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Methyl Ester Sulfonate: An Anionic Biosurfactant for Enhanced Oil Recovery in Harsh Condition

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ABSTRACT - Chemical enhanced oil recovery (EOR) is a tertiary phase method used to extract significant amounts of residual crude oil that primary and secondary recovery phases cannot recover. Surfactants are crucial in chemical EOR for their impact on rock surfaces and water-oil interfaces. Optimizing these formulations under reservoir conditions is essential before their use in oil recovery. However, screening is challenging due to the variety of surfactants and their sensitivity to reservoir conditions and rock types. This study introduces methyl ester sulfonate (MES), an anionic bio-surfactant, to improve the oil recovery factor (RF). Spontaneous imbibition (SI) experiments measured MES's ability to enhance oil RF in sandstone reservoir rocks under high salinity and temperature. The results showed MES's excellent performance even under high salinity conditions. On day 14, MES samples under 30 kppm salinity and 80°C with concentrations of 0.5 mM, 2 mM, and 3 mM had RF values of 12%, 18%, and 26%, respectively. Under 40 kppm salinity and 80°C, the RF values were 17%, 19%, and 27%, respectively. MES enhances oil recovery efficiency and preserves environmental health due to its biodegradability, making it a safer alternative to traditional surfactants. Its use can significantly improve chemical EOR processes under challenging conditions. As a novelty, this study also explains the mechanism of MES in changing the wettability of sandstone to the intermolecular scale.

Keywords: EOR, biosurfactant, MES, anionic, high-salinity.

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INTRODUCTION

By 2040, worldwide energy demand is projected to rise by 30% compared to 2010, with oil consumption expected to reach 111.1 million barrels per day (Karatayev et al. 2019). With dwindling oil reserves and increasing energy demand due to population growth and industrial development, improving oil recovery from declining reservoirs is crucial (Joshi et al. 2015). Oil recovery consists of three phases: primary, secondary, and tertiary. The primary and secondary phases are conventional extraction methods, while the tertiary phase, known as enhanced oil recovery (EOR), involves advanced techniques (Pogaku et al. 2018). Primary recovery yields less than 30% of original oil in place (OOIP) through natural flow and artificial lift, relying on mechanisms like solution-gas drive, gas-cap drive, water drive, rock and liquid expansion, and gravity drainage (Aljuboori et al. 2019). A combination of these mechanisms often supports primary recovery (Gyan et al. 2019).

Continuous oil production leads to a drop in pressure gradient in the reservoir, reducing production rates as per Darcy's law (Höök et al. 2014). To boost oil production, drawdown pressure is increased by lowering the bottom-hole pressure (BHP) in the production well through artificial lift. This method compensates for the decreased energy from natural drive mechanisms over time (Davarpanah & Mirshekari 2018). Various artificial lift systems are used globally, including hydraulic jet pumping, gas lift, plunger lift, beam pumping, and hydraulic piston pumping. The choice of lift system depends on factors like downhole pressure/temperature, fluid properties, completion type, hole characteristics, well location, operating personnel, surface climate, available power sources, and economics (Brown 1982).

If primary oil recovery is no longer viable, secondary recovery methods like water flooding and gas injection are used (Haq et al. 2020). Water flooding involves injecting water into the reservoir through several wells to maintain pressure and displacing oil, which is then collected through production wells (Al-Obaidi & Khalaf, 2019). However, water injection has limitations on reservoir heterogeneities can cause water to flow through highly permeable pathways, leaving parts of the reservoir unswept, and oil can be trapped in small rock matrix interstices due to oil–water surface tension (Blunt et al. 1993).

After the primary and secondary recovery phases, significant amounts of crude oil, averaging 40%, remain unrecovered (Massarweh & Abushaikha 2020). To address this, the tertiary recovery phase, known as enhanced oil recovery (EOR), is used to increase oil recovery (Sugihardjo 2022). EOR includes methods like chemical flooding, gas injection, microbial recovery, and thermal recovery (F. Jin et al. 2020). These operations enhance oil displacement efficiency by improving microscopic and macroscopic displacement by adjusting oil viscosity, rock wettability, interfacial tension (IFT), capillary forces, and mobility ratios of displacing and displaced fluids (Haruna et al. 2020).

Spontaneous imbibition, driven by capillary pressure, pulls a wetting fluid into a porous medium through capillary action (Haugen et al. 2014). Capillary pressure, the product of interfacial tension and curvature, depends on surface forces and pore geometry (Morrow & Mason 2001). When the curvature is concave relative to the porous phase and conditions allow, spontaneous displacement occurs (Li et al. 2022). The dynamic effects of this process influence the contact angle and interface shape. This mechanism is vital for extracting oil from low-permeability rock matrices. Understanding these pore-scale processes is key to designing and optimizing oil recovery methods.

Chemical EOR employs a variety of agents like surfactants, alkalis, polymers, and nanoparticles (Olayiwola & Dejam 2019). Surfactants are key in the petroleum industry for their effect on rock surfaces and water-oil interfaces (Zulkifli et al. 2020). Optimizing surfactant formulations under reservoir conditions is necessary before use in oil recovery. This involves a challenging process called surfactant screening, which requires significant time and resources (Wang et al. 2019). Screening is difficult because surfactant types are highly affected by reservoir conditions and rock types, and there's a wide range of potential surfactants for EOR (Ivanova et al. 2020). Thus, selecting the right group for initial screening is complex (Miller et al. 2020).

MES is an anionic bio-based surfactant known for its self-assembly, excellent surface activity, water solubility, and good wetting power. It is produced through the sulfonation of fatty acid methyl esters or the alkaline neutralization of methyl ester sulfonic acid (Soy et al. 2020). MES features carbon chains and a sulfonic group, representing the hydrophobic and hydrophilic parts, making it ideal for surfactant-enhanced remediation in organic-contaminated soil (Y. Jin et al. 2016). As a degradable surfactant with excellent interfacial properties, MES is more environmentally friendly than traditional surfactants, effectively reducing the interfacial tension (IFT) at the oil-water interface and changing rock wettability from oil-wet to water-wet (Gbadamosi et al. 2022). Various bio-based surfactants have shown similar potential in reducing IFT and altering rock wettability (Daniati et al. 2023). Our study introduces MES surfactant as an alternative option for chemical enhanced oil recovery operations in harsh salinity and high temperature conditions. MES surfactant was tested to measure its ability to increase the recovery factor value by using the spontaneous imbibition experiment method. In addition to increasing the value of the oil recovery factor, the use of MES surfactant, which is eco-friendly, is an innovative step towards chemical EOR operation in terms of preserving environmental health. The mechanism of MES in increasing the oil recovery factor value is visualised using several schematic objects displayed in this report. This breakthrough is expected to be a very impactful solution to the challenges faced by chemical EOR operations.

METHODOLOGY

Materials

Rock sample

This study employed Berea sandstones as a representative sample of sandstone rocks. As shown in Table 1, the predominant mineralogical composition of sandstone is quartz, which is 80.2 % of the total.

Table 1
Berea sandstone mineral compositions

Minerals	Composition (%)
Quartz	80.2
Microline	7.4
Albite	4.6
Kaolinite	4.2
Muscovite	3.2
Ankerite	0.4

Rock samples were prepared by dividing the Berea sandstone into 6 pieces. Each piece was sized to be as similar as possible in diameter and length. The porosity of the six core samples was measured using a helium porosimeter instrument. For the saturation of the core samples, firstly, the core samples had to be made dry by placing them in an oven at 110 for 7 days and then measuring the dry weight. Secondly, the cores were immersed in saline water and left in an 80 oven for 120 minutes and then measured the weight of the water saturated cores. Thirdly, the cores were immersed in crude oil samples and left in a vacuum oven at 80 for 7 days and then measured the weight of the water-oil saturated cores.

$$m_w = m_{wc} - m_d \qquad \text{Equation 1}$$

$$m_{wo} = m_{woc} - m_d \qquad \text{Equation 2}$$

$$m_o = m_{wo} - m_w \qquad \text{Equation 3}$$

$$V_{oi} = \frac{m_o}{\rho_o} \qquad \text{Equation 4}$$

$$V_w = \frac{m_w}{\rho_w} \qquad \text{Equation 5}$$

$$V_p = V_{oi} + V_w \qquad \text{Equation 6}$$

$$S_w = \frac{V_w}{V_p} \qquad \text{Equation 7}$$

$$S_{oi} = \frac{V_{oi}}{V_p} \qquad \text{Equation 8}$$

Equation 1 to equation 8 are used sequentially to support the preparation of core samples. is mass of dry core, is mass of saturated water, is mass of saturated oil, is the mass of saturated water-oil, is mass of water saturated core, and is mass of water-oil saturated core, all mass is in gram [g] unit. is volume of saturated water, is volume of initial saturated oil, and is core pore volume, and all volume is in milliliter units [mL]. is density of saturated water, and is density of saturated oil, all density is in gram per milliliter [g/mL] unit. is water saturation, and is initial oil saturation, all saturation is in percentage.

Table 2
Core samples properties

Properties	Core					
	#1	#2	#3	#4	#5	#6
d (cm)	3.2	3.2	3.2	3.2	3.2	3.2
l (cm)	4.5	4.4	4.6	4.6	4.4	4.4
V_b (mL)	36.19	35.39	36.19	37.00	36.19	35.39
V_p (mL)	6.91	6.65	6.84	6.88	6.73	6.65
V_{oi} (mL)	6.91	6.65	6.84	6.88	6.73	6.65
ϕ (%)	19.1	18.8	19.0	18.6	18.2	18.8
S_{oi} (%)	99.99	99.99	99.99	99.98	99.99	99.99

After completing all measurements and calculations, record the oil saturation values from core #1 to core #6, as shown in Table 2. These values represent the initial oil saturation *(*S_{oi}*)* for spontaneous imbibition testing. In addition, other properties are also shown in Table 2 such as diameter *(d)*, length *(l)*, bulk volume *(*V_b*)*, pore volume *(*V_p*)*, initial oil volume *(*V_{oi}*)* and porosity *(*ϕ*)*.

Crude oil

The crude oil sample used in this study was obtained from an oil production field in Sumatra, Indonesia. This oil sample has a light crude oil class with a value of 33.8. The properties of the crude oil used in this study are detailed in Table 3.

Table 3
Crude oil properties

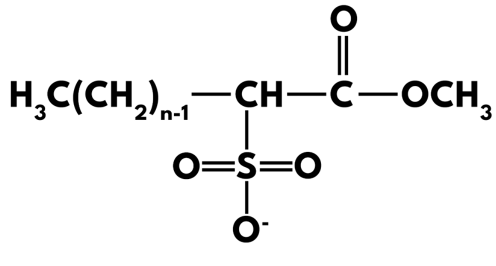
Properties	Magnitude
μ	14 cP
ρ	0.856 g/mL
$^{\circ}API$	33.8
Class	Light Crude Oil

Saline water

Two types of concentrations of saline water were used in this study. The first is synthetic saline water with concentrations of 30 kilo ppm and the second type is synthetic saline water with concentrations of 40 kilo ppm [kppm]. Both types of saline water were composed of pure NaCl only.

Surfactant

Methyl ester sulfonate (MES) is an anionic eco-friendly surfactant from palm oil, noted for its low manufacturing costs, high detergency with minimal dosage, biodegradability, and high tolerance to hard water (Low et al. 2021). Being carbon neutral and effective in hard water, MES is gaining global attention for its high performance and low eco-toxicity. MES contains a negative ion on its oxygen atom (O). Naturally, sodium (Na) acts as the counterion for MES, as illustrated in Figure 1.



$$H_3C(CH_2)_{n-1}-\underset{\underset{\underset{O^-}{|}}{O=S=O}}{\underset{|}{CH}}-\overset{\overset{O}{\|}}{C}-OCH_3$$

Figure 1
Molecule structure of MES

MES surfactant was prepared in three concentrations which are 0.5, 1, and 2 millimolar [mM]. Two bulk solutions were used, containing 30 and 40 kppm of synthetic saline waters, as detailed in Table 4. The two types of bulk solutions were selected based on previous solubility tests, which demonstrated that MES surfactant maintains stable solubility at these specific salinity concentrations.

Table 4
Concentration of MES surfactant samples

Samples	Concentration	Salinity
MES 1	0.5 mM	30 kppm
MES 2	2.0 mM	30 kppm
MES 3	3.0 mM	30 kppm
MES 4	0.5 mM	40 kppm
MES 5	2.0 mM	40 kppm
MES 6	3.0 mM	40 kppm

METHODOLOGY

The method for measuring interfacial tension (IFT) in this study was the spinning drop tensiometer (SDT). The spinning drop tensiometer is widely used method in measuring IFT (Deng et al. 2023). The spinning drop tensiometer was provided by Kruss. The IFT measurement relies on the Young-Laplace theory, which determines the IFT by analyzing the shape of a rotating drop of an immiscible liquid around a horizontal axis (Viades-Trejo & Gracia-Fadrique 2007). As centrifugal force increases to a certain point, the drop stretches into a cylindrical shape (Princen 1995). The elongation stops when the centrifugal forces are balanced by the interfacial tension forces. The IFT is measured under ambient conditions, with a temperature of 80 and a pressure of 1 atm.

The Contact angle (CA) was measured using the Geniometer Ramé-hart to track alterations in rock wettability during the initial conditions, 7 days, and 14 days. Prior to conducting CA measurements, sandstone samples were prepared. The rock sample was segmented into several coin-shaped pieces and the surface of these rock coins was smoothened using sandpaper. Subsequently, the rock coins were rinsed with deionized water and oven-dried for 7 days to remove any residual deionized water. Following this, the rock coins were placed in a vacuum for 1 day and then saturated with crude oil for a fortnight. Once the rock sample preparation was finalized, initial CA measurements were performed on all rock coins and air as surrounding phase. After confirming the initial CA, the rock coins were immersed in MES surfactant solutions. Finally, all the samples were placed in an oven set at a temperature of 80ºC. The second measurement was taken on the seventh , and the third measurement was taken on the fourteenth day with air as the surrounding phase. Measurements was conducted in conditions of 1 atm pressure and 25°C temperature.

Spontaneous imbibition (SI) experiment in porous media is the most important method to quantify oil production and predict the oil recovery rate (You et al. 2018). The Amott test is a commonly used laboratory method to quantify the oil recovery performance through spontaneous imbibition (Alkan et al. 2019). With this experiment, the rock of interest is saturated with the nonwetting phase, oil, and placed in a glass bottle with a graduated cylinder. The bottle is then filled with the wetting phase, such as surfactant, resulting in counter-current flow, where the extracted oil from the rock is measured over time.

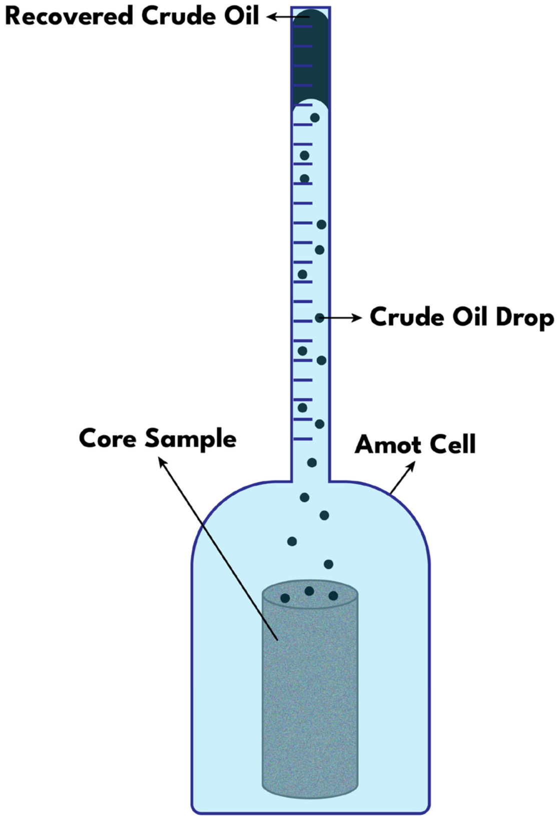


Figure 2
Spontaneous imbibition experiment using amott cell

This study presents the Amott concept in a spontaneous imbibition experiment, as shown in Figure 2. A total of six Amott cells were each prepared to hold six core samples to be treated by MES surfactant. All core samples were treated at the same time and under the same temperature conditions at 80. The experiment was carried out for 14 days, and every day a record was made of the volume of oil that rise to the top of the cell as recovered oil.

RESULT AND DISCUSSION

Result

Interfacial tension, a measure of the force at the interface between two immiscible liquids like oil and water, stems from the differing molecular attractions within each liquid compared to those at the interface. This phenomenon is essential in processes such as emulsification, wetting, and fluid dynamics in porous media. In the context of chemical enhanced oil recovery, decreasing interfacial tension is critical, as it diminishes capillary forces, thereby facilitating the mobilization of oil from rock pores. This improves volumetric sweep efficiency and increases the capillary number, ultimately enhancing oil recovery rates by allowing injected fluids to displace the oil within the reservoir more effectively (Auni et al. 2023).

Figure 3 shows the result of interfacial tension (IFT) measurements in condition of 1 atm pressure and 80. IFT value continues to decrease as MES concentration increases for both salinity conditions, 30 kppm and 40 kppm. The lowest IFT of MES+30 kppm is 0.04 mN/m at a concentration of 0.4 mM. Meanwhile, the lowest IFT value of MES+40 kppm is 0.02 mN/m at concentration of 0.3 mM. With those values, MES has proven to be potentially applicable as IFT reducer of light crude oil for chemical injection in high salinity EOR operation.

The contact angle, which forms where a liquid interfaces with a solid surface, indicates how well a liquid spreads and measures wettability. A lower contact angle means the liquid spreads easily, signifying high wettability, whereas a higher contact angle indicates poor wettability, with the liquid forming droplets. In chemical enhanced oil recovery (EOR), altering the wettability of reservoir rocks from oil-wet to water-wet is crucial for improving oil recovery rates. This alteration, achieved through surfactants or nanofluids that modify rock surface properties, allows water to spread more effectively and displace oil, potentially boosting recovery rates.

As illustrated in Figure 4, methyl ester sulfonate with 2.0 mM concentration consistently reduces the contact angle even in high salinity and high temperature condition. Before being treated with MES, the initial contact angles of sandstone are 115 and 111, which is oil-wet. After being treated with MES, the contact angles of sandstone are 41 and 40 in only 7 days. In 14 days, contact angles of sandstone are 37 and 30, which is strongly water-wet. With those values, MES has proven to be potentially applicable for chemical injection as a wettability modifier of sandstone rock in high salinity EOR operation.

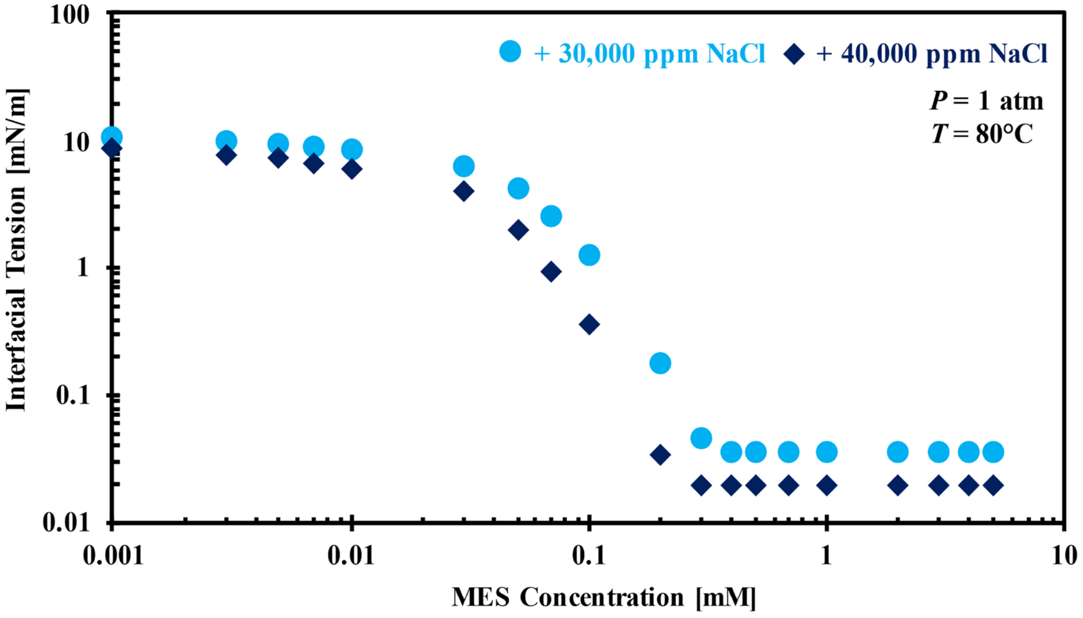


Figure 3
Interfacial tension measurement results

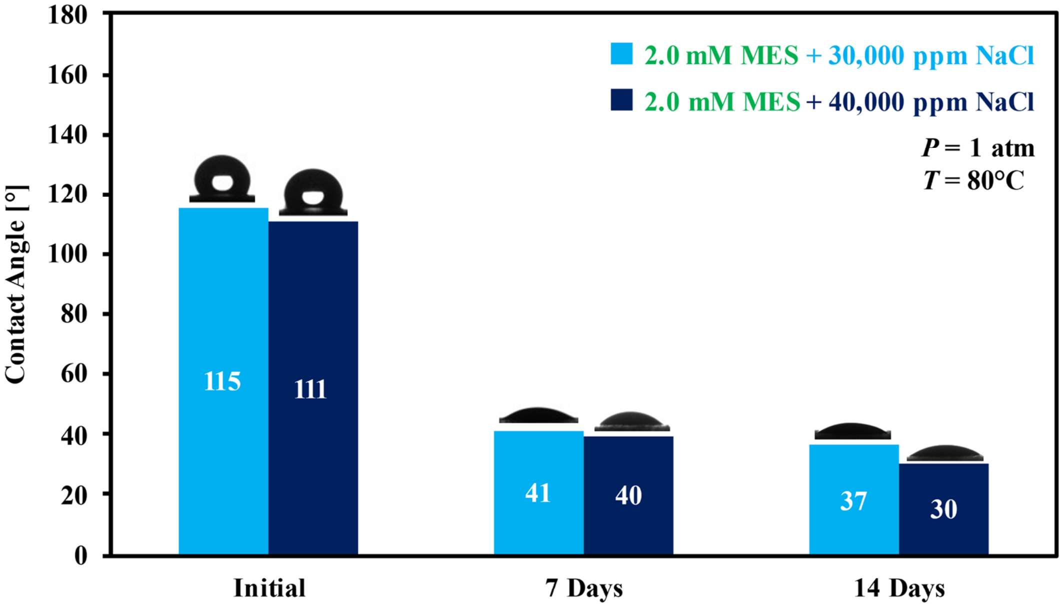


Figure 4
Contact angle measurement results

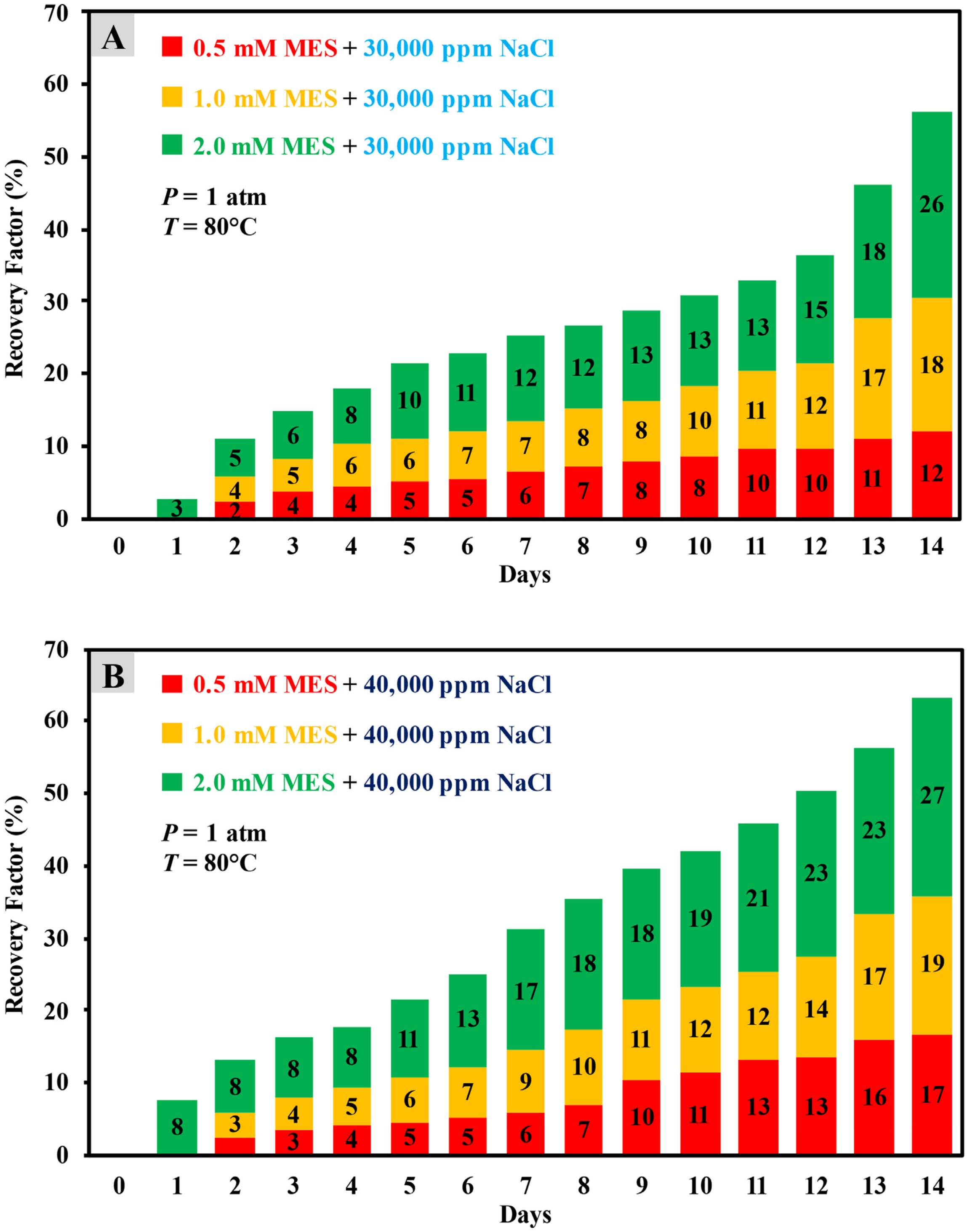


Figure 5
Spontaneous imbibition experiment result, (A) MES + 30 kppm NaCl, (B) MES + 40 kppm NaCl

Spontaneous imbibition, where a wetting fluid naturally seeps into porous rock driven by capillary forces, displaces non-wetting fluids without the need for external pressure. This essential mechanism in naturally fractured reservoirs relies on capillary pressure to facilitate fluid movement between fractures and the surrounding rock matrix (Oktaviany et al., 2022). In chemical enhanced oil recovery, the efficiency of spontaneous imbibition is vital for improving recovery rates, as it enhances oil displacement from the rock matrix. By utilizing chemicals like surfactants that reduce interfacial tension and modify wettability, the process becomes even more effective, significantly increasing the overall recovery factor and making it an invaluable technique in oil recovery method.

As presented in Figure 5A, MES surfactant with 30 kppm saline water demonstrated positive results. The recovery factor (RF) values increased gradually and stabilized at all concentrations. On day 7, the RF values were 6% for 0.5 mM MES, 7% for 1.0 mM MES, and 12% for 2.0 mM MES. By day 14, these RF values increased to 12%, 18%, and 26%, respectively.

Meanwhile, MES surfactant with 40 kppm saline water also shows good results, as shown in Figure 5B. The recovery factor (RF) values increased gradually at all concentrations. On day 7, the RF values were 6% for 0.5 mM MES, 9% for 1 mM MES, and 17% for 2 mM MES. By day 14, these RF values increased to 17%, 19%, and 27%, respectively.

Table 5
Treated cores by MES surfactant

Samples		V_{oi}	V_{or}	RF
Rock	**MES**	**(mL)**	**(mL)**	**(%)**
Core 1	MES 1	6.91	0.84	12
Core 2	MES 2	6.65	1.22	18
Core 3	MES 3	6.84	1.76	26
Core 4	MES 4	6.88	1.15	17
Core 5	MES 5	6.73	1.29	19
Core 6	MES 6	6.65	1.83	27

The details of core samples treated by MES surfactant with both 30 and 40 kpmm salinity can be seen in Table 5. It can be noticed that as the concentration of MES increases, the volume of recovered oil increases and has an impact on increasing the oil recovery factor value.

Discussion

Crude oil that has been released from the rock surface will be attached to the tail of the MES molecule which is hydrophobic and carried to the outside of the core sample. The arrangement of the MES molecule has a non-polar region that hydrophobic on the carbon chain in the tail area and a polar part on the oxygen atom in the head area. The nonpolar tail of MES will attach to oil and the head of MES will attach to water's minerals so that the tension between oil-water interface will be decreased (Maurya & Mandal, 2018). This phenomenon caused an emulsion to occur in the rock's pore (Nesterenko et al., 2014). The oil will emulsify in water in the form of small droplets, as shown in Figure 6. The crude oil that comes out of the core sample represents the crude oil that is successfully produced.

The key mechanisms of MES in increasing recovery factor are rock's wettability alteration and oil-water's interfacial tension reduction (Deng et al., 2021). Initially, crude oil is absorbed into the pore of the rock and adheres to the rock surface. MES will be adsorbed to the rock surface and form a polar layer, causing the wettability of the rock to alter to water-wet. MES is adsorbed to the rock surface by penetrating the crude oil layer attached to the rock surface. This phenomenon is caused by interaction of intermolecular forces (IMF) between MES and silica oxide (SiO_2) minerals (Huang et al., 2021). Thus, the crude oil layer that was initially attached to the rock surface will be penetrated by MES molecules and released into the rock pore.

The silica oxide molecule consists of one silicon (Si) atom and two oxygen (O) atoms. The oxygen atom has an electronegativity of 3.44 while the silicon atom has an electronegativity of 1.9. Both oxygen atoms that have a higher electronegativity attract more electrons in the SiO_2 molecule. As a result, the distribution of the number of electrons that occur in the molecule is uneven. As shown in Figure 7, electron clouds with many electrons tend to have a negative charge while electron clouds with few electrons have a positive charge (Rantih et al., 2019). This is what causes the IMF phenomenon of attraction between MES and silica oxide. MES which has a negative charge attracts each other with the silicon atoms of the SiO_2 molecule. This force of attraction is called ion-induced dipole type IMF. Ion-induced dipole IMF have an energy of 3-15 kJ/mol (Stone, 2013).

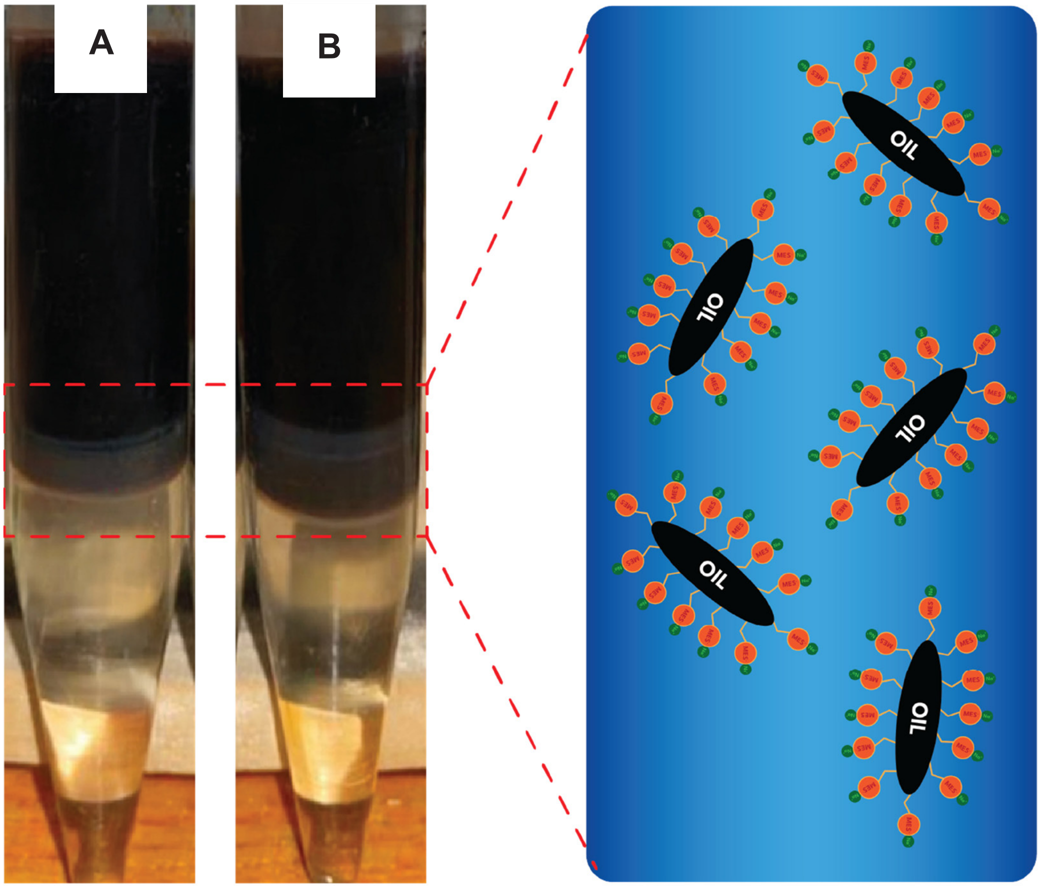


Figure 6
Oil-water emulsification by MES addition, (A) MES + 30 kppm NaCl, (B) MES + 40 kppm NaCl

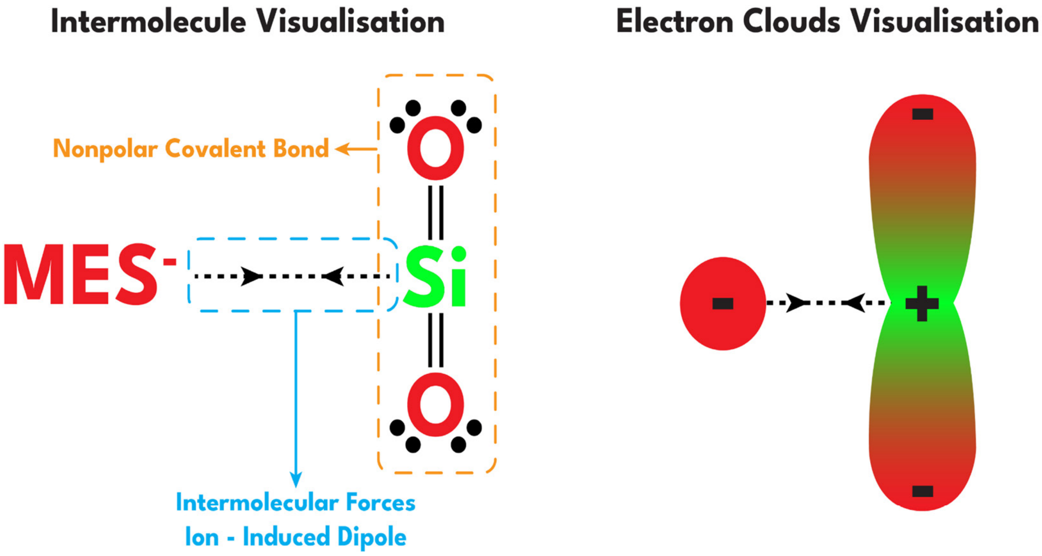


Figure 7
Intermolecular forces of MES - silica oxide

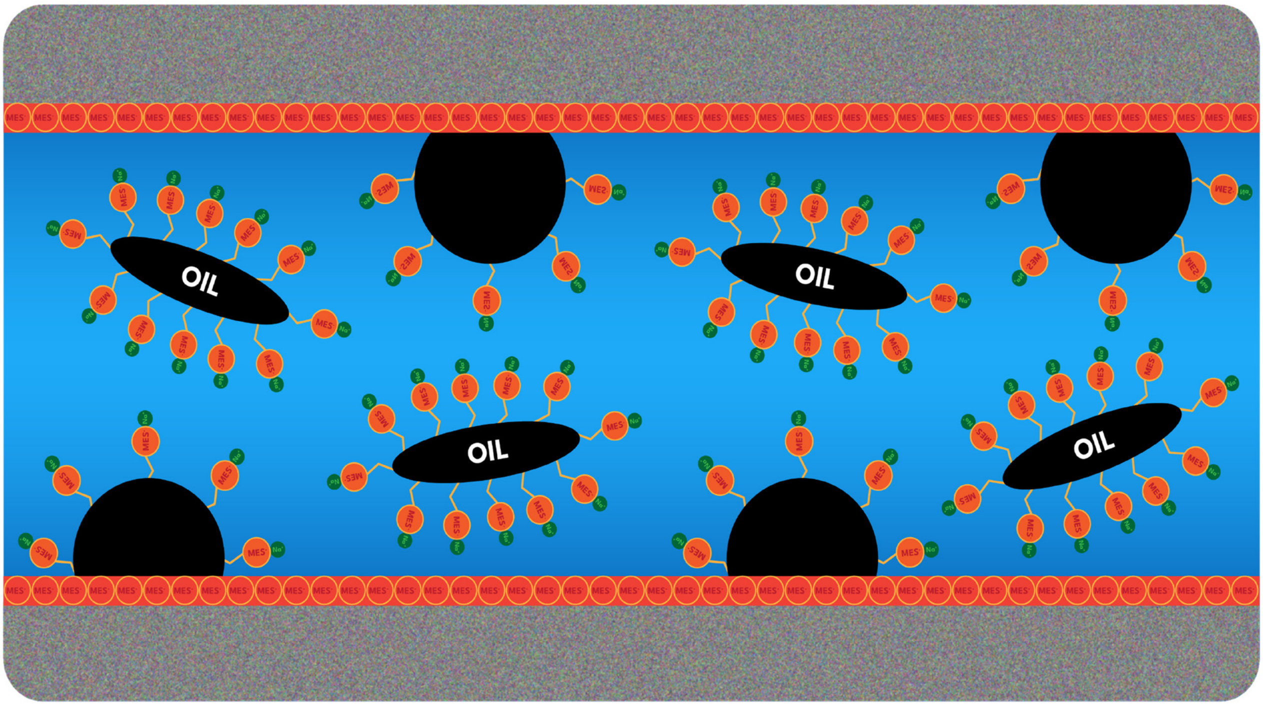


Figure 8
Conditions inside the rock pore

These two mechanisms, wettability alteration and IFT reduction, combine to be the key to increase the recovery factor value by MES anionic bio-surfactant through the experimental method of spontaneous imbibition under extreme salinity and high temperature. In this study, MES firstly changes the wettability of berea sandstone to water-wet and releases the oil adsorbed on the rock surface into the rock pore. The oil that has been released into the rock pore is bound by the tails of the MES molecules and carried to the outside of the core. The combination of these two key mechanisms is visualized at the rock pore scale in Figure 8.

CONCLUSION

The primary goal of chemical enhanced oil recovery (EOR) is to increase the recovery factor by improving the properties of the injected water. The injected water must be able to change the wettability of the rock and reduce the oil-water interfacial tension (IFT). This study, using the spontaneous imbibition (SI) experimental method, contact angle (CA), and IFT measurement, demonstrates that MES, an anionic bio-surfactant, effectively supports the injected water in achieving these properties under extreme salinity and high-temperature conditions. MES reduces the IFT of oil-water to 0.04 mN/m at a concentration of 0.4 mM in 30 kppm salinity and further decreases the IFT to 0.02 mN/m at a concentration of 0.3 mM in 40 kppm salinity. Additionally, MES effectively alters the wettability of sandstone by reducing the CA value. In 30 kppm salinity, 0.2 mM MES lowers the CA from 115 to 37, and in 40 kppm salinity, 0.2 mM MES reduces the CA from 111 to 30. SI experimental results using MES samples in 30 kppm salinity and 80 showed positive increases in oil recovery factor (RF) values, with 0.5 mM MES achieving an RF of 12%, 1.0 mM MES reaching 18%, and 2.0 mM MES achieving 26% by day 14. Similarly, in 40 kppm salinity and 80, 0.5 mM MES had an RF value of 17%, 1.0 mM MES reached 19%, and 2.0 mM MES achieved 27% by day 14.

This study indicates that MES surfactant is a promising innovative alternative for chemical EOR operations in extreme and harsh conditions. MES not only enhances oil recovery efficiency but also contributes to environmental preservation due to its eco-friendly nature behavior. Its excellent biodegradability makes it a safer choice than traditional surfactants, thereby addressing environmental health concerns. Additionally, using MES can significantly improve the effectiveness of chemical EOR processes under challenging conditions.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
MES	Methyl Ester Sulfonate	[ ]
RF	Recovery Factor	[%]
SI	Spontaneous Imbibition	[ ]
EOR	Enhanced Oil Recovery	[ ]
OOIP	Original Oil in Place	[STB]
IFT	Interfacial Tension	[mN/m]
m_d	Mass of Dry Core	[g]
m_w	Mass of Saturated Water	[g]
m_o	Mass of Saturated Oil	[g]
m_{wo}	Mass of Oil Saturated Core	[g]
m_{wc}	Mass of Water Saturated Core	[g]
m_{woc}	Mass of Oil-water Saturated Core	[g]
V_w	Volume of Saturated Water	[mL]
V_{oi}	Volume of Initial Saturated Oil	[mL]
V_p	Pore Core Volume	[mL]
ρ_w	Density of Saturated Water	[g/mL]
ρ_o	Density of Saturated Oil	[g/mL]
S_w	Water Saturation	[%]
S_{oi}	Initial Oil Saturation	[%]
d	Core Diameter	[cm]
l	Core Length	[cm]
V_b	Core Bulk Volume	[mL]
V_p	Core Pore Volume	[mL]
ϕ	Core Porosity	[%]
μ	Viscosity	[cP]
API	American Petroleum Institute	[ ]
SDT	Spinning Drop Tensiometer	[ ]
CA	Contact Angle	[°]
P	Pressure	[atm]
T	Temperature	[$°C$]
V_{or}	Volume of Recovered Oil	[mL]
IMF	Intermolecular Forces	[kJ/mol]

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