil recovery (EOR) technologies have been developed to increase displacement efficiency through injection of external energy or chemical agents into the reservoir (Ansyori 2018; Setiati et al., 2022; Sheng 2011). Among the various EOR techniques, chemical EOR (CEOR) particularly surfactant flooding has shown potential in reducing interfacial tension (IFT) and modifying wettability to mobilize trapped oil droplets (Schramm 2000; Majidaie et al., 2011; Nuraini et al., 2024) .

Surfactants function by reducing IFT between oil and water phases, allowing the capillary number to increase and promoting the displacement of immobile oil. They can also alter the rock surface from oil-wet to more water-wet conditions, improving microscopic and macroscopic sweep efficiency (Ishak et al., 2017; Maurad et al., 2020). However, conventional petroleum-based surfactants such as alkylbenzene sulfonates pose challenges due to high cost, limited biodegradability, and potential toxicity (Zhao et al., 2021). These issues have encouraged the exploration of biosurfactants and surfactants derived from renewable resources as environmentally friendly alternatives (Rahmawati et al., 2024).

One promising candidate is methyl ester sulfonate (MES), an anionic surfactant synthesized from natural methyl esters through sulfonation. MES can be produced from various vegetable oils including coconut and palm oils making it abundant and renewable (Murni et al., 2015). In Indonesia, the availability of palm oil provides an opportunity for large-scale and cost-effective MES production. Palm-oil-derived MES has favorable surface-active properties, good thermal stability, and biodegradability, aligning with sustainable and environmentally responsible EOR practices (Cahyaningtyas et al., 2025; Rivai et al., 2011).

Based on previous research, the characteristics of palm oil MES were analyzed using a variation in surfactant concentrations of 0.3%, 0.5%, and 1%, with a low salinity of 18,200 ppm, and light crude oil of 40°API (Sugihardjo & Eni, 2014). Likewise, another study with the same conditions used low salinity of 10,000 ppm (Merdhah & Mohd Yassin 2012). The current study used a higher concentration of surfactant than the previous study of 1.5% with a low salinity of 10,000 ppm, but used an intermediate crude oil of 33°API at 60°C as a temperature interpretation in the reservoir and used sandstone rocks.

Previous studies have also indicated that methyl -ester-based surfactants can reduce interfacial tension and enhance recovery in core-flood experiments (Eni et al., 2017; Suhascaryo & Dhaff 2024). However, the quantitative relationship among MES concentration, interfacial-tension reduction, wettability alteration, and recovery factor under controlled laboratory conditions remains underexplored. Therefore, this study aimed to evaluate the performance of palm-oil-derived MES in reducing residual oil saturation and improving oil recovery at a laboratory scale. The findings expectedly contribute to the development of locally sourced and environmentally friendly surfactants for future chemical EOR applications in Indonesian oil fields (Eni 2014; Usman & Haans 2017).

METHODOLOGY

The surfactant used in this study is methyl ester sulfonate (MES), which is synthesized from palm-oil methyl ester through a sulfonation process. The surfactant solution is prepared by dissolving MES in synthetic brine with a low salinity of 10,000 ppm. In addition, the intermediate crude oil sample used in this study has an API gravity of 33°API, ensuring that the fluid properties remain consistent throughout the experiments. Experiment was conducted in the Enhanced Oil Recovery Laboratory of Petroleum Engineering Department of Universitas Trisakti.

Berea sandstone cores are used as the porous media for the core-flooding experiments, as they represent a standard and homogeneous reservoir rock. Each core sample is cleaned, oven-dried, and saturated with brine before testing to ensure uniform initial conditions. This preparation step ensures that variations in core properties do not influence the experimental results.The experiments are conducted at 60 °C and consist of two main stages: waterflooding (secondary recovery) and surfactant injection (tertiary recovery). In the first stage, the core saturated with crude oil and brine is subjected to waterflooding until no more oil is produced, marking the end of the secondary recovery. This stage provides a baseline for evaluating the subsequent improvement achieved by the surfactant injection.

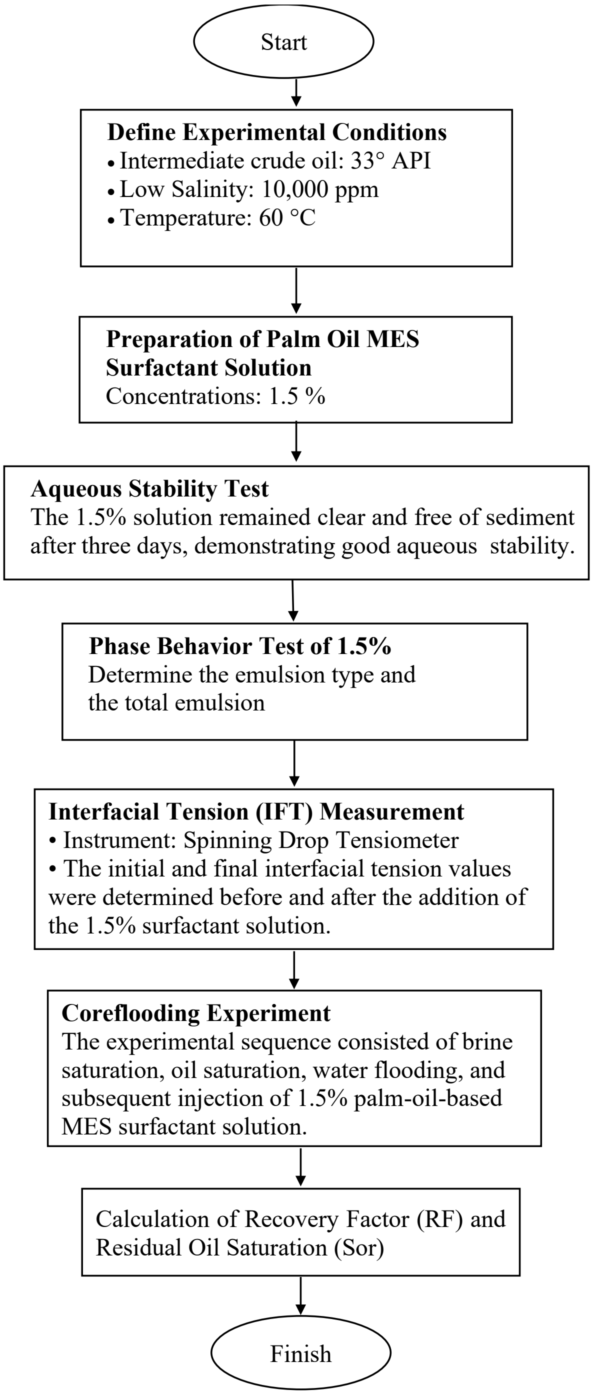

Figure 1. Flowchart

RESULT AND DISCUSSION

The experiment began by defining the *experimental conditions*, which utilized *intermediate crude oil* with an API gravity of 33°, low salinity of 10,000 ppm, and temperature of 60 °C. These conditions were selected to simulate typical reservoir environments of medium oil systems. Subsequently, *palm oil MES solutions* at a concentration of 1.5% were prepared. Finally, the *recovery factor (RF)* and *residual oil saturation* (S_{or}) were calculated to quantify the improvement in oil recovery resulting from the surfactant injection. This sequential workflow from setup to core-flooding was used to ensure a comprehensive evaluation of the performance of the *palm oil MES* in reducing interfacial tension and enhancing oil recovery potential under controlled laboratory conditions.

Aqueous stability test

An aqueous stability test was then conducted to observe phase separation or precipitation. After three days, the 1.5% *Palm Oil MES* solution remained clear and stable, indicating good compatibility and solubility under the test conditions.

Phase behaviour test

A phase behaviour test was carried out to determine the emulsion type formed between the surfactant and crude oil phases. The results showed a middle-phase emulsion (Type III), with 1.75% total emulsion volume observed at the 1.5% surfactant concentration, suggesting an optimal microemulsion formation (Table 1).

Interfacial tension test (IFT)

Interfacial tension (IFT) measurements are performed using a spinning drop tensiometer to evaluate the effectiveness of the surfactant. The initial IFT between the crude oil and brine is 2.24 dyne/cm, indicating relatively strong interfacial forces. After the addition of 1.5% Palm Oil MES, the IFT decreases significantly to 0.455 dyne/cm, demonstrating a substantial reduction in interfacial tension that supports improved oil mobilization, as shown in Table 2.

Table 2. Results of IFT of 1.5 % palm oil MES.

Oil	***Intermediate crude Oil*** **33^0 API**
Salinity (ppm)	10,000
IFT initial (dyne/cm)	2.24
IFT after 1.5% surfactant addition (dyne/cm)	0.455

Coreflooding experiment

A *core-flooding experiment* was subsequently conducted to evaluate the displacement efficiency under reservoir-like conditions. The flooding sequence consisted of *brine saturation*, *oil saturation*, *waterflooding*, and finally *surfactant injection* using the 1.5% MES solution. The physical properties of the Berea sandstone cores used for the flooding experiments are summarized in Table 3. The cores had a diameter of 2.58 cm, a height of 3 cm, a permeability of 170 mD, and a porosity of 22 %.

Table 3. Physical properties of core samples of Berea sandstone

Properties	Measurement
Diameter	2.58 cm
Hight	3.00 cm
Core Permeability	170.00 mD
Core Porosity	22.00 %

Table 1. Results of phase behaviour palm oil MES test

Oil	Surfactant composition	Phase	Emulsion volume to time (hour)				Total emulsion volume	Type emulsion phase
			0	24	168	504	(%)	
Crude	Salinity	Oil	0	1.9	1.9	1.94		
Oil 33	10,000 ppm	Emulsion	3	0.12	0.11	0.07	1.75%	Medium (Winsor III)
°API	1.50%	Surfacrtant	1	1.98	1.99	1.99		

Following the core preparation, the brine- and oil-saturation stages were completed under vacuum conditions to ensure uniform fluid distribution within the pore spaces. The calculated pore volume from the brine-saturation stage was 2.97 cm^3, which indicates that the core was fully saturated and that the measurement was reliable. This result also confirms that the samples were homogeneous and suitable for use in laboratory-scale reservoir simulation, as summarized in Table 4.

Table 4. Brine saturation results on core

Tests	Results
Dry core weight before saturation	37.82 gr
Core wet weight after saturation	40.80 gr
PV brine	2.97 cm^3

After the brine saturation and the current core condition was 100% water, the next step was to saturate the core with oil. This study used intermediate crude oil of 33 °API. When oil saturation occurs, water will come out because it is replaced by oil, the amount of water that comes out indicates the amount of OOIP of the core used. Complete results can be seen in Table 5.

Table 5. Oil saturation results of 33ºAPI crude oil on the core

Tests	Results
Replaced water	2.50 cm^3
Oil in place (OOIP)	2.50 cm^3
Oil saturated (Soi)	84.12 %
The volume of water in the core	0.47 cm^3
Saturation water connat (Swc)	15.88 %

After the brine and oil saturation, the fluid injection stage was carried out. Before injecting the palm oil MES, waterflooding was first carried out. Waterflooding is a secondary recovery stage conducted to enhance oil production by injecting water into the reservoir. In this test, waterflooding injection was carried out using 3.00 PV of brine. The waterflooding experiment results indicated a substantial reduction in core oil saturation, from an initial oil saturation (Soi) of 84.12% (Table 5) to a residual oil saturation (Sor) of 31.29%. This decrease in oil saturation demonstrates the effectiveness of waterflooding as a baseline displacement mechanism prior to surfactant injection. However, the remaining trapped oil highlights the limitations of waterflooding in overcoming capillary forces in porous media. These observations justify the subsequent introduction of Palm Oil MES, which is designed to further reduce interfacial tension and mobilize the remaining oil that cannot be displaced by water alone(Table 6).

Table 6. Results of waterflooding tests on core samples of Berea sandstone rocks

Test	Results
Amount of water injected	3.00 PV
Volume of oil produced	1.57 cm^3
Recovery factor (RF)	62.8 % of OOIP
Remaining oil volume	0.93 cm^3
Residual oil saturation (Sor)	31.29 %

Injection of 1.5% palm oil MES was carried out with an injection volume equivalent to 1 PV. This procedure was designed to evaluate the surfactant's effectiveness in mobilizing the remaining oil within the reservoir system. The results of the palm oil MES injection, including performance indicators and recovery outcomes, can be seen in Table 7.

Table 7. Results of injection of 1.5% palm oil MES on

Volume of injected Surfactant	**1 PV**
Volume of oil produced	0.15 cm^3
Incremental recovery factor (RF)	6 % of OOIP
Total recovery factor	68,8% of OOIP
Residual oil in rocks	0.78 cm^3
Residual oil saturation (Sor)	26.25 %

During the surfactant flooding stage, a 1.5% solution of palm-oil-derived methyl ester sulfonate (MES) was injected at 60°C to evaluate its effectiveness in mobilizing residual oil. The process was conducted under controlled laboratory conditions to ensure consistent temperature and flow behavior throughout the flooding sequence. As summarized in Tables 6 and 7, the recovery factor increased from 62.8% to 68.8%, indicating an incremental oil recovery of approximately 6%.

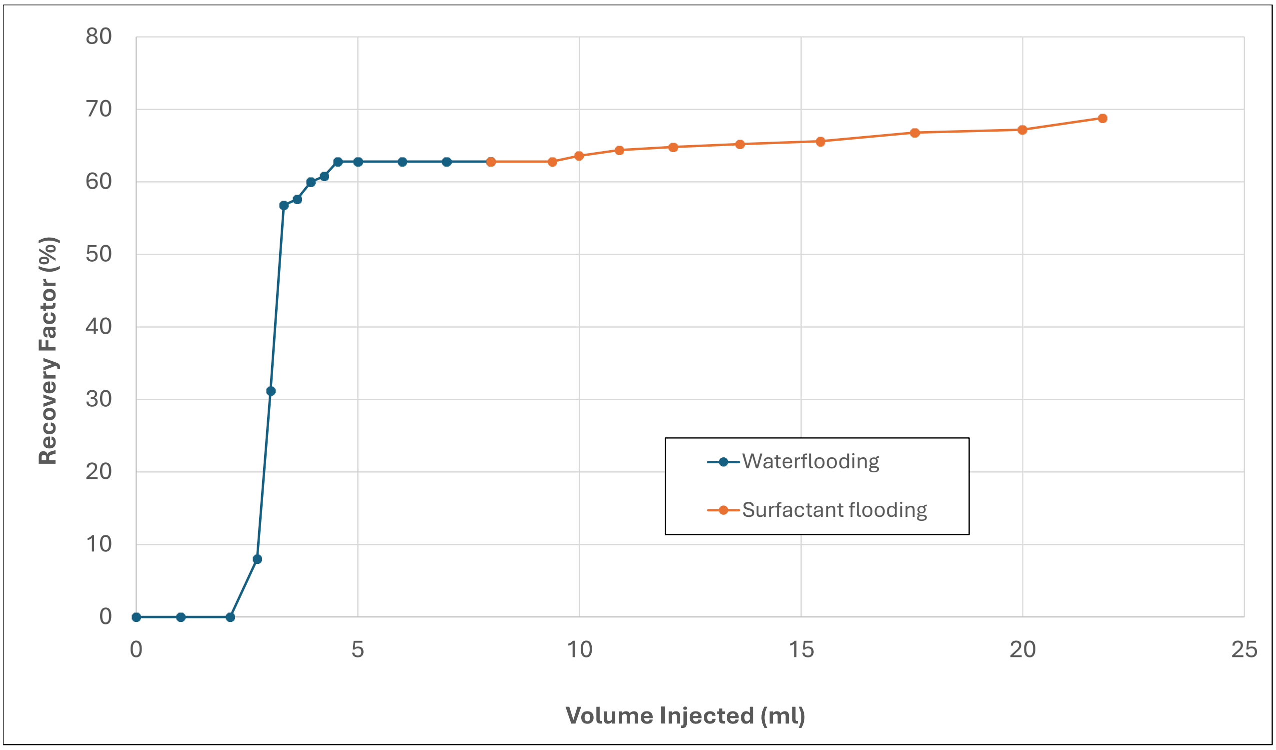

Figure 2. RF increase on injection fluid volume

This result demonstrates the potential of palm-oil-based MES as a viable surfactant for enhanced oil recovery applications.

During the surfactant flooding stage, a 1.5% solution of palm-oil-derived methyl ester sulfonate (MES) was injected at 60 °C to evaluate its effectiveness in mobilizing the remaining residual oil. The MES solution was introduced into the core at a constant injection rate to maintain uniform displacement conditions. These carefully controlled parameters ensured that any changes in oil recovery were directly attributable to the performance of the surfactant system rather than operational fluctuations.

The entire flooding process was carried out under controlled laboratory conditions to maintain stable temperature and flow behavior throughout the injection sequence. Maintaining the system at 60 °C was crucial because surfactant properties such as solubility, interfacial tension reduction, and microemulsion formation are highly temperature dependent. By ensuring consistent thermal and hydrodynamic conditions, the experiment minimized uncertainty and improved the reliability of the observed recovery performance.

As summarized in Tables 6 and 7, the recovery factor increased markedly from 62.8% after waterflooding to 68.8% following MES injection. This improvement represents an incremental oil recovery of approximately 6%, which is significant given that surfactant flooding targets the most difficult fraction of oil to mobilize. The increase in recovery clearly indicates that the MES solution successfully reduced capillary forces and mobilized trapped oil remaining in the pore network.

This positive result demonstrates the strong potential of palm-oil-based MES as a viable surfactant for enhanced oil recovery applications. The ability of MES to lower interfacial tension and form stable microemulsions contributes directly to its displacement efficiency. Furthermore, the bio-based origin of the surfactant offers an environmentally friendlier alternative to conventional petroleum-derived surfactants, aligning with industry efforts to adopt greener chemical solutions.

Overall, the findings from this experiment provide valuable insights into the capability of MES to improve oil recovery under controlled laboratory conditions. The promising performance observed suggests that additional optimization such as adjusting salinity, injection sequencing, or combining MES with co-surfactants—may further enhance recovery outcomes. This improvement confirmed that the MES effectively mobilized a portion of the residual oil remaining after waterflooding. The cumulative oil production profile shown in Figure 2 further supports this conclusion, as it illustrates a noticeable increase in oil production immediately after the injection of the palm-oil-based MES solution. The production rate then gradually stabilized as the system approached equilibrium, indicating a consistent response to the surfactant flooding process.

The results in Table 5 and the production trend in Figure 2 confirm that MES achieved a significant reduction in residual-oil saturation. The uniform permeability (170 mD) of the cores helped maintain a stable displacement front, minimizing fingering and ensuring even surfactant propagation through the pore network. The magnitude of incremental recovery observed in this study is consistent with values reported in previous laboratory investigations using biosurfactants synthesized from vegetable-oil feedstocks (Sheng, 2011; Murni et al., 2015).

The experimental evidence presented in Tables 5 to 7 and Figure 2 demonstrate that palm-oil-derived MES can increase oil recovery from 62.8 % to 68.8 % and decrease the residual-oil saturation from 31.29 % to 26.25 %. These findings validate MES as a technically viable and environmentally sustainable surfactant for chemical EOR under laboratory conditions, with potential applicability to the reservoirs.

CONCLUSION

This study evaluated the performance of a palm-oil-derived methyl ester sulfonate (MES) for enhanced oil recovery under laboratory core-flooding conditions. The experiments were conducted using Berea sandstone cores, an intermediate crude oil with an API gravity of 33°, and synthetic brine with a low salinity of 10,000 ppm. A 1.5% palm-oil-based MES solution was injected at 60°C. The results indicated that the MES significantly enhanced the oil recovery efficiency compared with conventional waterflooding, yielding an incremental recovery of approximately 6%, which reduced the residual oil saturation from 31.29% to 26.25%.

Further research is recommended to investigate the field-scale applicability of MES, including assessments of surfactant adsorption, stability in saline environments, and compatibility with other EOR agents such as polymers or alkaline solutions. Such investigations are essential to generate comprehensive technical data that can support informed decision-making for future implementation. These studies would also provide critical insights for scaling MES application from laboratory settings to actual reservoir conditions and for developing integrated, eco-efficient CEOR strategies suitable for Indonesian oil fields.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
API	American Petroleum Institute gravity	
IFT	Interfacial Tension	mN/m
PV	Pore volume	cm
ϕ	Porosity	
μ	Viscosity	cP

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