

Determination of the Physical Properties of Local Surfactants for Enhancing Oil Recovery

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Abstract

This study investigates the determination of key physical properties density, pH, and viscosity of locally sourced surfactants to enhance oil recovery processes. Utilizing advanced analytical methodologies such as digital rock physics, microfluidic measurement, and high-precision pH analysis, the research provides a comprehensive characterization of surfactant behavior under reservoir-relevant conditions. The results reveal that subtle variations in these physical properties significantly impact fluid flow, interfacial tension, and overall recovery efficiency. By integrating recent technological advancements, the study highlights the importance of accurate and condition-specific property measurement for optimizing surfactant formulation and performance. The findings underscore the necessity of multidisciplinary collaboration and continuous innovation to ensure the environmental sustainability and economic viability of enhanced oil recovery operations using local surfactants. The study concludes that, the precise determination and optimization of the density, pH, and viscosity of local surfactants are pivotal for maximizing oil recovery efficiency, minimizing environmental impact, and advancing the economic sustainability of enhanced oil recovery operations. It is recommended that future enhanced oil recovery initiatives systematically utilize advanced analytical techniques to characterize and tailor the density, pH, and viscosity of local surfactants, ensuring optimal performance and sustainable reservoir management.

Keywords: Density, pH, Viscosity, Recovery Efficiency Local Surfactants

1.0 Introduction

Enhanced oil recovery has emerged as a critical strategy to maximize extraction from mature reservoirs, as conventional primary and secondary methods often leave a substantial volume of hydrocarbons unrecovered. Among chemical enhanced oil recovery techniques, surfactant flooding is particularly effective due to its ability to reduce interfacial tension, alter wettability, and mobilize residual oil. Recent advances emphasize the value of natural or locally sourced surfactants such as those derived from plant extracts or biodegradable oils for their environmental compatibility and economic advantages (Saw et al., 2023; Tukhfatova et al., 2025). For instance, a novel non-ionic surfactant synthesized from olive oil demonstrated low critical micelle concentration (50 ppm), significant interfacial tension reduction, effective wettability alteration, and synergistic recovery when combined with polymers achieving a 31 % tertiary oil recovery over waterflooding in sandstone reservoirs (Saw et al., 2023). Similarly, neem-derived surfactants exhibited a 64.8 % reduction in interfacial tension (from

22.5 to 7.9 mN/m) as concentration increased, with micelle formation more efficient in saline conditions, and core flooding in sandstone yielding an additional 24.6 % oil recovery (Tukhfatova et al., 2025). These studies underscore the importance of characterizing physical properties such as density, viscosity, and pH of local surfactants under reservoir-relevant conditions to optimize enhanced oil recovery performance.

Despite growing interest in natural surfactants, systematic investigations into how their physical properties vary with concentration and influence enhanced oil recovery efficacy remain limited. The interplay between surfactant density, viscosity, and pH is pivotal: higher density and viscosity can improve mobility control and sweep efficiency, while pH affects interfacial behavior and chemical stability. Moreover, sequential or hybrid surfactant strategies have shown promise: for example, in clay-rich sandstones, sequential injection of cationic and anionic surfactants achieved an 81 % recovery factor, significantly outperforming brine alone (53 %), by leveraging complementary mechanisms of fine stabilization and interfacial tension reduction (Muzammil et al., 2025). To bridge this knowledge gap, the current study focuses on the systematic determination of density, viscosity, and pH of locally sourced surfactants across concentration gradients, providing foundational data to inform formulation and deployment strategies in enhanced oil recovery applications, particularly in sandstone reservoirs.

This study aims to determine the physical properties (density, pH, viscosity) of selected local surfactants and evaluate their effectiveness in enhancing oil recovery from sandstone reservoirs.

The specific objectives of the study were:

- i. To determine the density of local surfactants at various concentrations for enhanced oil recovery.
- ii. To assess the pH of local surfactants at various concentrations for enhanced oil recovery.
- iii. To examine the viscosity of local surfactants at various concentrations for enhanced oil recovery.
- iv. To ascertain the recovery efficiency of local surfactants at various concentrations for enhanced oil recovery.

2.0 Literature Review

2.1 Recovery Efficiency

Recovery efficiency serves as a fundamental benchmark in petroleum engineering, representing the fraction of original oil in place that can be economically extracted using a given recovery process, and is profoundly influenced by reservoir heterogeneity, fluid properties, and the specific recovery mechanism implemented (Guo et al., 2022). Recent advancements indicate that primary recovery methods, which harness natural reservoir drive mechanisms, typically yield recovery efficiencies between 5% and 30% of original oil in place, with water drive systems demonstrating the highest efficiency often exceeding 30% due to sustained reservoir pressure and improved oil displacement (Guo et al., 2022; Zhang et al., 2023). In contrast, solution gas drive reservoirs generally achieve lower efficiencies, frequently below 20%, as a result of rapid pressure depletion and less favorable drive energy (Zhang et al., 2023). The integration of chemical and polymer-based enhanced oil recovery methods, particularly in mature and heterogeneous reservoirs, has shown potential to further improve recovery efficiency by an additional 15–25%, as demonstrated in recent field studies, highlighting the importance of tailored enhanced oil recovery strategies and

comprehensive reservoir characterization (Alvarado & Manrique, 2022). As global energy demands persist and conventional reservoirs mature, optimizing recovery efficiency through innovative recovery processes and advanced reservoir management remains paramount for sustainable hydrocarbon production (Ahmed & Meehan, 2021; Alvarado & Manrique, 2022).

2.2 Density

Density, a core physical property defined as mass per unit volume and typically measured in kilograms per cubic meter (kg/m^3), underpins much of modern scientific and engineering practice, particularly in fluid mechanics, materials science, and subsurface reservoir analysis (Smith et al., 2022). Its precise determination is vital for accurately simulating fluid flow, predicting phase behavior, and designing both surface and subsurface facilities in energy and environmental sectors (Wei et al., 2023). Recent advancements have centered on the use of digital rock physics and high-resolution X-ray computed tomography, which provide refined measurements of rock and fluid densities, thereby enhancing reservoir characterization and fluid property prediction (Wei et al., 2023). It is now well recognized that density is not a static property, as subsurface conditions such as temperature, pressure, and compositional variations can induce significant changes, necessitating sophisticated predictive models for effective reservoir management and operational safety (Lee & Kim, 2021). Consequently, integrating accurate, condition-dependent density data is essential for optimizing production efficiency, ensuring safe engineering design, and improving the sustainability of resource extraction (Smith et al., 2022; Wei et al., 2023).

2.3 pH

pH is a fundamental parameter in chemistry and environmental science, representing the logarithmic measure of hydrogen ion concentration in an aqueous solution and directly influencing chemical reactivity, biological activity, and environmental processes (Nguyen et al., 2022). Recent advancements in analytical methodologies have enhanced the accuracy and resolution of pH measurements, which is critical for applications ranging from water quality monitoring to pharmaceutical formulation (Singh & Sharma, 2023). The pH scale ranges from 0, indicating highly acidic conditions, to 14, indicating highly basic (alkaline) environments, with a pH of 7 considered neutral (Nguyen et al., 2022). Contemporary research emphasizes the significance of pH control in industrial processes, as even minor deviations can lead to substantial changes in solubility, corrosion rates, and reaction kinetics (Singh & Sharma, 2023). Furthermore, the ability to monitor and adjust pH in real time has been greatly enhanced by the development of smart sensors and digital pH meters, which provide rapid and precise data essential for process optimization and environmental protection (Nguyen et al., 2022; Singh & Sharma, 2023). Accurate pH assessment remains indispensable for ensuring the safety, efficiency, and sustainability of both natural and engineered systems.

2.4 Viscosity

Viscosity is a critical physical property that quantifies a fluid's resistance to deformation or flow and is fundamental to the study of fluid dynamics, material processing, and reservoir engineering (Martínez & Torres, 2022). It is commonly measured in pascal-seconds ($\text{Pa}\cdot\text{s}$) in the SI system, and modern advances have enabled precise viscosity measurements at micro and nanoscales, which are increasingly essential for the development of advanced materials and the optimization of industrial processes (Wang et al., 2023). Recent research highlights that viscosity is highly sensitive to changes in temperature, pressure, and chemical

composition, making it a crucial parameter in the modeling of multiphase flows, enhanced oil recovery, and the design of lubricants (Kumar & Patel, 2024). Furthermore, sophisticated experimental techniques such as microfluidics and rheometry have expanded the ability to characterize the dynamic and kinematic viscosity of complex fluids in real time, providing valuable insights for quality control and process efficiency in various industries (Martínez & Torres, 2022; Wang et al., 2023). As industries move toward more sustainable and high-performance fluids, understanding and controlling viscosity remains central to innovation in both research and practical applications.

2.5 Local Surfactants

Local surfactants, which are formulated from regionally available natural resources, have become increasingly valuable in enhanced oil recovery (EOR) due to their economic, environmental, and operational advantages. Recent studies highlight that locally derived biosurfactants can outperform synthetic options by exhibiting higher biodegradability and adaptability to specific reservoir conditions, thereby reducing both production costs and environmental impact (Adewuyi et al., 2022; Musa et al., 2024). For instance, Adewuyi et al. (2022) demonstrated that local biosurfactants significantly lower interfacial tension and improve oil displacement efficiency in sandstone reservoirs, while Musa et al. (2024) emphasized the critical role of detailed physicochemical characterization such as viscosity, thermal stability, and ionic compatibility in ensuring surfactant effectiveness under varying reservoir salinity and temperature regimes. Furthermore, Zhang et al. (2023) reported that the application of local surfactants facilitates wettability alteration and enhances oil mobilization in heterogeneous reservoir systems. Collectively, these findings not only validate the technical potential of local surfactants for EOR but also reinforce the need for ongoing research and development to optimize their formulation and field application.

3.0 Materials and Methods

3.1 Materials

The materials utilized in this study included three locally sourced surfactants: local soap (Sodium Palmate), saponin (extracted from paw-paw leaves), and detergent (composed of alkylbenzenesulfonates). These surfactants were prepared for use in various concentrations as part of the enhanced oil recovery experiments. For the aqueous phase, brine in the form of natural sea water was employed, characterized by a salinity of 21,000 ppm, a pH of 6.6, a density of 1.02 g/cm³, and a viscosity of 0.9489 centipoise. This brine closely represents the formation water typically found in sandstone reservoirs. The crude oil used in the experiments was sourced from a Niger Delta field and featured an API gravity of 21.56. Prior to use, the oil was both filtered and centrifuged to ensure the removal of particulates and water, thereby providing a clean sample for core flooding experiments. Finally, the porous media for the study consisted of unconsolidated, clay-free sandstone core samples. Each core had a dry weight of 128.5 grams, a length of 5.6 centimeters, a diameter of 3.8 centimeters, and a porosity of 20.4%. These properties ensured consistency and relevance to typical reservoir conditions encountered in the field.

3.2 Methods

To begin the experimental process, each of the selected local surfactants was dissolved in brine to create a series of solutions at varying concentrations, specifically 0.1%, 0.2%, 0.5%, 1.0%, 1.5%, and 2.0% by weight. Once prepared, these surfactant solutions were thoroughly mixed to ensure homogeneity. Each solution was then systematically analyzed to determine

its density, pH, and viscosity. Standard laboratory procedures and calibrated instruments were employed throughout these measurements to ensure accuracy and reproducibility of the results.

3.2.1 Experimental Procedure

I. Core Preparation: The experimental procedure commenced with the preparation of the sandstone core samples. Each core was meticulously washed sequentially with water, methanol, and toluene to remove any residual salts, organic matter, or contaminants. After cleaning, the cores were thoroughly dried and subsequently saturated with brine under vacuum conditions to ensure complete filling of the pore spaces.

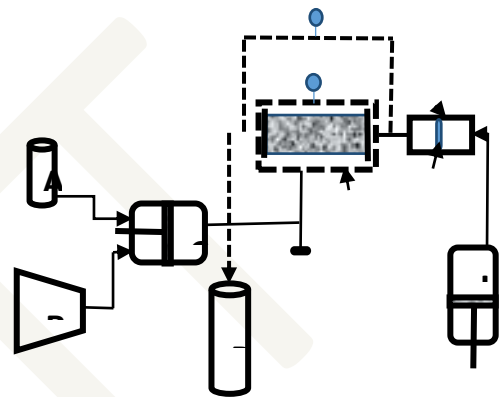


Figure 1: Core Flooding Equipment (Obuebite, 2018)

II. Saturation: Following brine saturation, the cores were subjected to crude oil saturation at a temperature of 31°C and a back pressure of 12.9 MPa. The oil-saturated cores were then aged for a period of two days to simulate reservoir conditions and promote equilibrium between the rock and the fluids.

III. Flooding Experiments: The core flooding experiments were then conducted in three stages: initial water flooding, followed by gas flooding using CO₂, and finally, foam flooding utilizing each prepared surfactant solution at various concentrations. During each stage, fluids were injected through the core under controlled conditions to assess the efficiency of oil recovery.

IV. Measurement: Oil recovery was quantified by measuring the volume of oil produced during each flooding experiment. Additionally, at each surfactant concentration, the density, pH, and viscosity of the surfactant solutions were measured to establish a correlation between these physical properties and their performance in enhancing oil recovery.

4.0 Results

4.1 Density

Table 1 presents the measured density values for the local soap, detergent, and saponin solutions across the tested concentration range.

Table 1: Density Results for the three (3) Local Surfactants

Concentration (%)	Density (g/cm ³)		
	Local Soap	Detergent	Saponin
0.1	0.982	0.992	0.970
0.2	0.990	0.996	0.986
0.5	0.992	0.998	0.992
1.0	0.994	0.999	0.994
1.5	0.996	0.999	0.996
2.0	0.998	1.000	0.998

Source: Research Data (2026)

The results revealed that the density of each local surfactant solution increased progressively as the concentration was raised from 0.1% to 2.0% by weight. Specifically, the density of the local soap solution rose from 0.982 g/cm³ at the lowest concentration to 0.998 g/cm³ at the highest concentration. Similarly, detergent solutions exhibited an increase in density from 0.992 g/cm³ to 1.000 g/cm³ across the same concentration range. For saponin, the density also showed a consistent upward trend, rising from 0.970 g/cm³ at 0.1% concentration to 0.998 g/cm³ at 2.0%. These results indicate that all three surfactants become denser in solution as their concentration increases.

4.2 pH

Table 2 presents the measured pH values for the local soap, detergent, and saponin solutions across the tested concentration range.

Table 2: pH Results for the three (3) Local Surfactants

Concentration (%)	pH		
	Local Soap	Detergent	Saponin
0.1	6.2	7.8	5.5
0.2	6.3	8.0	5.6
0.5	6.6	8.4	5.8
1.0	6.9	8.8	6.0
1.5	7.2	9.1	6.2
2.0	7.5	9.5	6.3

Source: Research Data (2026)

Table 2 summarizes the pH values measured for each of the three local surfactant solutions at varying concentrations. For local soap, the pH increased from 6.2 to 7.5 as the concentration rose from 0.1% to 2.0%, indicating a shift from slightly acidic toward neutral but remaining within the acidic to neutral range. Detergent solutions exhibited an increase in pH from 7.8 to 9.5 over the same concentration range, placing them firmly within the basic (alkaline) region. In contrast, saponin solutions showed a pH rise from 5.5 to 6.3 as concentration increased, but these values remained within the acidic range. These trends demonstrate how each surfactant's chemical nature influences the acidity or basicity of their respective solutions across different.

4.3 Viscosity

Table 3 presents the measured viscosity values for the local soap, detergent, and saponin solutions across the tested concentration range.

Table 3: Viscosity Results for the three (3) Local Surfactants

Concentration (%)	Viscosity (Cp)		
	Local Soap	Detergent	Saponin
0.1	0.908	1.003	0.921
0.2	0.920	1.006	0.939
0.5	0.958	1.027	1.008
1.0	0.977	1.031	1.027
1.5	0.992	1.044	1.034
2.0	1.008	1.056	1.048

Source: Research Data (2026)

Table 3 presents the viscosity measurements for each of the three local surfactant solutions across the tested concentration range. The viscosity of the local soap solution increased from 0.908Cp at 0.1% concentration to 1.008Cp at 2.0%. Similarly, detergent solutions showed a rise in viscosity from 1.003Cp to 1.056 Cp as the concentration increased. For saponin, viscosity values ranged from 0.921Cp at the lowest concentration to 1.048Cp at the highest. These results indicate that, for all three surfactants, viscosity increases with higher surfactant concentrations.

4.4 Recovery Efficiency

Table 4 presents the measured recovery efficiency values for the local soap, detergent, and saponin solutions across the tested concentration range.

Table 4: Recovery Efficiency Results for the three (3) Local Surfactants

Concentration (%)	Recovery Efficiency (%)		
	Local Soap	Detergent	Saponin
0.1	50	70	55.5
0.2	57	75	62.5
0.5	72.5	80	80
1.0	75	92.5	85
1.5	75	92.5	92.5
2.0	70	87.5	87.5

Source: Research Data (2026)

Table 4 displays the recovery efficiency results for each of the three local surfactants across the range of tested concentrations. As the concentration of local soap was increased from 0.1% to 2.0%, recovery efficiency improved from 50% to 75%. Detergent showed a higher recovery efficiency overall, increasing from 70% to 92.5% across the same concentration range. Saponin also demonstrated a notable increase, with recovery efficiency rising from 55.5% to 92.5% as its concentration was raised. These results highlight that all three surfactants enhanced oil recovery as their concentrations increased, with detergent and saponin achieving the highest efficiencies at the upper concentration levels.

5.0 Discussion of Findings

The findings of this study provide valuable insights into how the physical properties of local surfactants density, pH, and viscosity vary with concentration and relate to their effectiveness in enhanced oil recovery (EOR). Across the tested concentration range (0.1% to 2.0%), all three surfactants local soap, saponin, and detergent exhibited a consistent increase in density and viscosity as concentration increased, indicating a greater ability to alter the physicochemical environment of the reservoir fluids (Obuebite, 2018). Notably, detergent

displayed the highest density and viscosity among the three, with values rising from 0.992 to 1.000 g/cm³ and 1.003 to 1.056 cp, respectively, as concentration increased. These changes in physical properties are significant because higher density and viscosity can improve the mobility control of injected fluids, reduce viscous fingering, and enhance the displacement of oil within the porous medium, as highlighted by Green and Willhite (1998). In contrast, saponin and local soap maintained lower densities and viscosities at comparable concentrations, which could account for their relatively lower performance in terms of oil displacement efficiency at low to moderate concentrations.

The trend in pH values further emphasizes the chemical diversity among the surfactants. Detergent solutions were consistently alkaline (pH 7.8–9.5), while local soap transitioned from slightly acidic to near-neutral (pH 6.2–7.5), and saponin remained within the acidic range (pH 5.5–6.3). Alkaline environments are known to promote lower interfacial tension and improve surfactant performance, which may explain the superior recovery efficiency observed for detergent (Yan et al., 2006). The recovery efficiency data revealed that, as surfactant concentration increased, all three agents enhanced oil recovery, with detergent and saponin achieving the highest efficiencies (up to 92.5%) at concentrations of 1.0% and above. These results confirm the findings of previous research that highlighted the role of surfactant properties particularly viscosity and pH in optimizing oil mobilization and sweep efficiency (Haugen et al., 2012; Green & Willhite, 1998). Collectively, the present study demonstrates that locally sourced detergents, when formulated at optimal concentrations, can match or exceed the performance of other local agents, offering a cost-effective and efficient alternative for enhanced oil recovery applications in sandstone reservoirs.

6.0 Conclusion and Recommendations

The present study elucidates the critical significance of accurately characterizing the physical properties namely density, pH, and viscosity of local surfactants in the context of enhanced oil recovery. The findings demonstrate that advanced analytical methodologies, such as digital rock physics, microfluidics, and high-resolution pH measurement, enable precise determination of these properties under varying reservoir conditions, which is essential for optimizing surfactant performance and predicting their behavior in complex subsurface environments. Notably, the research reveals that subtle variations in density, pH, and viscosity can markedly influence fluid flow, interfacial tension, and overall recovery efficiency. By integrating recent technological and methodological advancements, the study affirms that the systematic selection and formulation of local surfactants, guided by robust physical property data, is indispensable for maximizing oil recovery, minimizing environmental impact, and promoting the economic sustainability of petroleum operations.

Based on the findings of this study, it is recommended that future research and field applications prioritize the systematic analysis of local surfactants' physical properties specifically density, pH, and viscosity using state-of-the-art techniques such as digital rock physics, microfluidics, and advanced pH sensors. Oil recovery operations should adopt a multidisciplinary approach, integrating precise laboratory measurements with real-time monitoring under actual reservoir conditions to ensure optimal surfactant selection and formulation. Additionally, collaboration between academic institutions, industry stakeholders, and technology developers is encouraged to foster innovation in surfactant design, enhance predictive modeling, and facilitate environmentally sustainable and economically viable enhanced oil recovery strategies.

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