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Shamim Miraei
Shiraz University
Maysam Mohammadzadeh-Shirazi
m.mohammadzadeh@shirazu.ac.ir
Shiraz University
Azim Kalantari Asl
Shiraz University

Article

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Dynamic Evaluation of Sugarcane Drainage Water as a Sustainable Low-Salinity Injection Brine for Enhanced Oil Recovery: Integrated Micromodel Visualization and Coreflooding Study

Shamim Miraei [a,b], *Maysam Mohammadzadeh-Shirazi* [a,b,*] *and Azim Kalantari Asl* [a,b]

[a] Department of Petroleum Engineering, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran

[b] Formation Damage and Well Treatment Research Group, IOR/EOR Research Institute, Shiraz University, Shiraz, Iran

1. Abstract

The increasing scarcity of freshwater resources, coupled with the ecological challenges associated with the disposal of agricultural wastewater, has emphasized the need to develop sustainable injection fluids for enhanced oil recovery (EOR). This study provides the first dynamic evaluation of sugarcane field drainage water as a naturally occurring low-salinity injection brine through an integrated approach combining pore-scale and core-scale experiments. Unlike conventional low-salinity and smart-water studies that rely on synthetically engineered brines, this work demonstrates the direct utilization of an untreated agricultural effluent as an effective EOR injection fluid. Micromodel results demonstrated the coupled effects of injection rate and brine chemistry on oil recovery. At an injection rate of 10 mL min^{-1} and after injecting 20 pore volumes, the final recovery increased from 55.78% with distilled water to 72.08% and 81.16% with drainage water samples 1 and 2, respectively. Pore-scale observations revealed that the improved recovery resulted from interfacial tension reduction, wettability alteration from oil-wet toward neutral/water-wet conditions, and the formation of stable, finely dispersed emulsions, which enhanced microscopic displacement efficiency and reduced capillary trapping. Coreflooding experiments conducted at 80 °C under dynamic conditions confirmed these findings, where the final oil recovery increased from 29% with distilled water to 43% and 45% with the drainage waters. The superior performance of drainage water 2 was attributed to its ionic composition and stronger surface activity. In addition to improving oil recovery, this approach reduces freshwater consumption and provides a productive utilization pathway for large volumes of agricultural drainage water. The results demonstrate that sugarcane drainage water can serve as a sustainable and cost-effective injection brine for water-based EOR in mature reservoirs.

Keywords: Enhanced oil recovery, Low-salinity waterflooding, Sustainable injection brine, Sugarcane drainage water, Micromodel, Coreflood, Wettability alteration, Interfacial tension

[*] Maysam Mohammadzadeh-Shirazi - Assistant professor, IOR/EOR Research Institute, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran.
Email: mmohshirazi@gmail.com, m.mohammadzadeh@shirazu.ac.ir

Tel/ Fax (Department): +98 7136133680

2. Introduction

Enhanced oil recovery (EOR) techniques are playing an increasingly important role in addressing the decline of production from mature oil reservoirs, particularly those with complex geological features such as carbonates. Among the available methods, waterflooding has long been the most widely implemented secondary recovery approach. Traditionally, the salinity and composition of the injected brine received limited attention. However, over the past two decades, numerous studies have demonstrated that modifying brine chemistry particularly by lowering salinity can significantly improve oil recovery in both sandstone and carbonate reservoirs [1][2][3][4][5]. This process, known as low-salinity waterflooding (LSF), is now a well-established technique for enhancing recovery, especially in sandstones, where its main mechanism is believed to be the alteration of rock wettability toward a more water-wet state [6][7][8].

While LSF in sandstone reservoirs is well understood, its application in carbonate systems remains an active area of research. Carbonates present a more complex environment due to their heterogeneous pore structure and unique surface chemistry. Nevertheless, many laboratory investigations have reported encouraging results, linking enhanced recovery to wettability alteration [9][10][11]. Despite this progress, most studies have relied on laboratory-formulated or synthetic low-salinity brines. The use of naturally occurring water sources, particularly those from agricultural runoff, has not been fully explored.

Although water is considered a renewable resource, the rapid depletion of global freshwater supplies has created an urgent need to identify sustainable alternatives for industrial applications, including oil production. Agricultural drainage water, particularly that generated from sugarcane cultivation, offers a decentralized and underutilized water source. A large volume of irrigation water is not absorbed by crops and is eventually discharged as drainage water [12]. Following preliminary treatment, this water is often reused for irrigation or, after further purification, for groundwater recharge. Given its relatively low salinity, sugarcane drainage water is generally suitable for such purposes [13][14]. However, to date, its potential as an injection fluid in EOR applications has not been investigated.

From an environmental standpoint, this underused resource also presents challenges. The accumulation of nutrients and contaminants in agricultural drainage water can lead to significant ecological issues, including the degradation of surface and groundwater quality. In many cases, further treatment is required before this water can be safely reintroduced into the environment. For example, studies in the United States have identified agricultural runoff as the leading cause of lake pollution nationwide [13][14]. Effective management of both the volume and quality of discharged drainage water is essential to reduce these impacts. One proposed solution is the injection of this water into deep subsurface formations, which may serve the dual purpose of mitigating environmental risks and supporting oilfield operations [15][16].

In Iran, approximately 350 million cubic meters (equivalent to 2.2×10^9 barrels) of agricultural drainage water are produced each month. A prominent source is the Sugarcane Wetland a 35,000-hectare area in southern Ahvaz, near the Iraqi border where substantial volumes of sugarcane drainage water are generated and collected [17]. Given the growing limitations of freshwater availability, the environmental implications of uncontrolled drainage discharge, and the ongoing search for cost-effective injection fluids, sugarcane drainage water emerges as a compelling alternative for EOR processes.

In a previous study by the authors [12], sugarcane drainage water was introduced for the first time as a novel water-based agent for Enhanced Oil Recovery (EOR). That work focused on evaluating its physicochemical compatibility with crude oil and formation water, employing laboratory assessments of emulsion stability, interfacial tension (IFT), wettability alteration and mineral scale formation. Building upon those foundational findings, the present study investigates the dynamic recovery performance of sugarcane drainage water using coreflooding and micromodel experiments.

Coreflooding tests were conducted to evaluate oil displacement efficiency and to assess the influence of sugarcane drainage water on wettability alteration and interfacial behavior under reservoir-like conditions. In parallel, micromodel experiments provided real-time visualization of pore-scale displacement mechanisms. These two-dimensional transparent models simulate multiphase flow in porous media and are widely used to investigate phenomena such as capillary trapping, interfacial dynamics, and wettability behavior [18][19][20][21].

Together, these results provide new insight into the mechanisms of oil mobilization using this unconventional water source. By integrating environmental sustainability with petroleum engineering, this research highlights the potential of agricultural drainage water as a viable injection fluid offering benefits both for oil recovery and for responsible wastewater management in agricultural regions.

3. Materials and Methods

Materials

In this study, two sugarcane field drainage water samples were obtained directly from the Sugarcane and By-products Development Company (Khuzestan, Iran). The samples were provided to the research team with the company's permission for use in this study (Table 1). The selection of these two samples was based on both their high availability and the opportunity to perform comparative analysis. These samples were collected in March, a period during which no fertilization is typically applied to the fields. As a result, the concentrations of phosphate and nitrate were relatively low.

Table 1. Chemical parameters of the two sugarcane drainage water samples used in this study

Parameter (mg/L)	Sodium	Ammonia	Potassium	Calcium	Magnesium	Fluoride	Chloride	Bromide	Nitrate	Sulfate	Bicarbonate	TDS
Drainage Water 1	643.195	1.44	8.901	345.327	88.909	2.186	1509.56	0.915	71.887	1250.89	194	3318
Drainage Water 2	867.147	0.9	18.605	359.413	137.354	2.523	1636.97	1.805	67.603	1339.29	213	3996

In addition, the properties of the crude oil used in this study are presented in Table 2, including it’s compositional fractions. The crude oil was selected due to its suitability as a candidate for water injection-based EOR processes.

Table 2. Properties and composition of the crude oil used in this study

Crude Oil Type	API Gravity	Density at 25°C (g/mL)	Viscosity at 25°C (cP)	Saturates (%)	Asphaltenes (%)	Resins (%)	Aromatics (%)
Crude Oil	25.72	0.90	60.80	45.30	4.70	16.30	33.70

Methods

Micromodel fabrication and characteristics

A glass micromodel featuring a heterogeneous pore structure was designed, fabricated, and utilized for microfluidic experiments. The fabrication process involved three main steps: (a) designing the pore network pattern using CorelDraw software, (b) engraving the pattern onto a glass substrate via laser etching, and (c) sealing the etched glass with a blank glass cover plate by thermal fusion. The two glass plates were fused in a programmable laboratory furnace, gradually heated to 650 °C over a period of 4 hours. The temperature was held at 650 °C for approximately 15 minutes to ensure proper bonding between the plates. Following this, the furnace temperature was gradually reduced to room temperature (25 °C) over three days to prevent thermal shock and structural stress in the micromodel.

The micromodel pattern is depicted in Figure 1, where the black regions correspond to pores, inlet/outlet channels, and flow paths, while the white areas represent solid grains.

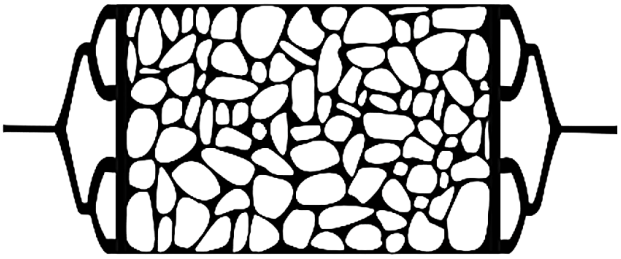


Figure 1. The heterogeneous micromodel pattern used in this study

Key geometrical and hydraulic properties of the micromodel are summarized in Table 3.

Table 3. The physical characteristics of micromodel

Length (mm)	Width (mm)	Porosity (%)	Permeability (D)	Pore Volume (cc)
100	54	0.267	18.5	0.21

Micromodel Flooding Experiments

The experimental setup for micromodel tests consisted of a syringe pump for injecting the sugarcane drainage water, a glass micromodel, and a digital camera connected to a computer. A schematic diagram of the experimental configuration is shown in Figure 2.

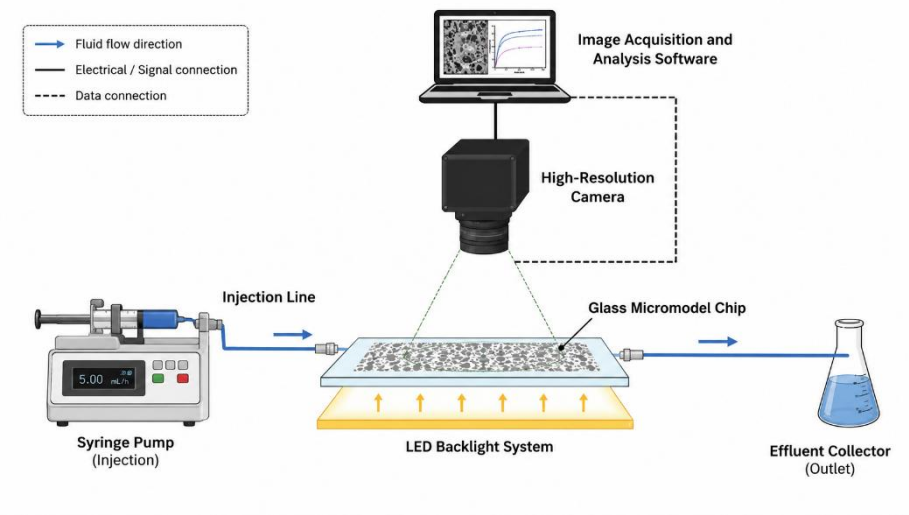


Figure 2. Schematic illustration of the experimental setup used for micromodel flooding experiments

All micromodel experiments were conducted at ambient temperature and pressure, on a completely flat horizontal surface. Before each test, all components of the micromodel system including the model itself and the connections were thoroughly cleaned and dried to eliminate any contamination or residual particles.

Initially, the micromodel was fully saturated with the selected crude oil, ensuring the complete removal of air bubbles. In these experiments, connate water was not considered, and its saturation was assumed to be zero. Following this, injection of the sugarcane drainage water commenced, and a defined volume corresponding to the pore space of the artificial porous medium was introduced. After injecting specific volumes, the flooding process was halted, and the oil recovery factor was calculated using the following formula:

$$RF = \frac{Total\ Area_{before\ flooding} - Total\ Area_{after\ flooding}}{Total\ Area_{before\ flooding}}$$

Subsequent to each experiment, the micromodel was cleaned three times alternately with toluene and distilled water. Using a vacuum pump, all residual fluids were extracted, and the model was placed in an oven at 80°C for 4 hours to ensure complete drying [22].

Coreflooding Experiments

Initially, core samples were washed with toluene to remove any potential organic contaminants. This was followed by methanol washing to eliminate salts and mineral deposits. After drying the cores in an oven, their porosity and permeability were measured. Next, the cores were placed in a desiccator and subjected to vacuum for 6 hours using a vacuum pump to ensure

complete removal of trapped air from the pore spaces. The physical dimensions of the cores were recorded and are summarized in Table 4.

Table 4. Petrophysical properties of dolomite core plugs

Sample	S1	S2	S3
Length (cm)	6.78	5.92	6.01
Diameter (cm)	3.8	3.8	3.8
Weight (g)	144.556	142.569	144.365
Porosity (%)	25.79	25.09	25.21
Pore Volume (cc)	17.75	16.85	17.19
Liquid Permeability (mD)	43	51	48
Water Saturated Pore Volume (cc)	16.99	16.08	16.61
Irreducible Water Saturation (%)	22.50	25.40	22.17
Initial Oil Saturation (%)	77.50	74.60	77.83
Diameter (cm)	3.8	3.8	3.8
Weight (g)	144.556	142.569	144.365
Porosity (%)	25.79	25.09	25.21

Synthetic formation water was then introduced into the desiccator-connected vessel, and due to the vacuum conditions, the water was imbibed into the cores, establishing initial water saturation. To enhance water saturation, the cores were placed in an accumulator under a pressure of 4000 psi for 24 hours, resulting in water saturation levels above 95%, with most cores reaching near 100%. The water-saturated cores were then placed into a core holder, and five pore volumes of crude oil were injected into each core at a rate of 0.3 cc/min. The overburden pressure for all flooding stages was maintained at 600 psi. The produced water was collected in a graduated cylinder and subjected to centrifugation at 10,000 rpm for 10 minutes to completely separate the water from the oil. The volume of produced water was measured, and the irreducible water saturation was determined. Following oil injection and attainment of irreducible water saturation, the cores were immersed in crude oil and aged in an oven at 80°C for 28 days. In the next step, the core was reinserted into the core holder, and fresh crude oil was injected at a rate of 0.3 cc/min, followed by injection of sugarcane drainage water at the same rate. The initial injection pressure was set to 2 bar. The volume of produced oil and the injection pressure were recorded throughout the process, and the oil recovery factor was calculated. This procedure was also conducted using distilled water, and the results were compared with those obtained from the two sugarcane drainage water samples [23][24]. A schematic diagram of the high-pressure, high-temperature coreflooding apparatus is shown in Figure 3.

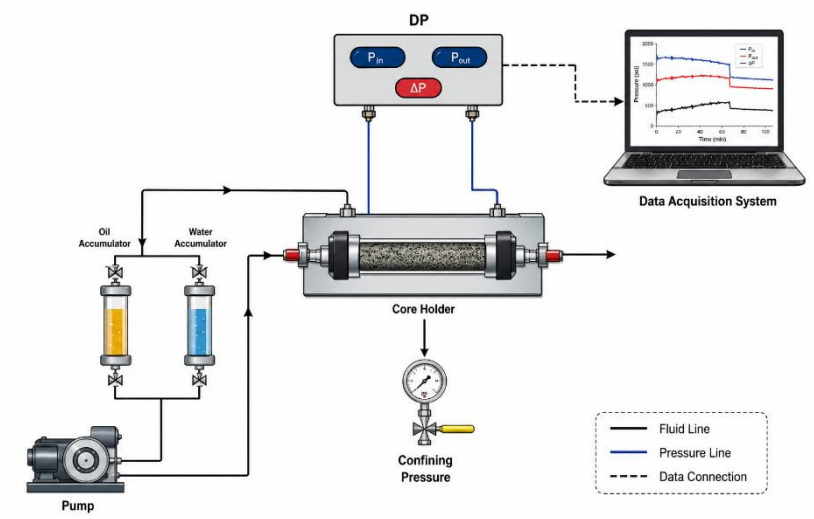


Figure 3. Schematic representation of the core flooding experimental setup (HTHP) used to evaluate the displacement performance of injection fluids

4. Results and Discussion

This section presents the results obtained from the micromodel and coreflooding experiments conducted to evaluate the enhanced oil recovery (EOR) potential of sugarcane drainage waters. The effects of injection rate, injected pore volume, and fluid composition on oil recovery were systematically investigated and compared with distilled water as the reference fluid. The experimental observations provide valuable insights into the displacement behavior of the tested fluids and the mechanisms responsible for improving oil recovery, including interfacial tension reduction, wettability alteration, and enhanced sweep efficiency.

Micromodel Experimental Results

The micromodel experiments were conducted to investigate the effects of injection rate and fluid composition on oil recovery from porous media. In the initial stage, distilled water was injected as a reference at rates of 0.1, 1, and 10 mL/min (Table 5). The results showed that at the lowest rate (0.1 mL/min), the oil recovery was limited to 21.73%, indicating the dominance of capillary forces and oil entrapment in fine pores. Increasing the injection rate to 1 mL/min improved the recovery to 33.28%, reflecting a reduced impact of capillarity and an increased influence of viscous forces. At 10 mL/min, recovery reached 46.26%, and with a further increase in injected volume to 20 PV, oil recovery significantly rose to 55.78%. These findings suggest that higher injection rates and volumes enhance viscous forces, reduce capillary trapping, and improve oil displacement efficiency (Table 6).

Table 5. Micromodel images before and after injecting 5PV of distilled water in diffrenet injection rates

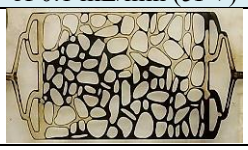
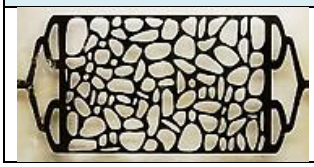
Before injection	After injection at a rate of 0.1 mL/min (5PV)	After injection at a rate of 1 mL/min (5PV)	After injection at a rate of 10 mL/min (5PV)
			

Table 6. Micromodel images before and after injecting 20PV of distilled water

Before injection	After injection at a rate of 10 mL/min (20PV)
	

The effect of drainage water 1 on oil recovery was then evaluated (Table 7). Injection of this fluid at 0.1 mL/min resulted in an oil recovery of 27.88%, representing a ~6.15% improvement compared to distilled water. This enhancement is attributed to the presence of surface-active components in the drainage water, which lower interfacial tension (IFT) and alter wettability. At injection rates of 1 and 10 mL/min, recoveries increased to 49.90% and 61.69%, respectively, indicating the synergistic effects of IFT reduction and stronger viscous displacement. With 20 PV injection, oil recovery reached 72.08%, the highest among the drainage water 1 micromodel tests (Table 8). These results clearly demonstrate that drainage water 1 improves EOR performance through multiple mechanisms, including IFT reduction and wettability alteration.

Table 7. Micromodel images before and after injecting 5PV of sugarcane drainage water 1 in diffrenet injection rates

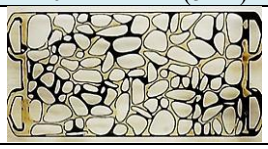
Before injection	After injection at a rate of 0.1 mL/min (5PV)	After injection at a rate of 1 mL/min (5PV)	After injection at a rate of 10 mL/min (5PV)
			

Table 8. Micromodel images before and after injecting 20PV of sugarcane drainage water 1

Before injection	After injection at a rate of 10 mL/min (20PV)
	

Drainage water 2 also showed remarkable performance (Table 9). At 0.1 mL/min, the oil recovery was 38.16%, surpassing that of drainage water 1. At higher rates, its performance continued to exceed expectations: 53.86% at 1 mL/min and 76.38% at 10 mL/min. With 20 PV injection, recovery reached 81.16%, the highest among all micromodel tests (Table 10). These findings suggest that drainage water 2 performs particularly well at medium and high injection rates, likely due to its distinctive chemical composition and stronger effect on IFT reduction. By significantly reducing IFT and altering the rock surface toward neutral or water-wet conditions, drainage water 2 facilitates easier oil mobilization in porous media.

Table 9. Micromodel images before and and after injecting 5PV of sugarcane drainage water 2 in diffrenet injection rates

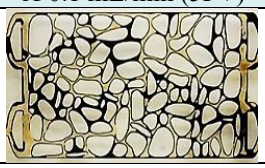
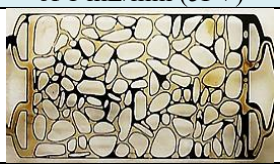
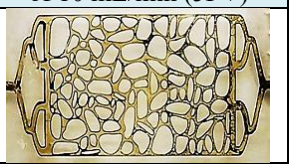
Before injection	After injection at a rate of 0.1 mL/min (5PV)	After injection at a rate of 1 mL/min (5PV)	After injection at a rate of 10 mL/min (5PV)
			

Table 10. Micromodel images before and after injecting 20PV of sugarcane drainage water 1

Before injection	After injection at a rate of 10 mL/min (20PV)
	

Sensitivity Analysis of Micromodel Tests

A sensitivity analysis was conducted focusing on two key parameters: injection rate and type of injection fluid, with the aim of elucidating their respective influences on oil recovery and flow behavior within porous media. This analysis enhances understanding of the governing mechanisms and facilitates optimization of operational conditions for improved EOR outcomes.

1. Effect of Injection Rate

Injection rate is a critical parameter in micromodel flooding, as it directly affects the balance between capillary and viscous forces. The results demonstrate that increasing the injection rate enhances the role of viscous forces, thereby promoting more effective displacement of trapped oil. At 0.1 mL/min, capillary forces dominated, resulting in significant oil entrapment in tight pores and throats, particularly within nano- to micro-scale pore structures. For instance, oil recovery with distilled water at this rate was limited to 21.73%. At 1 mL/min, the influence of viscous forces increased, leading to more stable and continuous flow through the porous medium. Oil recovery with distilled water improved to 28.33%. At 10 mL/min, viscous forces

strongly dominated. The injected fluid rapidly displaced oil even in narrower pore throats, though viscous fingering could occur. Oil recovery for distilled water, drainage water 1, and drainage water 2 at this rate reached 46.26%, 61.69%, and 76.38%, respectively. When the injected volume was increased to 20 PV, drainage water 2 yielded 81.16% oil recovery. While higher injection rates reduce capillary trapping and improve oil mobilization, very high rates may induce viscous fingering, leading to non-uniform sweep efficiency. However, in the present experiments, fingering effects were limited (Figure 4).

2. Effect of Injection Fluid Type

The chemical composition of the injection fluid plays a major role in its interaction with the oil and the rock surface. Three fluids were tested: distilled water (as a baseline), drainage water 1, and drainage water 2. Each fluid exhibited distinct behavior due to differences in ionic content and surface-active species .

Distilled Water contains no dissolved minerals or surfactants, offering limited capability for IFT reduction or wettability alteration. As a result, oil recovery was consistently lower across all injection rates, relying primarily on mechanical displacement mechanisms. Drainage Water 1, with natural minerals and surfactants, reduced IFT and improved wettability toward neutral conditions. At 1 mL/min, it achieved 49.9% recovery. Its chemical components enhanced oil mobility across all rates compared to distilled water. Drainage Water 2 outperformed both fluids at every rate. At 10 mL/min, oil recovery reached 76.38%, and with 20 PV injection, it exceeded 81%. This superior performance is attributed to the presence of more effective surface-active components, leading to significant IFT reduction and improved flow in micro- and nanoporous structures.

These results highlight that the chemical nature of sugarcane drainage waters especially drainage water 2 significantly enhances oil recovery by modifying interfacial properties and fluid–rock interactions (Figure 4).

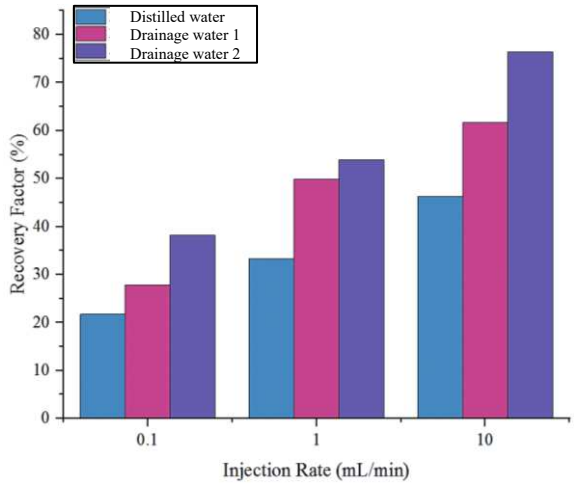


Figure 4. Recovery factor versus injection rate of drainage water and distilled water samples in an oil-saturated micromodel

Statistical and Mechanistic Interpretation

Statistical analysis of the micromodel data confirms that both injection rate and injection fluid type significantly influence oil recovery. As shown in the comparative plot (Figure 4), increasing the injection rate from 0.1 to 10 mL/min led to increased oil recovery for all fluids, demonstrating the growing dominance of viscous over capillary forces and the resultant improved mobilization of trapped oil. With respect to fluid type, sugarcane drainage waters consistently outperformed distilled water. Notably, drainage water 2 achieved the highest oil recovery across all injection rates, exceeding 81% at 10 mL/min. This enhanced performance is likely due to its unique ionic and surface-active composition, which reduces IFT and shifts wettability toward water-wet conditions. For example, at 0.1 mL/min, the difference in oil recovery between distilled water (21.73%) and drainage water 2 (38.27%) was substantial. At 10 mL/min, this gap widened further (46.26% vs. 76.38%). These results suggest that fluid type may exert a stronger influence than injection rate, although the combined optimization of both parameters yields the highest recovery (Table 11).

Table 11. Oil recovery percentages obtained from micromodel tests using different injected waters at three injection rates

Sample	Injected PV (cc)	Injection rate (mL/min)	Oil recovery (%)
Distilled Water	5	0.1	21.73 ± 1.2
		1	33.28 ± 0.9
		10	46.26 ± 1.5
	20	10	55.78 ± 1.2
Sugarcane Drainage Water 1	5	0.1	27.88 ± 0.8
		1	49.90 ± 0.64
		10	61.69 ± 1.1
	20	10	72.08 ± 0.92
Sugarcane Drainage Water 2	5	0.1	38.16 ± 0.88
		1	53.86 ± 1.3
		10	76.38 ± 1.03
	20	10	81.16 ± 0.79

Flow Behavior and Entrapment Mechanisms

Micromodel observations revealed multiple entrapment mechanisms dependent on rock texture, fluid properties, and injection rate:

At low injection rates (0.1 mL/min), capillary forces dominate, leading to oil entrapment in small, isolated pores, particularly in nano- and micro-sized pore structures.

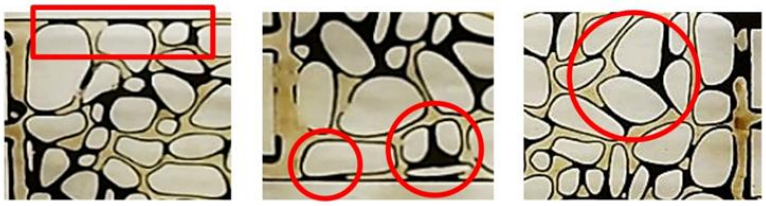


Figure 5. Trapped oil droplets in the micromodel after water injection

Figure 5 highlights regions within the porous network where discrete oil droplets remained immobilized following the injection of various water samples. The entrapment is primarily observed in dead-end pores and narrow pore throats, indicating capillary-dominated flow behavior.

At moderate rates (1mL/min), oil forms stable clusters due to adhesive forces and interfacial tension, partially blocking flow paths.

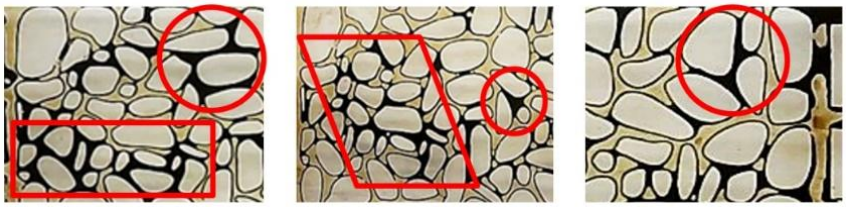


Figure 6. Formation of oil bottlenecks during injection in the micromodel

Figure 6 illustrates oil constrictions that developed due to pore-scale flow limitations during water injection. These bottlenecks obstructed continuous displacement, particularly in regions with complex pore geometry or low connectivity, reducing sweep efficiency.

At high injection rates (10mL/min), viscous forces overcome capillarity, displacing oil from tight pores, although some bypassing and fingering effects may arise.

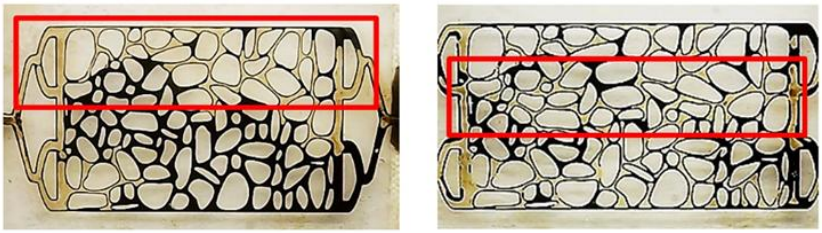


Figure 7. Development of viscous fingering during water injection

Instabilities at the displacement front led to the formation of finger-like patterns, especially at higher injection rates or when low-viscosity water was used. These fingering flows bypassed significant portions of the oil phase, resulting in early water breakthrough and reduced macroscopic sweep efficiency (Figure 7).

The superior performance of drainage water 1 and drainage water 2 confirms their potential to reduce IFT and alter wettability, minimizing oil entrapment and facilitating improved sweep efficiency in porous media.

Coreflooding Test Results

This set of coreflooding experiments was designed to evaluate the effect of sugarcane drainage waters on oil recovery under dynamic conditions. The operating parameters included a temperature of 80 °C, atmospheric outlet pressure, and an overburden pressure of 800 psi. To assess the impact of different injection fluids on recovery mechanisms, distilled water was first injected at a constant rate of 0.3 mL/min into oil-saturated cores as the baseline fluid. During the experiments, the volume of oil produced was recorded at one-minute intervals. In order to separate potential emulsified phases, the produced samples were processed using a centrifuge. According to the results, shown in Figure 8, distilled water achieved only 29% oil recovery. This recovery occurred solely through mechanical displacement, without the involvement of mechanisms such as interfacial tension (IFT) reduction or wettability alteration. Distilled water was intentionally selected due to its lack of active ions capable of modifying rock surface properties or reducing IFT, thus serving as a reference for evaluating the performance of sugarcane drainage waters. In the next phase, drainage water 2 was injected under the same conditions. The oil production profile over time is illustrated in Figure 8. This fluid increased oil recovery to 45%. Additional analysis of interfacial properties indicated that drainage water 2 significantly reduced the IFT between oil and water and altered the rock surface wettability toward a more neutral state. Such wettability alteration led to a reduction in capillary forces within the porous medium, facilitating oil flow toward the outlet. In the third experiment, drainage water 1 was injected at the same flow rate. The results, shown in Figure 8, revealed an oil recovery of approximately 43%. Similar to drainage water 2, this sample improved oil displacement by reducing IFT and modifying wettability.

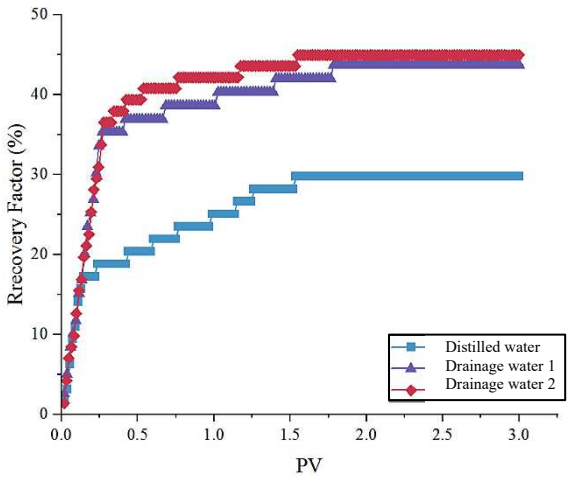


Figure 8. Recovery factor versus pore volume of injected drainage water and distilled water samples in an oil-saturated core

Comparison of the performance of sugarcane drainage waters with distilled water (Table 12) indicates that the key mechanisms contributing to enhanced recovery include interfacial tension reduction, emulsion stabilization, and wettability alteration. The performance difference among these fluids is primarily attributed to variations in their chemical compositions, particularly the type and concentration of surface-active compounds present in the drainage waters.

Table 12. Oil recovery percentage obtained from oil saturated cores after water flooding

Sample	Oil recovery percentage (%)
Distilled Water	29
Sugarcane Drainage Water 1	43
Sugarcane Drainage Water 2	45

These coreflooding findings are in full agreement with the micromodel results and confirm that IFT reduction and wettability modification are critical for mobilizing trapped oil in small pore spaces. Additionally, microscopic analysis of the resulting emulsions revealed that, in the presence of sugarcane drainage waters, water droplets were more uniformly distributed and smaller in size indicative of increased emulsion stability. This characteristic enhances the continuity of flow in porous media and facilitates oil displacement toward the production outlet. The higher recovery factors measured in the micromodel should not be interpreted as direct predictors of field-scale recovery. Instead, they reflect the simplified geometry, absence of connate water, extremely high permeability, and reduced heterogeneity of the micromodel system. Nevertheless, the consistency of fluid performance across both experimental approaches confirms the positive impact of sugarcane drainage water on oil displacement efficiency. Overall, these results demonstrate that sugarcane drainage waters, due to their favorable physicochemical properties, availability, low cost, and environmental benefits, can be considered a viable and sustainable alternative to conventional injection waters in oil recovery processes. The use of such fluids in future EOR design strategies could offer both operational and environmental advantages.

Correlation Between Micromodel and Coreflooding Results

Although the micromodel and coreflooding experiments were conducted at different scales and under different flow conditions, both approaches exhibited the same recovery trend, with Drainage Water 2 consistently providing the highest recovery, followed by Drainage Water 1 and distilled water. The reproducibility of this ranking across two independent experimental methods strengthens the reliability of the observed recovery behavior. To compare the performance of the tested fluids at both scales, the final oil recovery values obtained from the micromodel and coreflooding experiments are presented in Figure 9.

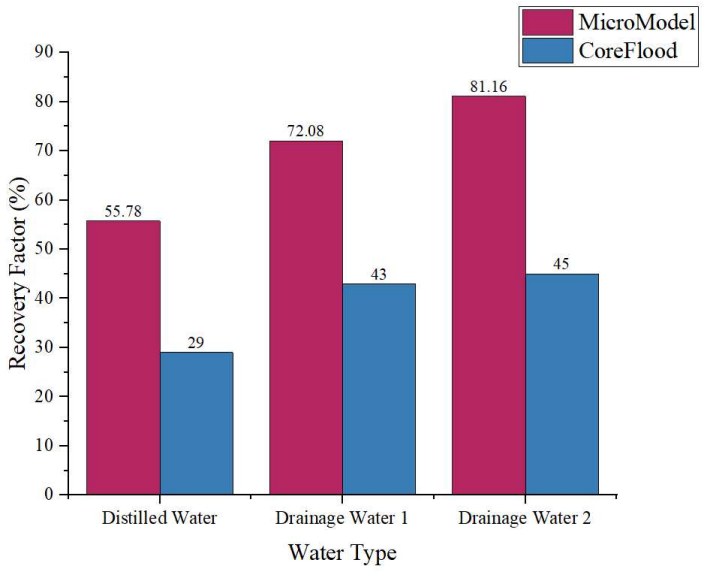


Figure 9. Comparison of oil recovery obtained from micromodel and coreflooding experiments for the investigated injection fluids.

As shown in Figure 9, the recovery factors obtained from the micromodel experiments were higher than those measured during coreflooding. This difference is expected because the micromodel represents a simplified two-dimensional porous system with very high permeability and reduced heterogeneity, whereas the core samples provide a more realistic representation of reservoir conditions and are therefore subject to stronger capillary trapping and flow restrictions. Despite the difference in absolute recovery values, the same fluid performance trend was observed in both experimental systems. In particular, Drainage Water 2 consistently outperformed the other tested fluids, indicating that its favorable displacement behavior was maintained across both pore-scale and core-scale evaluations. The agreement between the two experimental approaches suggests that the enhanced recovery associated with the sugarcane drainage waters is not merely a consequence of a specific laboratory setup, but reflects a consistent response to the injected fluid properties.

These findings provide additional support for the potential application of sugarcane drainage waters as low-salinity injection fluids for enhanced oil recovery and demonstrate that the observed recovery improvements remain evident across different experimental scales.

5. Conclusion

A comparison of the micromodel and coreflooding results shows that sugarcane drainage waters not only significantly improve oil recovery under laboratory conditions but also have strong potential for field-scale application as an effective and sustainable strategy for enhanced oil recovery (EOR). These findings provide a foundation for developing innovative EOR methods utilizing low-cost and sustainable water sources.

Key conclusions are summarized as follows:

1. Micromodel experiments confirmed that injection rate and fluid composition are critical in determining oil entrapment. At low rates, capillary forces dominate, trapping oil in

tight pores. At moderate rates, pore throat blockage reduces sweep efficiency. At high rates, viscous fingering leads to non-uniform displacement and limited recovery.

2. The chemical composition of injection fluids and the injection rate are two primary factors influencing oil recovery. Therefore, selecting an appropriate fluid and optimizing the injection rate must be tailored to reservoir characteristics and operational conditions.

3. Sugarcane drainage water, particularly drainage water 2, demonstrated strong performance by lowering IFT and improving wettability. Following 5 PV injection, oil recovery reached 76.38% for drainage water 2, 61.69% for drainage water 1, and 46.26% for distilled water.

4. Distilled water resulted in the lowest oil recovery, with high sensitivity to capillary forces. In contrast, drainage water 1 showed improved performance due to its surface activity, while drainage water 2 achieved the highest recovery across all rates, especially under high injection rates.

5. Coreflooding results confirmed that the chemical composition of the sugarcane drainage waters specifically their capacity to reduce IFT and modify wettability plays a significant role in their effectiveness in improving oil recovery.

6. Final oil recovery after coreflooding reached 45% with drainage water 2, 43% with drainage water 1, and only 29% with distilled water.

In conclusion, the use of sugarcane drainage water in EOR operations presents a promising alternative to freshwater, offering both enhanced recovery efficiency and environmental sustainability. This approach has the potential to contribute to more resilient and cost-effective oil production strategies.

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Data Availability

All data generated or analyzed during this study are included in this manuscript.

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