JURNAL LOCUS: Penelitian & Pengabdian
Volume 5 No. 7 July 2026
E-ISSN 2829-7334| P-ISSN 2829-5439
Hompage: https://locus.rivierapublishing.id/index.php/jl

Evaluating the Effectiveness of MES-Based Palm Oil Surfactant in EOR Using Core Flooding and Spontaneous Imbibition Techniques

Rini Setiati[1]*, Muhammad Furqon Haryono Bimantoro[2], Muh.Taufiq Fathaddin[3], Fahrurrozi Akbar[4], Bharoto[5], Iwan Sumirat[6], Ranggi Ramadhan[7]
Universitas Trisakti, Indonesia[1,2,3]
Badan Riset Inovasi Nasional, Indonesia[4,5,6]
Science & Technology Facilities Council, United Kingdom[7]
Email: rinisetiati@trisakti.ac.id[1]*, Muhammadfurqon78867@gmail.com[2], muh.taufiq@trisakti.ac.id[3], fahr006@brin.go.id[4], bharoto@brin.go.id[5], iwan008@brin.go.id[6], ranggi.ramadhan@stfc.ac.uk[7]

Keywords:
Enhanced Oil Recovery, Methyl Ester Sulfonate (MES), core flooding, spontaneous imbibition

Abstract:
The increasing decline in oil production from mature reservoirs has encouraged the development of more effective and environmentally friendly Enhanced Oil Recovery (EOR) technologies. Surfactant flooding is a promising chemical EOR method because it can reduce interfacial tension, modify rock wettability, and mobilize trapped residual oil. This study aimed to evaluate the effectiveness of palm oil-based Methyl Ester Sulfonate (MES) surfactant in improving oil recovery through core flooding and spontaneous imbibition techniques. The experiment used Berea sandstone cores with approximately 21% porosity and 100 mD permeability, light crude oil with a gravity of 39°API, and two surfactant solution conditions: 5,000 ppm salinity with 0.5% MES concentration and 10,000 ppm salinity with 2% MES concentration. The results showed that the low-salinity MES solution provided better performance than the high-salinity condition. In the core flooding test, the 5,000 ppm salinity and 0.5% MES solution achieved the highest recovery factor of 84.74%, whereas the 10,000 ppm salinity and 2% MES solution achieved 62.63%. In the spontaneous imbibition test, the low-salinity condition resulted in 51.94% oil recovery, compared with 45.24% under high-salinity conditions. These findings indicate that lower salinity enhances surfactant stability, improves interfacial tension reduction, and promotes oil mobilization. Therefore, palm oil-based MES surfactant demonstrates strong potential as a sustainable chemical EOR agent for sandstone reservoirs.

INTRODUCTION

Energy demand worldwide continues to increase due to rapid economic and industrial growth, creating a need for more efficient and sustainable approaches to petroleum resource management (Alotaibi et al. 2023; Bashir et al. 2022; Jie et al. 2023; Sun et al. 2025; Wang and Azam 2024; Wang and Xu 2024). In many oil fields, production declines over time because reservoir pressure decreases and crude oil becomes more viscous, making it increasingly difficult to extract oil from porous rock formations. Therefore, advanced technologies are required to recover oil that remains trapped within reservoir formations. One widely applied approach is Enhanced Oil Recovery (EOR), which involves injecting specialized fluids into reservoirs to improve oil mobility and increase recovery efficiency (Sheng, 2013a; Castle, 2002).

Among various EOR methods, including gas injection, thermal recovery, and chemical injection, surfactant flooding is considered one of the most effective techniques because it can reduce interfacial tension between oil and water and alter rock wettability, thereby facilitating the mobilization of trapped oil. However, the practical application of synthetic surfactants faces several challenges, including high cost, limited availability of raw materials, and potential environmental impacts (Sheng, 2013b; Isaac et al., 2022; Massarweh & Abushaikha, 2020). Therefore, the development of alternative surfactants that are more economical and environmentally sustainable is necessary. One promising option is a vegetable-based surfactant, particularly Methyl Ester Sulfonate (MES), which can be produced from palm oil and offers greater sustainability compared with conventional synthetic surfactants (Rachman et al., 2020; Setiati et al., 2023).

MES surfactants possess several advantages, including biodegradability, stability under reservoir conditions, and effective interfacial tension reduction (Chakraborty et al. 2025; Fattahanisa et al. 2024; Oktario et al. 2023). In this study, core flooding and spontaneous imbibition experiments were conducted to evaluate the effectiveness of palm oil-based MES surfactant in improving oil recovery. The experiments were performed under two different salinity conditions, namely 5,000 ppm with a 0.5% surfactant concentration and 10,000 ppm with a 2% surfactant concentration, to compare surfactant performance under different reservoir environments.

The specific issue addressed in this study was the need to evaluate the effectiveness of palm oil-based MES surfactant under varying salinity and concentration conditions using laboratory methods representing both dynamic and static oil recovery mechanisms. The study focused on palm oil-based MES surfactant tested through core flooding and spontaneous imbibition experiments using salinity variations of 5,000 ppm with 0.5% surfactant concentration and 10,000 ppm with 2% surfactant concentration. Synthetic Berea sandstone cores with approximately 21% porosity and 100 mD permeability, along with light crude oil of 39°API gravity, were used to evaluate the surfactant's ability to improve recovery factor under controlled experimental conditions. These parameters are critical because salinity, surfactant concentration, rock properties, and crude oil characteristics directly influence interfacial behavior, surfactant adsorption, wettability alteration, and the mobilization of trapped oil.

Previous research has demonstrated that surfactant performance in EOR is strongly associated with its ability to reduce interfacial tension and modify wettability. Massarweh and Abushaikha reviewed recent advances in surfactant-based EOR and reported that surfactant flooding enhances oil recovery through mechanisms including interfacial tension reduction, wettability alteration, foam generation, and emulsification. However, they also highlighted significant challenges, such as surfactant instability and excessive adsorption onto reservoir rocks. These issues are important because surfactant adsorption reduces the concentration of active surfactant available within the pore system, thereby decreasing the technical and economic efficiency of chemical flooding. Consequently, surfactant selection should consider not only recovery factor improvement but also adsorption behavior, salinity tolerance, and compatibility with specific rock and fluid systems.

Recent experimental studies have further demonstrated the importance of comparing core flooding and spontaneous imbibition techniques to comprehensively evaluate surfactant performance. Zhang et al. investigated surfactant-enhanced oil recovery in tight reservoir cores using spontaneous imbibition and core flooding methods. Their findings showed that oil recovery from brine imbibition ranged from 4.3% to 15%, whereas surfactant-assisted imbibition increased recovery to approximately 9%–28%. In core flooding experiments, brine flooding achieved approximately 23%–25% recovery, while subsequent surfactant flooding increased recovery to approximately 33%–35%. These findings confirm that surfactants can significantly enhance oil recovery; however, the magnitude of improvement depends on pore structure, mineral composition, surfactant characteristics, and the applied displacement mechanism.

Studies on MES-based surfactants further indicate that bio-based anionic surfactants have considerable potential for EOR applications. Palm oil-based MES has been reported to reduce interfacial tension between oil and water and improve recovery performance in core flooding systems. Furthermore, MES has been investigated as an anionic biosurfactant for spontaneous imbibition applications in sandstone reservoir rocks under challenging salinity and temperature conditions. However, previous studies differ in terms of crude oil properties, salinity levels, core characteristics, surfactant concentrations, and experimental approaches. This variation highlights the need for more focused laboratory evaluations that directly compare low- and high-salinity conditions using both dynamic injection and spontaneous imbibition mechanisms. Such comparisons are necessary to determine whether palm oil-based MES performs more effectively as an injected chemical agent, an imbibition fluid, or both.

The research gap lies in the limited integration of palm oil-based MES surfactant evaluations across two complementary laboratory mechanisms—core flooding and spontaneous imbibition—under clearly differentiated salinity and concentration conditions. Many previous studies have investigated surfactant flooding or spontaneous imbibition separately, whereas fewer studies have compared both methods using the same surfactant system and comparable rock–fluid conditions. Furthermore, although bio-based surfactants are increasingly recognized as environmentally preferable alternatives, their performance requires further laboratory validation before broader field-scale application. This gap is particularly relevant because surfactant behavior is highly sensitive to salinity variations; excessive salt concentrations may disrupt micelle stability, increase surfactant adsorption, induce salting-out effects, and reduce interfacial tension reduction efficiency. Therefore, a systematic comparison between 5,000 ppm and 10,000 ppm salinity conditions can provide clearer evidence regarding the optimal operating range for palm oil-based MES applications in EOR.

The urgency of this research is supported by three interconnected considerations: energy security, mature-field productivity, and environmental sustainability. From an energy security perspective, improving recovery from existing reservoirs can reduce dependence on new exploration activities and extend the productive lifespan of current oil assets. From a technical perspective, surfactant-based EOR can address residual oil saturation remaining after waterflooding, thereby increasing recovery factor without requiring significant modifications to existing reservoir infrastructure. From an environmental perspective, palm oil-based MES provides a more sustainable alternative to conventional synthetic surfactants because it is derived from renewable feedstock and possesses potential biodegradability advantages. For

Indonesia and other palm oil-producing countries, this research is also strategically important because it connects domestic biomass resources with high-value petroleum technology applications.

The novelty of this research lies in the evaluation of palm oil-based MES surfactant through an integrated comparison of core flooding and spontaneous imbibition under two salinity–concentration combinations: 5,000 ppm with 0.5% MES and 10,000 ppm with 2% MES. This approach enables comparison between forced displacement and capillary-driven oil recovery mechanisms within the same experimental framework. The purpose of this study was to determine the effectiveness of palm oil-based MES surfactant in improving oil recovery and to identify the salinity and concentration conditions that provide superior recovery performance. The main objective was to evaluate how MES surfactant influences recovery factor through mechanisms including interfacial tension reduction, wettability alteration, and oil mobilization in sandstone core samples. The expected contribution of this study is to enrich the chemical EOR literature by providing laboratory-based evidence regarding bio-based surfactant performance. Practically, the findings may support the development of more sustainable, locally sourced, and technically feasible surfactant formulations for enhanced oil recovery applications.

METHOD

This study was conducted to evaluate the effectiveness of palm oil-based MES vegetable surfactant in improving the recovery factor during the EOR process using two main experimental methods: core flooding and spontaneous imbibition tests. These methods were applied to assess the surfactant's ability to enhance oil recovery (Zhang et al., 2023; Obuebite et al., 2023; Xie et al., 2024). The research consisted of several stages, including sample preparation, surfactant solution preparation, laboratory testing, and data analysis.

The core samples used in this study had dimensions of approximately 3 inches in length and 1.5 inches in diameter. The cores consisted of clean synthetic Berea sandstone with a porosity of approximately 21% and permeability of approximately 100 mD. The crude oil used was light crude oil with a gravity of 39°API, which exhibited relatively lower viscosity and higher mobility compared with heavy oil.

Surfactant Solution Preparation

MES Palm oil surfactant solutions were prepared under two conditions, namely:

1. Salinity of 5,000 ppm with a surfactant concentration of 0.5%, and
2. Salinity of 10,000 ppm with a surfactant concentration of 2%.

Synthetic formation water was prepared by dissolving NaCl salt into distilled water according to the desired salinity value (Swadesi et al., 2025; Wei et al., 2021; Druetta & Picchioni, 2020). MES surfactant was then added to the solution and stirred until homogeneous. The resulting surfactant solution was used as the injection fluid in both tests.

Core Flooding Test

To represent how fluid move inside reservoir rock in dynamic way, so it can show the performance of palm oil MES surfactant in improving oil recovery. Before the experiment begin, the core sample already in dry condition and physical properties like porosity and permeability already measured, then the core placed in core holder which connected to injection system with pressure and also pressure transducer for see pressure change during process. In the first step, the rock injected with synthetic brine until it reach full saturation, then crude oil injected continuously until no water produced again from the outlet, so it indicate that the core already fully filled by oil and ready for next stage.

Waterflooding process was done by injecting formation water first to get initial oil recovery before surfactant used. The flow rate used about 0.3 ml/minute and temperature set around 60 °C. After that, next step is injecting palm oil MES surfactant solution with two different condition, which is salinity 5,000 ppm with concentration 0.5% and also salinity 10,000 ppm with concentration 2%. The injection done continuously with constant flow rate using pressure pump until no more oil come out from core sample or production already drop very much. During all stage, volume of produced oil from waterflooding and surfactant flooding was collected and recorded, then used to calculate recovery factor by comparing produced oil with total initial oil inside rock (original oil in place).

$$\mathrm{RF} = \frac{Np}{\mathrm{OOIP}} \mathrm{X100} \qquad (1)$$

Spontaneous Imbibition Test

This test try to represent real reservoir condition where fluid can enter pore space by itself and push trapped oil out. Before experiment start, core sample was dried and checked for porosity and permeability so the property become consistent. After that, the rock first saturated with synthetic brine, then saturated again with crude oil until reach irreducible water saturation condition. Then the core which already full of oil placed vertically inside container filled with MES surfactant solution with two variation, which is 5,000 ppm salinity with 0.5% concentration and 10,000 ppm salinity with 2% concentration, to observe how oil can come out naturally from rock over time.

During soaking process, the oil that come out from core sample because of capillary force and wettability change was collected in measuring tube step by step to record how much oil produced over time. This process done in static condition with constant laboratory temperature until no more oil come out or the oil movement already become stable. The data of oil volume then used to calculate recovery factor, which is comparison between produced oil and total initial oil inside the rock (original oil in place). Besides that, visual observation also done to see how fluid enter the rock, how long the optimum soaking time, and also how stable the surfactant solution when interact with the rock. From this test, it can give general idea about effectiveness of MES surfactant in improving oil recovery by spontaneous imbibition mechanism, and also show the influence of salinity and concentration variation to the surfactant performance.

Data Analysis

The recovery factor from both test method was compared to find which condition is the most optimal. Analysis also done to see how salinity and surfactant concentration give effect to oil recovery efficiency. The highest recovery factor result then used as main reference to decide the effectiveness of palm oil MES surfactant as potential EOR agent in improving oil production.

RESULTS AND DISCUSSION

The results of this study were obtained from two main testing methods, namely the core flooding test and the spontaneous imbibition test, which aimed to assess the effectiveness of palm oil-based MES surfactants in increasing oil recovery. Both tests were conducted with two variations in salinity and concentration, namely 5,000 ppm at a concentration of 0.5% and 10,000 ppm at a concentration of 2%, to observe the effect of salt content and surfactant concentration on the efficiency of oil production enhancement.

The result from IFT test show that palm oil MES surfactant at salinity 10,000 ppm with light crude oil 39° API give IFT value around 1.049 dyne/cm. Meanwhile, in lower salinity condition 5,000 ppm, the same surfactant tested on light crude oil 39° API produce lower IFT value about 0.513 dyne/cm, which mean better ability to reduce tension between oil and water.

Adsorption test was carried out using surfactant concentration 0.5% and 2% with salinity 5,000 ppm and 10,000 ppm. In this test, two method was used which is static adsorption and dynamic adsorption. The result show that dynamic adsorption value is lower than static adsorption value. For condition 0.5% concentration and 5,000 ppm salinity, dynamic adsorption recorded around 0.40635 mg/g, while static adsorption reach about 12.434 mg/g. Also for 2% concentration and 10,000 ppm salinity, dynamic adsorption value is about 8.9 mg/g, while static adsorption much higher around 56,252 mg/g. This difference happen because static adsorption method use crushed rock, so surface area become more large and contact between rock and surfactant also increase. Because of that, adsorption value in static condition become higher, while dynamic adsorption give lower value.

Table 1. Static and Dynamic Adsorption test results

Types of Adsorption	MES 0,5%, salinity 5.000 ppm	MES 2%, salinity 10.000 ppm
Static Adsorption (mg/g)	12.434	56.252
Dynamic Adsorption (mg/g)	0.40635	8.900

3.1 Core Flooding Test

In this test, two different condition was applied, which is salinity 5,000 ppm with concentration 0.5% and also salinity 10,000 ppm with concentration 2%, to see how the variation of salinity and surfactant concentration can influence the efficiency of oil recovery in the system.

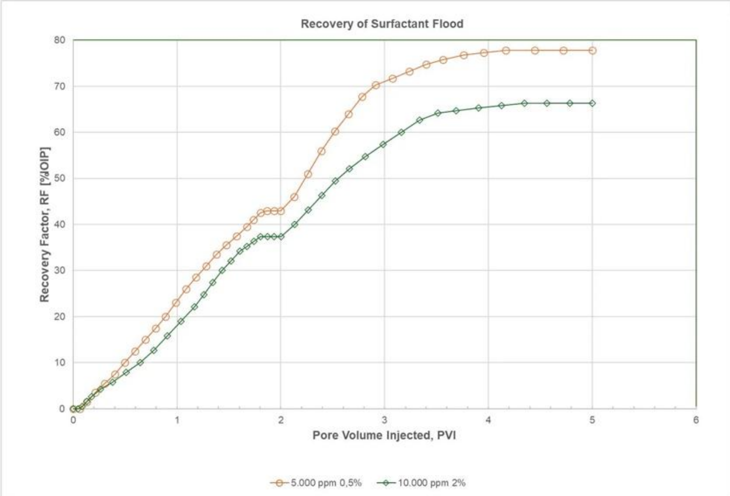

Figure 1. Comparison of core flooding performance at salinity 5,000 ppm and 10,000 ppm.

Figure 1 shows the comparison of core flooding performance at salinity 5,000 ppm and 10,000 ppm using palm oil-based MES surfactant. The low salinity condition of 5,000 ppm with surfactant concentration 0.5% demonstrated the highest recovery performance, where the recovery factor reached 84.74% at the end of the injection process. During the initial waterflooding stage up to approximately 2 PV, the recovery factor increased significantly to around 50%. After surfactant injection of about 1 PV, the recovery factor further increased to approximately 78.75%, and continued to rise during the post-flush stage until reaching its final value. This result indicates that the MES surfactant performed more effectively under low salinity conditions because the micelle stability and interfacial tension reduction became more optimal.

In addition, the lower salinity minimized the salting-out effect, allowing the surfactant to remain active in mobilizing the trapped oil throughout the flooding process. In contrast, the higher salinity condition of 10,000 ppm with surfactant concentration 2% showed a lower recovery performance during the core flooding test. The recovery factor increased more gradually, reaching only around 42.11% during the waterflooding stage, followed by an increase to 58.95% after surfactant injection and finally achieving 62.63% during the post-flush stage. The lower recovery efficiency suggests that surfactant performance decreased at higher salinity conditions. This behavior may be caused by stronger ionic interactions between salt ions and surfactant molecules, which can disturb micelle stability and reduce the surfactant ability to lower interfacial tension. Furthermore, part of the surfactant may have been adsorbed onto the rock surface, decreasing the amount of active surfactant available inside the pore system. As a result, the mobilization of residual oil became less effective compared to the low salinity condition.

3.2 Spontaneous Imbibition Testing

Spontaneous imbibition test was carried out to evaluate how palm oil based MES surfactant can improve oil recovery through natural soaking mechanism caused by capillary force and low interfacial tension. The graph in Figure 3 and Figure 4 show how recovery factor change over time during imbibition process, where oil slowly come out from the rock as the surfactant penetrate into pore and push the trapped oil.

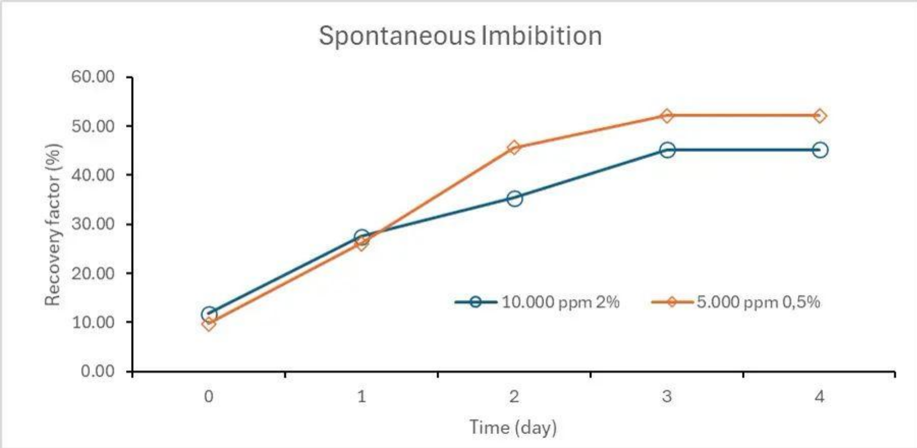

Figure 2. Comparison of spontaneous imbibition performance at salinity 5,000 ppm and 10,000 ppm.

Figure 2 shows the comparison of spontaneous imbibition performance at salinity 5,000 ppm and 10,000 ppm using palm oil-based MES surfactant. Under the low salinity condition of 5,000 ppm with surfactant concentration 0.5%, the recovery factor increased rapidly during the first two days, rising from approximately 10% to around 45%. On the third day, the recovery factor reached about 51.94% and then became relatively stable until the fourth day, indicating that equilibrium had been achieved between the adhesion and cohesion forces within the fluid-rock system. The significant increase in recovery factor demonstrates that the MES surfactant worked effectively under low salinity conditions by reducing interfacial tension and altering the rock wettability toward a more water-wet state. As a result, the trapped oil could be displaced more easily from the pore spaces of the core sample.

In contrast, the spontaneous imbibition test at salinity 10,000 ppm with surfactant concentration 2% showed a slower and lower recovery performance compared to the low salinity condition. The recovery factor gradually increased and only reached around 45.24% on the third day, after which the value remained almost constant with no significant improvement. This behavior suggests that high salinity negatively affected the performance of the surfactant. Strong ionic interactions at high salinity may reduce micelle stability and promote the salting-out effect, causing the surfactant to lose its effectiveness in reducing interfacial tension and altering rock wettability. Consequently, the surfactant penetration into the core matrix became less effective, resulting in lower oil recovery.

Overall, both experimental methods showed consistent trends where lower salinity condition (5,000 ppm) resulted in better oil recovery compared to higher salinity condition (10,000 ppm). However, the core flooding test produced higher recovery factors than spontaneous imbibition because the injection pressure during flooding provided additional driving force for oil displacement. In spontaneous imbibition, the recovery process mainly depended on natural capillary force and surfactant diffusion, causing the oil recovery to occur more gradually. These results confirm that palm oil-based MES surfactant has good potential for enhanced oil recovery applications, particularly under low salinity reservoir conditions where surfactant stability and interfacial tension reduction become more optimal.

CONCLUSION

This study concludes that palm oil-based Methyl Ester Sulfonate (MES) surfactant has strong potential as an environmentally friendly chemical agent for Enhanced Oil Recovery (EOR), particularly under low-salinity conditions. The experimental results from both core flooding and spontaneous imbibition tests consistently demonstrated that the 5,000 ppm salinity condition with 0.5% MES concentration provided better oil recovery performance than the 10,000 ppm salinity condition with 2% MES concentration. In the core flooding test, the low-salinity MES solution achieved the highest recovery factor of 84.74%, whereas the higher-salinity condition achieved 62.63%. Similarly, in the spontaneous imbibition test, the 5,000 ppm salinity condition resulted in a recovery factor of 51.94%, compared with 45.24% under the 10,000 ppm condition. These findings indicate that lower salinity enhances MES surfactant performance by promoting more effective interfacial tension reduction, improved micelle stability, reduced adsorption tendency, and more favorable wettability alteration. Therefore, palm oil-based MES surfactant can be considered a promising bio-based alternative to conventional synthetic surfactants for improving oil recovery, particularly in sandstone reservoirs with suitable salinity conditions.

Future research should expand the evaluation of palm oil-based MES surfactant under more diverse reservoir conditions, including variations in crude oil viscosity, rock mineralogy, temperature, pressure, and brine composition. Further studies should investigate broader surfactant concentration and salinity ranges to determine the optimal formulation window more accurately. Since surfactant adsorption remains a major challenge in surfactant flooding applications, future research should explore adsorption mitigation strategies, such as the application of co-surfactants, alkaline agents, polymers, or nanoparticles to improve surfactant efficiency and displacement performance. In addition, reservoir simulation and pilot-scale testing are required to validate laboratory findings and evaluate the economic feasibility of palm oil-based MES surfactant for field-scale EOR applications. Future studies may also compare palm oil-based MES with other bio-based and synthetic surfactants to assess its relative technical, environmental, and economic advantages for sustainable petroleum recovery.

REFERENCES

Alotaibi, B. A., Baig, M. B., Najim, M. M. M., Shah, A. A., & Alamri, Y. A. (2023). Water scarcity management to ensure food security through sustainable water resources management in Saudi Arabia. *Sustainability, 15*(13), 10648. https://doi.org/10.3390/su151310648

Bashir, M. F., Sadiq, M., Talbi, B., Shahzad, L., & Bashir, M. A. (2022). An outlook on the development of renewable energy, policy measures to reshape the current energy mix, and how to achieve sustainable economic growth in the post COVID-19 era. *Environmental Science and Pollution Research, 29*(29), 43636–43647.

Boni Swadesi, B., Azmi, F. B., Pratiknyo, A. K., Kurniawan, A., & Suwardi. (2025). Salinity effects on anionic AEC surfactant with crude oil: IFT, phase behavior, solubilization, microemulsion viscosity. *Journal of Earth Energy Science, Engineering, and Technology, 8*(3), 91–98. https://doi.org/10.25105/tqms0g23

Castle, W. F. (2002). Air separation and liquefaction: Recent developments and prospects for the beginning of the new millennium. *International Journal of Refrigeration, 25*(1).

https://doi.org/10.1016/S0140-7007(01)00003-2
Chakraborty, R., Jangid, L., Pandey, R., Pasivedala, R. K., Shaw, T., Dutta, R., & Mandal, A. (2025). Synergistic effects of nonionic surfactant and organic alkali for enhanced oil recovery: Optimizing interfacial tension reduction, emulsion stability, and corrosion control under optimal salinity conditions. *Energy & Fuels, 39*(7), 3462–3476.
Druetta, P., & Picchioni, F. (2020). Surfactant flooding: The influence of the physical properties on the recovery efficiency. *Petroleum, 6*(2), 149–162. https://doi.org/10.1016/j.petlm.2019.07.001
Fattahanisa, A., Fathaddin, M. T., Setiati, R., & Chusniyah, D. A. (2024). Effect of temperature on palm oil MES surfactant on oil recovery improvement. In *Understanding Global Digital Era Technologies and Transformations in Social, Environment, Peace & Business Development Perspectives in Society* (Vol. 229).
Isaac, O. T., Pu, H., Oni, B. A., & Samson, F. A. (2022). Surfactants employed in conventional and unconventional reservoirs for enhanced oil recovery—A review. *Energy Reports, 8*, 2806–2830. https://doi.org/10.1016/j.egyr.2022.01.187
Jie, H., Khan, I., Alharthi, M., Zafar, M. W., & Saeed, A. (2023). Sustainable energy policy, socio-economic development, and ecological footprint: The economic significance of natural resources, population growth, and industrial development. *Utilities Policy, 81*, 101490.
Kun Xie, K., Wu, Z., Liu, C., Mei, J., Cao, W., Ding, H., Zhang, X., Xu, H., Suo, Y., Tian, X., & Lu, X. (2024). A review of mechanisms and ML-based research on factors affecting spontaneous imbibition of surfactant. *Geoenergy Science and Engineering, 240*, 213071. https://doi.org/10.1016/j.geoen.2024.213071
Massarweh, O., & Abushaikha, A. S. (2020). The use of surfactants in enhanced oil recovery: A review of recent advances. *Energy Reports, 6*, 3150–3178. https://doi.org/10.1016/j.egyr.2020.11.009
Oktario, R., Setiati, R., Bimantoro, M. F. H., Triatmaja, R. F., & Yanti, W. (2023). Phase behavior with salinity levels of 10,000 and 5,000 ppm using MES surfactant with 48 API oil on laboratory. In *Technology, Sustainability, and Industrial Applications: Evidence from Energy Systems, Accounting, and Design Studies* (Vol. 73).
Obuebite, A. A., Yousuo, D., & Okwonna, O. (2023). Spontaneous imbibition and core flooding analysis of pH adjusted alkali and surfactant system in high salinity sandstone reservoir. *World Journal of Advanced Engineering Technology and Sciences, 8*(2), 254–266. https://doi.org/10.30574/wjaets.2023.8.2.0102
Rachman, A., Setiati, R., & Hartono, K. F. (2020). Laboratory studies to increase oil production using methyl ester sulfonate injection on X field. *Journal of Earth Energy Science Engineering and Technology, 2*(3), 62–67. https://doi.org/10.25105/jeeset.v2i3.6385
Setiati, R., Fathaddin, M. T., & Hani, B. (2023). Emulsion formation in palm oil methyl ester sulfonate surfactant to light crude oil. *Journal of Earth Energy Science Engineering and Technology, 6*(2), 70–75. https://doi.org/10.25105/jeeset.v6i2.179
Sheng, J. J. (2013). *Enhanced oil recovery*. Gulf Professional Publishing. https://doi.org/10.1016/C2010-0-67974-0
Sheng, J. J. (2013). Surfactant enhanced oil recovery in carbonate reservoirs. In *Enhanced oil recovery field case studies* (pp. 281–299). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-12-386545-8.00012-9
Sun, H., Wang, Z., Meng, Q., & White, S. (2025). Advancements in hydrogen storage technologies: Enhancing efficiency, safety, and economic viability for sustainable energy transition. *International Journal of Hydrogen Energy, 105*, 10–22.
Wang, J., & Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers, 15*(2),

101757.
Wang, X., & Xu, X. (2024). Sustainable resource management and green economic growth: A global prospective. *Resources Policy, 89*, 104634.
Wei, B., Wang, L., Song, T., Zhong, M., & Varfolomeev, M. A. (2021). Enhanced oil recovery by low-salinity water spontaneous imbibition (LSW-SI) in a typical tight sandstone formation of Mahu Sag from core scale to field scale. *Petroleum, 7*(3), 272–281. https://doi.org/10.1016/j.petlm.2020.09.005
Zhang, S., Zhu, F., Xu, J., Liu, P., Chen, S., & Wang, Y. (2023). Spontaneous imbibition and core flooding experiments of enhanced oil recovery in tight reservoirs with surfactants. *Energies, 16*(4), 1815. https://doi.org/10.3390/en16041815