

Performance Evaluation of Synthetic and Natural-Based Surfactants for Chemical Enhanced Oil Recovery

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Contemporary studies have demonstrated the ability of some natural materials to recover oil thereby replacing synthetic materials; however, the effectiveness of these natural materials in recovering oil at high temperatures, pressures and in hard waters needs to be determined. The research aims at comparing the recoverability of a natural and synthetic surfactant with divalent ions being present and under reservoir conditions after which a cost analysis at field scale is conducted. Two surfactants namely, Hibiscus calyx extract and sodium dodecyl sulphate (SDS) were assessed in the laboratory using hard brine. Phase behaviour and sandstone core analysis was conducted to ascertain the effectiveness of these surfactants in recovering residual oil at high temperature and pressure of 80°C and 8000 psi respectively. Upscaling from laboratory to field scale and a comparative cost analysis was performed. Results showed a high compatibility of both surfactants in hard brine with an absence of Type III micro emulsion. At reservoir conditions, Hibiscus calyx extract resulted in an increased oil displacement efficiency and additional recovery of 88% and 24% than SDS which resulted in a displacement efficiency and additional recovery of 72% and 19% respectively. Using an upscaling factor to field scale, a chemical injection rate of about 5 barrels/day was attained. Comparative cost analysis showed that the natural surfactant is more cost-effective.

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This study proposes the use of natural surfactants in harsh oilfield conditions, eliminating processes of brine softening with economic advantages of reusing produced water to prepare chemical slugs for EOR treatments.

Keywords: Surfactant flooding; hard brine solution; microemulsions; SDS; Hibiscus calyx.

ABBREVIATIONS

SDS : Sodium dodecyl sulfate
IFT : Interfacial tension
EOR : Enhanced Oil Recovery
AS : Alkaline Surfactant
Pc : Capillary pressure
OOIP : Original oil in place
CMC : Critical Micelle Concentration.

1. INTRODUCTION

The injection into an oil reservoir of surface-active chemicals also known as surfactants via injection wells often reduces the interfacial tension (IFT) that exist between the aqueous and oleic fluids from 10–30 mN/m to 0.001 mN/m thereby leading to an additional mobilization of oil initially trapped by capillary forces. The primary duty of surfactants during enhanced oil recovery process is to reduce the interfacial tension that exist between immiscible fluids such as oil and water thereby allowing a continuous flow of the emulsion phase [1]. When the interfacial tension (IFT) is low, it negates the restrictive capillary forces which originally traps the residual oil thereby causing the oil droplets to integrate resulting in a continuous flow of oil.

Surfactants are compounds with molecules that have a specific chemical composition with a hydrophilic head (soluble in polar medium) and a hydrophobic tail (soluble in nonpolar medium), indicating that surfactants have both oil-soluble and water-soluble component making them amphiphilic in nature. Surfactants are classified depending on the nature of the hydrophilic part (polarity) which could be anionic (-ve), cationic (+ve), zwitterionic (both -ve and +ve), and non-ionic surfactants (no ionic charge) [2]. These amphiphilic substances adhere on surfaces or interfaces of the rock thereby altering the surface or interfacial pressure. Anionic surfactants which are negatively charged are commonly used during chemical flooding on sandstone formations principally because of their more stable nature. After secondary recovery, bypassed or residual oil are not displaced due to lack of high energy required to overcome capillary pressure (Pc). However, when

surfactants are introduced, they reduce the capillary pressure and the oil–water interfacial tension and this allows the easy displacement of oil droplets thereby improving the amount of oil recovered. Due to the increasing cost of these surfactants chemicals and their high rate of adsorption on rock matrix, the use of insitu surfactants (formed from the interaction between the alkali chemicals and the naphthenic acid in the crude oil) reduces the adsorption of synthetic surfactants onto the rock. The mechanism for improving oil recovery using synthetic and insitu surfactants is the attainment of an ultra-low interfacial tension (IFT) between the aqueous - oil phase as well as the alteration of rock's wettability from oil wet to water wet. Liu et al. [3] observed that the injection of insitu surfactant resulted in an over-optimised condition. However, with the introduction of synthetic surfactant in minute quantities alongside the insitu surfactant, an optimised salinity was obtained vis-a-vis an ultra-low interfacial tension. This indicates that a well-designed and formulated surfactant is a prerequisite in attaining a high recovery factor. Several field tests using alkaline-surfactant (AS) flooding including the Upper Assam Field, India showed that a properly formulated surfactant is required to attain a higher oil recovery. Tabary et al. [4] noted the challenges encountered when surfactants are used under certain harsh conditions such as increased temperatures, hard brines and high salinities due to the increasing rate of surfactant adsorption when in contact with divalent ions resulting in precipitation which contributes to surfactant retention and poor surfactant performance. Anionic surfactant, sodium dodecyl sulfate (SDS) which is commonly used in petroleum industry due to their reduced level of adsorption and relative stability especially on sandstone reservoirs has been proven to effectively attain an ultra-low interfacial tension. Experimental studies have shown that sulfate-based surfactant retention in sandstone reservoirs is mostly caused by surfactant precipitation resulting from divalent ions present in the formation brine as well as surfactant adsorption on the rock edges due to the clay content on the rock matrix. Xu et al. [5] noted that SDS just like other sulfate-based surfactants are

susceptible to high temperatures and hard brine. With the declining crude oil prices and the costly nature of these synthetic surfactants, the use of these chemical has become less attractive and uneconomical as they have become more costly than the price of the produced crude oil.

The development of an efficient and cost-effective surfactant flooding scheme is dependent on the amount of surfactant that can be sacrificed economically while recovering additional residual oil. More so, the associated toxic effect of these synthetic surfactants has proven to be dangerous to the environment, aquatic, and human lives. Thus, in line with acceptable global practices of ensuring a clean and green environment, the need to design a surfactant chemical that is environmentally friendly is pertinent [6].

Experimental studies bothering on the usage of alternative natural sources as surfactants have gained increasing attention. Jahan et al. [7] confirmed in their comparison between biosurfactants and their synthetic counterparts that biosurfactants can act as a natural substitute to synthetic surfactant. Several researchers [8-12] have carried out laboratory studies using certain natural materials capable of acting as surfactants. The effectiveness of natural materials such as Glycine max, Carica papaya leaf extract, detergent powder, local bar soap, extract of Cocos nucifera, Vernonia amygdalina extract in enhancing oil recovery were evaluated. Momodu et al. [11] in comparing between detergent, liquid soap and bar soap, reported that detergent is a better surfactant probably owing to its sodium content. Ojukwu et al. [10] used lecithin derived from soybeans as a natural surfactant and reported an oil recovery factor of 23.3% original oil in place (OOIP). Uzoho et al. [9] using agricultural waste, Carica papaya leaf extract, Cocos nucifera and Vernonia amygdalina as natural surfactant agents compared their displacement efficiency to that of commonly used surfactant, SDS. The study showed that SDS performed slightly better with a displacement efficiency of 97% compared to 94.5% for Cocos nucifera. However, Ogolo et al. [13] noted that some of these natural agents if modified can replace the synthetic surfactants. Obuebite et al. [8] compared the efficiency of certain natural surfactants (modified and unmodified) with SDS, they concluded that glycol-modified surfactant, Alkasurf X performed better than SDS implying that these natural surfactants are

suitable alternatives being that they are more accessible, highly efficient, cost-effective and non-toxic. Hibiscus Calyx contains mainly polyhydroxy compounds, saponins, which is a glucoside with inherent foaming components belonging to a class of plant metabolites that have rich surface-active properties [14]. This study seeks to ascertain the efficiency and oil recoverability of a natural surfactant at reservoir condition in the presence of divalent ions in comparison to the displacement efficiency of a synthetic surfactant, SDS, at laboratory and field scale and conduct a comparative cost analysis of the process with a bid to determine the most environmentally friendly and highly effective surfactant chemical.

2. MATERIALS AND METHODS

2.1 Materials

Calyx of Hibiscus and potash were locally sourced from an open market at Mbiama (5.0641°N, 6.4483°E) in Ahoada LGA, Rivers State. Distilled water, sodium chloride, calcium chloride, magnesium chloride and sodium dodecyl sulfate (SDS) were purchased from local suppliers. The reagents used were of high analytical grade. The crude oil used was obtained from a Niger Delta oil field X. Apparatus used include: water bath, thermometer, rotary evaporator, core flooding apparatus, conductivity meter, pH meter, magnetic stirrer, filter paper, core plug, funnels, beakers, glass tubes and pipettes.

2.2 Methods

The methods adopted for this study include: preparation of agro waste sample, extraction of the samples, preparation of brine sample, phase behaviour analysis, coreflooding analysis and cost analysis.

2.2.1 Preparation of natural surfactant

The calyx of Hibiscus were properly selected, sun-dried under atmospheric pressure and temperature conditions of 32 °C for 2 h to reduce moisture content. The dried calyx were pulverized to increase the surface area for extraction, and thereafter filtered to remove impurities and transferred to an airtight container. Potash was also pulverished, sun-dried under the same condition and sealed in an air tight container. They were both labelled appropriately.

2.2.2 Preparation of brine

Synthetic brine sample was prepared to replicate the formation brine using distilled water. The brine contained varying concentrations of sodium chloride, potassium chloride, calcium and magnesium chloride with a total dissolved solids (TDS) of 30,000 ppm with 5,000 mg/l being total concentrations of calcium and magnesium chloride (divalent ions). The composition of the brine is outlined in Table 1.

Table 1. Brine composition

Brine component	Concentration (ppm)
NaCl	22,000
KCl	3,000
MgCl ₂	2,000
CaCl ₂	3,000
TDS	30,000

2.2.3 Extraction process

A cold extraction process was conducted using 10% potash solution as the solvent. The solvent was a mixture of potash and distilled water in the ratio of 70:30. The powdered Hibiscus calyx was completely dissolved in 10% potash solution and allow to stand for 48 h in an enclosed glass beaker. The filtrate was extracted from the solvent using the rotary evaporator (concentration of sample) and the resultant extract was collected.

2.2.4 Aqueous stability test

To determine the compatibility of the fluids at different concentrations, a compatibility test between Hibiscus calyx extract (natural surfactant) and the hard brine solution was performed. Similar test was conducted using SDS. Varying concentrations of both surfactants (0.1 to 1.0%) were analyzed. The well-sealed beakers were vigorously stirred with the aid of a magnetic stirrer. This was carried out under laboratory temperatures and later controlled to an increased temperature of 100 °C.

2.2.5 Critical Micelle Concentration (CMC)

CMC is a key attribute of surfactants which was determined to certify an optimum surfactant concentration. Values of measured electrical conductivity of both surfactants was plotted against surfactant concentration. The flex point on the plot was considered as the CMC.

2.2.6 Salinity scan test

A scan of salinity range was performed out to ascertain the salinity tolerance of both surfactants at varying brine concentration. Using a 10 ml glass test tube, the CMC of the surfactant at a corresponding calculated volume was kept constant, while varying the brine concentration and their corresponding pH value was measured.

2.2.7 Phase separation (Pipette) test

Phase separation test was carried out to observe the compatibility of the aqueous and the oleic phases. Using pipettes containing equal volumes of aqueous solution (at different concentrations) and crude oil, the tightly sealed pipettes were carefully inverted to ensure a proper mix of the two phases at laboratory and reservoir temperature of 100 °C.

2.2.8 Visual assessment

Fluid surfaces were observed under laboratory and reservoir conditions over time (7days) for the presence of microemulsion. Only solutions containing Type III microemulsion were selected as that is indicative of an ultra-low interfacial tension. Afterwards, readings obtained for the aqueous, oleic and microemulsion were recorded and their individual volumes and solubilisation ratio was calculated and plotted against salinity values to obtain an optimum salinity.

2.2.9 Oil Displacement test

Absolute porosity and pore volume of the core sample was calculated. Sandstone core flooding using both surfactants at different times was conducted. The recovery factor of the natural and synthetic surfactant was determined. An AFS-300 Core flooding system was used in conducting the oil displacement experiment at reservoir conditions of 80 °C and 8000 psi. The core flooding experiment followed a sequence from drainage, imbibition and then surfactant flooding.

2.2.10 Drainage

The fully saturated sandstone core was placed in the core holder. The medium crude served as the displacing fluid at 1.4PV to completely expel out brine till an initial drop of oil was observed. The volume of the displaced brine was measured and recorded as the OOIP. The initial oil saturation and irreducible water saturation was determined.

2.2.11 Imbibition (secondary flooding)

10PV of brine was deployed to completely displace oil until oil was no longer produced. The collected volume of displaced oil was measured, and the residual oil saturation was calculated.

2.2.12 Surfactant flooding

2PV of the surfactant solution serving as the displacing fluid was injected into the core to enhance the recovery of the residual oil at reservoir temperature. Surfactant flooding continued until an oil cut of less than 1% was recorded.

2.3 Cost Analysis

Cost analysis was conducted by determining the unit cost of both surfactants. Prior to this, results obtained from the laboratory were up scaled to field scale whereas the individual cost of these surfactants on a field scale was calculated. A comparative analysis between the two surfactants was performed based on their recoverability, displacement efficiency, affordability, availability and their eco-friendliness.

3. RESULTS AND DISCUSSIONS

3.1 Physicochemical Property Analysis

Certain physical properties of the crude oil sample was determined and the results of these properties are outlined in Table 2. Results of API gravity indicates that the crude oil is a medium crude.

Porosity of the core sample was calculated to determine the measure of void spaces wherein fluid can accumulate. Table 3 shows the calculated properties of sandstone core sample with a calculated pore volume and absolute porosity of 14.4 cm³ and 27%, respectively measured using the saturation method. The porosity value is typical of a sandstone rock type which has higher porosity values ranging from 5-35% as compared to limestones or dolomites [15].

3.2 Aqueous Stability Test

Results of compatibility test of the natural surfactant extract in brine solution as well as that of the synthetic surfactant in brine at varying concentrations produced highly compatible fluids. It was discovered that for SDS, the higher the concentration and temperature, the soapier the

solution. SDS at 0.1% conc. produced cloudy solution but as the concentration and temperature increased, solubility also increased while Hibiscus calyx extract produced clear, compatible solutions for all concentrations at laboratory conditions and under an elevated temperature of 100 °C. This implies that both surfactant types have high solubility and are highly tolerant of divalent ions even under high temperature. This affirms the findings of Chhetri et al. [16] who studied the effect of heat on IFT using natural surfactants and observed that a higher interfacial tension reduction was obtained after heat was introduced. They can chelate the effect of divalent ions and as such can be used even in the presence of hard waters without the need to soften the water (brine).

Table 2. Properties of crude oil sample

Physical Properties	Values
Density @ 29°C	0.91 g/cm ³
API Gravity	23.9°
Viscosity	44.21 cP @ 34°C
Colour	Brownish black

The results obtained indicate that viscosity is a function of concentration, in other words, an increase in viscosity gave a corresponding increase in the concentration of both surfactant grades. Table 4 shows viscosity readings taken at elevated temperature of 40°C with SDS having a slightly higher viscosity than the Hibiscus calyx extract. In surfactant flooding, the pH value of a surfactant is considered a more important parameter than its viscosity, this is because the pH alters the wettability of the rock from oil-wet to water-wet and reduces the adsorption of surfactant on the rock surface which invariably reduces the surfactant quantity used as well as the cost. It was observed that the pH of the natural surfactant decreased with increasing concentration (inverse relationship) while the pH of the synthetic surfactant was directly proportional to its concentration. Furthermore, it can be deduced from the result that the Hibiscus calyx extract with a pH of 8-9 is a better candidate for surfactant flooding than SDS. The use of Potash for the extraction process also contributed to high pH value of the Hibiscus calyx. The results of the CMC of surfactants (Figs. 1 and 2) indicate that SDS has a lower CMC value (0.2%) than the natural surfactant, Hibiscus calyx (0.3%). The CMC was used as the surfactant concentration because an increase in concentration above the CMC does not reduce the interfacial energy [17].

Table 3. Calculated properties of core sample

Core Length (cm)	Core Plug Diameter (cm)	Bulk Volume (cm ³)	Dry Sample mass (g)	Saturated Sample mass (g)	Mass of Brine (g)	Brine density (g/cm ³)	Pore Volume Vp (cm ³)	Porosity (%)
5.8	3.4	52.66	128.44	143.159	14.72	1.02	14.4	27.36

Table 4. Physical properties of selected surfactants in Hard Brine

Hard Brine Conc (%)	Hibiscus calyx extract			Sodium Dodecyl Sulphate (SDS)		
	pH value	Conductivity (s/m)	Viscosity (cP)	pH value	Conductivity (s/m)	Viscosity (cP)
0.1	9.2	0.47	0.9	6.0	0.72	1.0
0.2	9.1	0.47	1.0	6.1	0.72	1.1
0.3	9.1	0.49	1.0	6.2	0.73	1.1
0.4	9	0.50	1.0	6.3	0.74	1.1
0.5	8.9	0.52	1.0	6.4	0.75	1.1
0.8	8.7	0.54	1.1	6.7	0.75	1.2
1	8.3	0.55	1.2	6.9	0.76	1.3

3.3 Salinity Scan Test

Salinity scan test was performed on both surfactants. The CMC of the surfactant was kept constant while the salinity of the brine was varied. Results showed clear, compatible solution for both surfactants at low and high salinities under varying temperatures. As seen in Fig. 3, the pH value of SDS increased as the brine salinity increased while the pH of the natural surfactant, Hibiscus calyx decreased as the brine salinity increased as shown in Fig. 4. Liu et al. [3] noted that a direct relationship exists between the salinity and pH while an inverse relationship exists between pH and concentration of synthetic surfactants.

3.4 Phase Separation Test

Phase separation test was conducted for both surfactants in brines constituting the aqueous phase and the oleic phase (crude oil). Clear SDS solution at varying salinities (obtained during the salinity scan) and crude oil resulted in Type I or lower phase microemulsion. Similar test on the natural surfactant, Hibiscus calyx also resulted in Type I microemulsion. The pipettes were further subjected to increased temperature of 100°C for an equilibration period of 7days. With this, both surfactants at varying concentration still maintained Type I microemulsion indicating a lower salinity than optimum making it impossible to attain ultra-low interfacial tension [18]. Moreover, Liu et al. [3] and Obuebite et al. [8] noted that only the

mixture of an insitu and an injected surfactant achieves the lowest interfacial tension (IFT).

Core flooding analysis was performed on the two selected surfactant agents, SDS and the Hibiscus calyx extract at reservoir temperatures. Another type of brine was formulated without any divalent ion but composed of only sodium chloride (soft brine). Soft brine was used as a control measure. The values for irreducible water saturation and initial oil saturation were obtained after crude oil was injected to displace brine (Table 5). Afterwards, 10PV brine was injected into the reservoir to displace oil at an injection rate of 0.107 ml/sec for 2 hrs. and 39mins and residual oil saturation was determined. Surfactant flooding as a type of chemical enhanced oil recovery (CEOR) was carried out. 2PV of the selected surfactant was injected at a rate of 0.107ml/sec for about 2 hrs. and 27 mins. In addition, it was observed that in the absence of divalent ions, natural surfactant Hibiscus calyx performed slightly better with a displacement efficiency of 84% as opposed to SDS having a displacement efficiency of 80% (Fig. 5) and this corroborates the work of Obuebite et al. [19]. In the presence of divalent ions, the natural surfactant also had a higher oil displacement efficiency of about 88% and thus performed better than SDS (72%). Enhanced oil recovery (after secondary/brine flooding) using the selected surfactants (Fig. 6 and Table 6) resulted in additional recovery of 24% OOIP and 19% OOIP for Hibiscus calyx and SDS, respectively when flooded with brine containing divalent ions. This implies that the presence of

divalent ions which is mostly found on the rock surfaces impedes oil recovery whereas synthetic surfactants are more susceptible to the effect of divalent ions. The natural surfactant, Hibiscus calyx is a more effective surfactant than SDS in the presence of divalent ions due to its ability to chelate these divalent ions and recover more oil even under harsh conditions. This also agrees with the findings of Wojton et al. [20] which reports that natural surfactants can reduce surface or interfacial tension even in hard waters.

3.5 Upscaling to Field scale

The laboratory model obtained was up-scaled to field scale, to evaluate the parameters from the up-scaled model on a reservoir scale. An upscaling factor, R was determined by the ratio of the average length between two wells to the length of the core. The assumed length between the wells, the core length and the calculated value of the upscaling factor, R are shown (Table 7) while parameters such as brine and surfactant injection calculated at pore and field scale are also presented (Table 8).

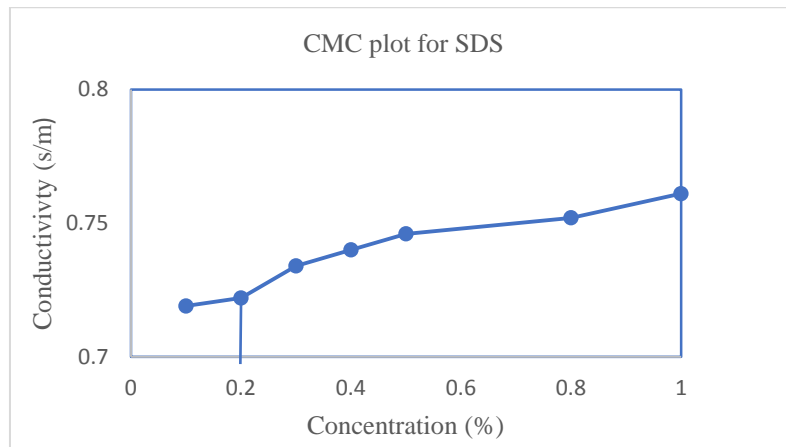


Fig. 1. Plot of CMC of Surfactant, SDS

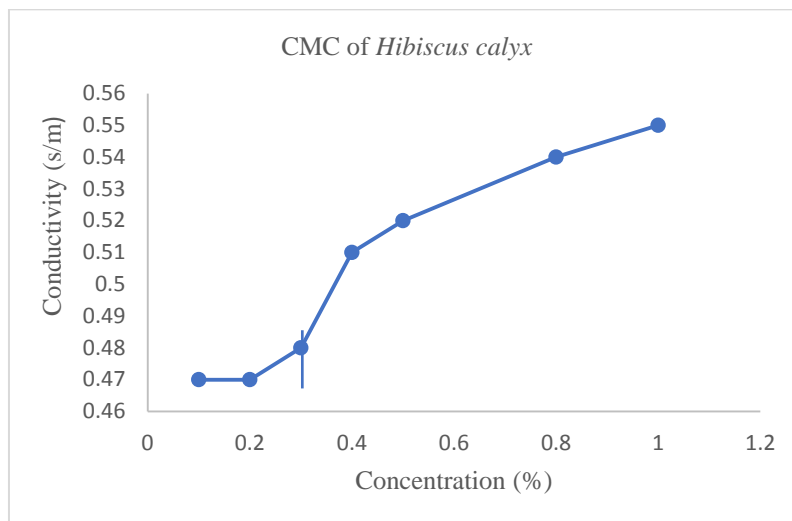


Fig. 2. Plot of CMC of surfactant, *H. calyx*

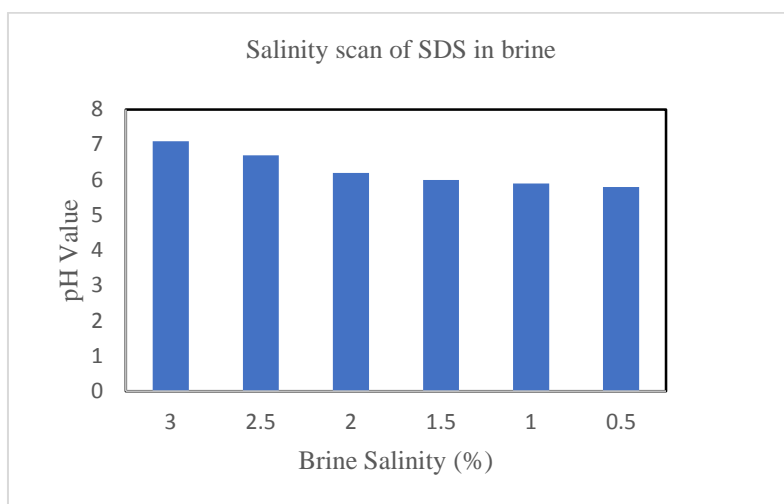


Fig. 3. Brine salinity vs pH value of SDS

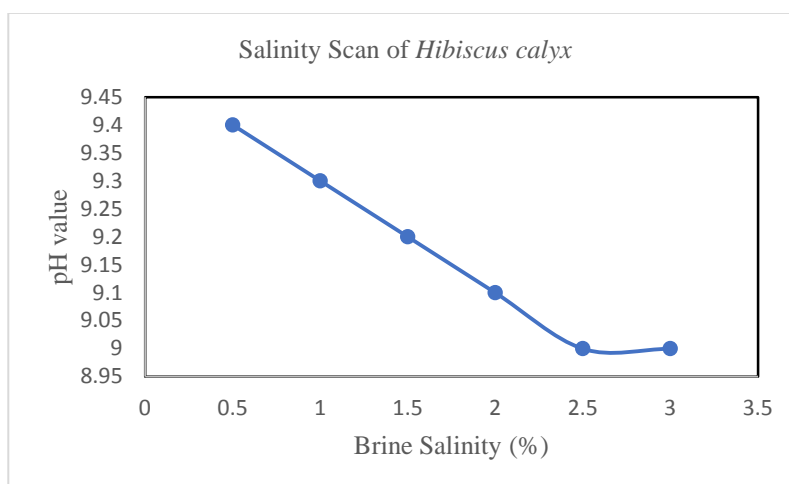


Fig. 4. Brine salinity vs pH value of *H. calyx*

Table 5. Calculated values for drainage, imbibition and tertiary recovery using SDS

Input Data (Drainage)	Value	Units
Pore Volume	14.38	ml
Dead Volume	6	ml
Flow rate	0.017	ml/sec
OOIP	12	ml
Irreducible water saturation	14.41	%
Initial oil saturation	85.6	%
Imbibition (Hard brine)	Value	Units
Total vol. of oil recovered	8.8	ml
OOIP	12	ml
Recovery factor	73.3	%
Residual oil Saturation	26.7	%
SDS Flooding	Value	Units
Produced oil	2.3	ml
OOIP	12	ml
Displacement efficiency	72	%
Additional recovery	19	%

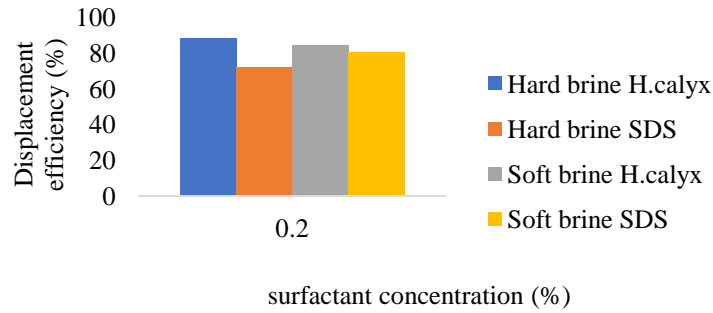


Fig. 5. Surfactant Concentration vs Displacement Efficiency for flooding at 80 °C

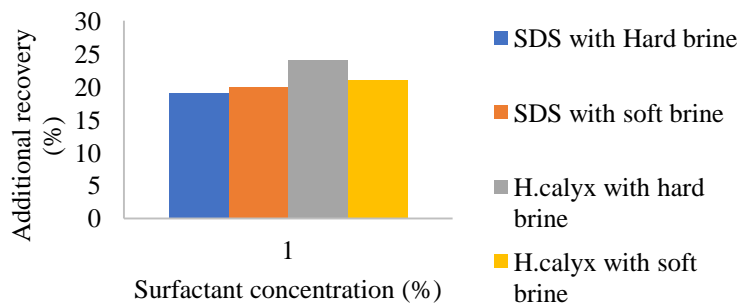


Fig. 6. Surfactant Concentration vs additional recovery

Table 6. Calculated values of additional oil recovery obtained after tertiary recovery

Parameters	SDS with hard brine	SDS with soft brine	Hibiscus calyx with hard brine	Hibiscus calyx with soft brine
Vol of oil recovered (ml)	2.3	3.2	2.4	3.2
OOIP (ml)	12	16	10	15
Vol. of oil recovered after imbibition (ml)	8.8	12	7.3	11.2
Additional recovery after imbibition (%)	73	75	73	75
Displacement efficiency (%)	72	80	88	84
Additional recovery after tertiary flooding (%)	19	20	24	21

Table 7. Reservoir model parameters

Parameters	Description
Length – Average spacing of well	400 ft.
Core length	5.8cm.
Upscaling factor	2,102.066

Table 8. Up-scaled model parameters

Parameters	Pore scale	Conversion	Field scale
Pore Volume	14.4ml		98,280 ft ³
Brine injection rate	144ml/min	0.010937 barrels/day	22.99 barrels/day
Surfactant injection rate	28.8ml/min	0.002366 barrels/day	4.98 barrels/day

3.6 Cost Analysis

The value of 28.8 ml/min at laboratory scale was upscaled to field scale to be 5 barrels/day of surfactant needed during the flooding process. The cost price needed to purchase the amount of surfactant equivalent to 5 barrels was estimated. One fluid barrel is equivalent to 119 litres of fluid.

Cost determination for SDS

1kg/ litre of SDS = \$3
Since, 119litres = 1 barrel of SDS
Cost of 119litres of SDS = \$ 3,094 (cost for one barrel);
Cost of 5barrels = \$ 3,094 x 5
= \$ 15,470.00

Cost determination for Hibiscus calyx

1 litre of Hibiscus calyx = \$3
Since, 119litres = 1 barrel of Hibiscus calyx
Cost of 1barrel in litres = \$ 357
Cost of 5barrels = \$357 x 5
= \$1,716.40

The unit cost of 1 litre of SDS is estimated at \$26. The results obtained during the surfactant flooding requires about 5barrels of surfactant per day to obtain an additional recovery of 19% OOIP on a field scale. From the calculation, it implies that about \$ 15,470.00is required daily to purchase the synthetic surfactant, SDS. On the other hand, the unit cost of 1litre of locally sourced, natural surfactant, Hibiscus calyx and Potash that was used for the extraction process is estimated at \$3. Surfactant flooding indicates that about 5 barrels of surfactant per day is required to obtain an additional recovery of 24% OOIP on a field scale. A total cost of about \$1,716.40 is required to daily to purchase the natural surfactant, Hibiscus calyx while the cost of Brent crude oil is \$71/barrel (as of December 1, 2021). The present cost of SDS is much higher than Hibiscus calyx. Hibiscus calyx being a locally grown plant is readily available, less expensive, highly effective and non- toxic to the environment and could therefore be considered a suitable alternative for the synthetic surfactant, SDS due to its availability, performance and cost.

4. CONCLUSION

Based on the outcome of this study, selected surfactants showed a high solubility in brine at all concentrations including at reservoir temperature of 100°C.Synthetic surfactant, SDS is slightly

more viscous than the natural surfactant. The Hibiscus calyx extract showed a higher pH than SDS. Furthermore, the CMC of the surfactants showed that SDS had the least value of 0.2% compared to that of the natural surfactant (0.3%). Salinity scan test conducted on the selected surfactants produced compatible solutions at high and low concentration with an increase in pH value observed with increased brine salinity. In addition, phase separation test resulted in Type I microemulsion is indicative of low salinity. The oil displacement results showed that natural surfactants can recover residual oil. The natural surfactant, gave a higher additional oil recovery of 24% than the synthetic surfactant at 19% in the presence of divalent ions.At field scale, a surfactant injection rate of 4.98 bpd is needed to achieve an additional recovery of 24% OOIP. Moreover,the cost analysis shows that the cost of SDS is about nine times the cost of natural surfactant. Hence, Hibiscus calyx extract can be considered as a novel natural surfactant for chemical enhanced oil recovery and could be considered a suitable alternative for SDS especially when flooding with hard waters.

STATEMENTS AND DECLARATION

Availability of data and materials: All data were generated during this study as provided by the authors. This manuscript is an original research article and it is novel.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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