



Experimental and Economic Evaluation of Cocoa-Pod Waste as a Bio-Surfactant for Enhanced Oil Recovery in Niger Delta Sandstone Reservoirs

Ibeh Nkiruka Joy, Usiayo, Afoke Victor, M. Horsfall

Abstract

This study evaluates the potential of cocoa-pod waste (CPW) as a bio-surfactant for enhanced oil recovery (EOR) in Niger Delta sandstone reservoirs. Characterization showed key elements (potassium: 2.45 mg/g, calcium: 1.82 mg/g) and phytochemicals (saponins, alkaloids) contributing to its surfactant properties. Core flooding experiments at concentrations of 1000–3000 ppm yielded additional displacement efficiencies of 9.09–13.63% beyond secondary recovery and oil recovery rates of 77.27–85.71%, with the highest recovery (85.71%) at 2500 ppm. Economic analysis indicated a preparation cost of ₦800/kg and a maximum net present value (NPV) of ₦528 per run at 1500 ppm, highlighting cost-effectiveness compared to synthetic surfactants. The use of CPW repurposes agricultural waste, reducing landfill pollution and supporting Nigeria's agricultural economy. These findings suggest that CPW is a sustainable and economically viable EOR agent for sandstone reservoirs.

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Keywords: Enhanced Oil Recovery, Cocoa-Pod Waste, Bio-Surfactant, Niger Delta, Sandstone Reservoirs, Core Flooding, Economic Analysis

Author Contributions

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Article history

Received: June 28, 2025

Received in revised form: August 19, 2025

Accepted for publication: August 25, 2025

Available online: August 27, 2025

1.0 Introduction

Global energy demands and the depletion of conventional oil reserves have prioritized maximizing hydrocarbon recovery techniques from existing fields (Lake, 1989). In Nigeria's Niger Delta, sandstone reservoirs retain significant residual oil after primary and secondary recovery due to capillary forces, reservoir heterogeneity and unfavorable wettability conditions (Adekomaya *et al.*, 2019). Enhanced Oil Recovery (EOR) also known as tertiary recovery mobilizes this residual oil by altering the physical or chemical properties of oil or the reservoir by extracting 30 – 60% or more of a reservoir's oil compared to 20 – 40% using primary and secondary methods (U.S. Department of Energy, 2015; Electric Power Research Institute, 1999; Clean Air Task Force, 2009).

EOR techniques including thermal, gas, chemical and hybrid methods have been widely applied with their success dependent on reservoir-specific conditions (Seidy-Esfahlan *et al.*, 2024). Chemical EOR, particularly surfactant flooding techniques has been found to reduce interfacial tension (IFT) and improves sweep efficiency in sandstone reservoirs (Green & Willhite, 1998). For example, polymer flooding in Oman's Marmul field increased oil recovery by 10% (Mahruqi *et al.*, 2024), while alkaline-surfactant-polymer (ASP) flooding technique used in Canada's Lloydminster field added 7 – 10% (Seidy-Esfahlan *et al.*, 2024). Thermal methods like steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS) techniques have been found to effectively recover heavy oil reservoirs in Canada (Seidy-Esfahlan *et al.*, 2024) and CO₂ injection has improved sweep efficiency in heterogeneous reservoirs in Russia and China (Lang *et al.*, 2020). Novel approaches, such as nanoparticle-assisted polymer flooding, show laboratory promise but face scalability challenges (Salem *et al.*, 2024). However, the high cost and

environmental impact of synthetic surfactants, such as sodium dodecyl sulfate, limit their use in resource-constrained regions like Nigeria (Iggunnu & Chen, 2012).

In Nigeria, reliance on imported EOR chemicals depletes foreign reserves and poses environmental risks, necessitating sustainable alternatives. Cocoa-pod waste (CPW), an abundant agricultural by-product, offers a bio-surfactant solution due to its surfactant-like properties and local availability (Ofori-Boateng *et al.*, 2020). Nigeria produces over 250,000 tonnes of cocoa annually, with 80% of the pod weight discarded as waste, contributing to landfill pollution (Oddoye *et al.*, 2013). Previous studies have shown that CPW reduces IFT in sandstone reservoirs, achieving up to 15% additional oil recovery (Mohammed *et al.*, 2019). Other bio-based materials, such as guar gum and chitosan, have similarly enhanced oil displacement by altering wettability (Taha *et al.*, 2019; Liu *et al.*, 2019). Utilizing CPW in EOR could address waste management challenges while providing an economically viable and environmentally sustainable solution (Vasquez *et al.*, 2019).

This study aims to carry out an experimental and economic evaluation of cocoa-pod waste (CPW) as a bio-surfactant for enhanced oil recovery in Niger Delta Sandstone Reservoirs. The specific objectives are to:

1. Characterize the elemental and phytochemical composition of CPW to confirm its surfactant properties.
2. Compare the displacement efficiency and oil recovery performance of CPW with conventional surfactants through core flooding experiments
3. Conduct an economic evaluation to assess CPW's cost-effectiveness for EOR applications.

4. Evaluate the environmental benefits of CPW to promote sustainable EOR practices.

2.0 Materials and Methods

This study was conducted in two primary phases: (1) phytochemical and elemental characterization of cocoa-pod waste (CPW) to confirm its bio-surfactant properties, performed in a chemistry laboratory; and (2) core flooding experiments to evaluate its efficacy as an enhanced oil recovery (EOR) agent, conducted in a petroleum engineering laboratory at the University of Port Harcourt, Nigeria.

Materials and Equipment

Laboratory analyses employed a laboratory coat, gloves, sieves (600 μm), blender, heating mantle, fume cupboard, hydrochloric acid, nitric acid, and an Atomic Absorption Spectrophotometer (AAS). Core flooding experiments utilized unconsolidated Niger Delta sand, fossil fuel samples, saline solutions (NaCl/KCl), a core holder, accumulators, vacuum pump, viscometer, weighing balance, oven, hydrometer, pH meter, and magnetic stirrer.

Sample Preparation and Characterization

Cocoa pods were purchased locally, cleaned, de-seeded, sun-dried to constant weight, crushed, blended, and sieved into powder. The powder was digested with nitric acid and HCl (1:3 ratio) in a fume cupboard, and elemental composition determined using AAS.

Core Preparation and Petrophysical Analysis

Unconsolidated sand was cleaned, oven-dried, and packed into foil-wrapped plugs with stainless steel screens. Plug dimensions and mass were recorded. Porosity was calculated from the difference between brine-saturated and dry plug masses, while permeability was determined using Darcy's law.

Crude Oil Properties

Specific gravity was measured with a hydrometer, API gravity calculated, and density determined using a pycnometer. Viscosity measurements for crude oil, brine, and cocoa pod solutions were performed with a Cannon U-tube viscometer.

Solution Preparation

Synthetic brine (30,000 ppm) was prepared by dissolving NaCl and KCl in distilled water. Cocoa pod solutions were prepared at 1000, 1500, 2000, 2500, and 3000 ppm concentrations by dissolving weighed samples in distilled water.

Core Flooding Procedure

- i. **Secondary Recovery (Waterflooding):** Brine-saturated plugs were oil-flooded to determine the Original Oil in Place (OOIP), then waterflooded to measure secondary oil recovery.
- ii. **Tertiary Recovery (Chemical EOR):** Sequential flooding with cocoa pod solutions of increasing concentration recovered residual oil after water flooding.

Displacement efficiency, cumulative oil recovery, and residual oil saturation were calculated for each run. The following equations were used to calculate the displacement efficiency of the local materials:

$$\text{Displacement Efficiency} = \frac{\text{Tertiary Recovery}}{\text{OOIP}} \times 100 \quad (1)$$

$$\text{Residual Oil Saturation} = \text{OOIP} - (\text{Secondary} + \text{Tertiary Reclamation}) \quad (2)$$

$$\text{Irreducible Water Saturation} = \text{Pore Volume} - \text{Displaced Water} \quad (3)$$

The oil reclamation efficiency was determined by the following equations:

$$\text{Cumulative Oil Reclamation} = \text{Secondary reclamation} + \text{Tertiary reclamation} \quad (4)$$

$$\text{percent Recovery} = \frac{\text{Cumulative Oil Recovery}}{\text{OIIP}} \times 100 \quad (5)$$

Economic Assessment

Cash-out and cash-in analyses were conducted using Equations (7) and (8), with net cash flow (NCF) and net present value (NPV) calculated at a 10% discount rate. The fossil fuel cost per mL and cash in was evaluated using Equations (6) and (7) respectively.

Crude oil cost (NGN/mL)

$$= \text{Crude oil price} \left(\frac{\$}{\text{bbl}} \right) \times \text{Exchange rate} \left(\frac{\text{₦}}{\$} \right) \times 6.2897 \times 10^{-3} \quad (6)$$

Cash In(NGN)

$$= \text{Crude oil cost} \left(\frac{\text{₦}}{\text{mL}} \right) \times \text{Volume of oil recovered (mL)} \quad (7)$$

where 1.2897×10^{-3} = Conversion factor from barrel (bbl) to milliliter (mL), ₦ = Nigerian Naira and \$ = United State Dollar. Equations (8) and (9) were used, respectively to evaluate the Net Cash Flow (NCF) and Net Present Value (NPV). An arbitrary value of 10 percent was selected as discount rate.

$$NF = \text{Cash In} - \text{Cash out} \quad (8)$$

$$NPV = \frac{NCF}{(1+i)^t} \quad (9)$$

where, i is the discount rate, with an arbitrary value of 10 percent and t is time in years (in this case $t = 1$).

3.0 Results and Discussion

Results

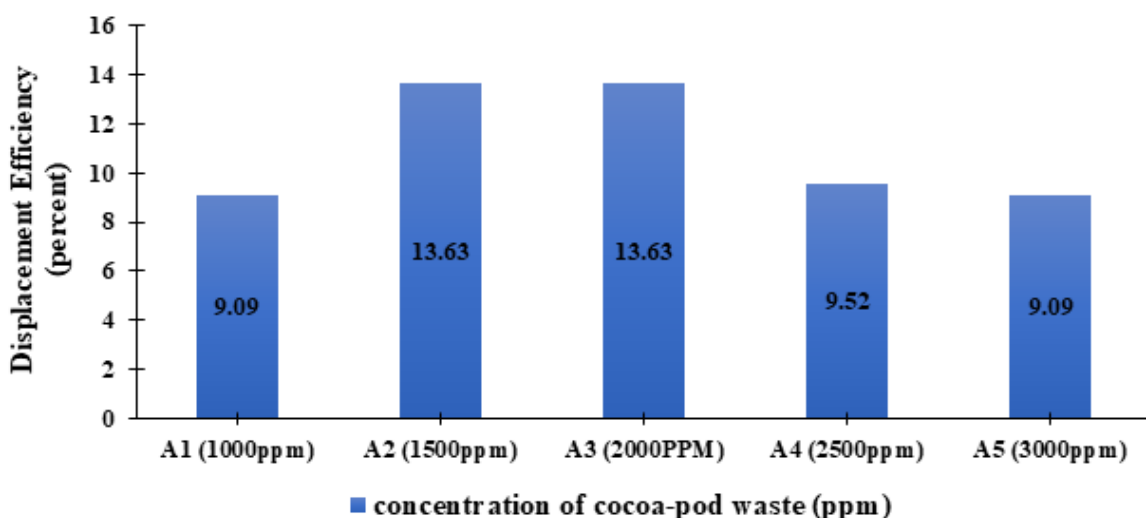
Table 1 shows the elemental composition of cocoa-pod waste (Sample SA 1), with phosphorus (3.42%, 5.38% P_2O_5), potassium (0.004%, equivalent to 2.45 mg/g, 0.28% K_2O), calcium (0.21%, equivalent to 1.82 mg/g, no CaO detected), sodium (0.012%, 0.34% Na_2O), and

sulfur (1.26 %, 1.18 % SO_3). These elements indicated that cocoa-pod waste has surfactant-like properties, as potassium and calcium contribute to reducing interfacial tension (IFT) between oil and water, aiding oil mobilization in enhanced oil recovery (EOR). Compared to other materials like Achi (50.20 % Ca) or Bitter leaf (44.1 % K), cocoa-pod waste has lower concentrations but remains effective due to its availability and low cost, making it suitable for EOR in Niger Delta sandstone reservoirs.

Figure 1 illustrates displacement efficiency across concentrations (1000–3000 ppm), peaking at 13.63 % for 1500 and 2000 ppm, then dropping to 9.5 2% (2500 ppm) and 9.90 % (3000 ppm). This trend shows that intermediate concentrations (1500–2000 ppm) optimize oil displacement, likely due to a balance between surfactant activity and fluid injectivity in the sandstone reservoir (permeability: 150 mD). The decline at higher concentrations suggests possible viscosity increases or adsorption losses affecting efficiency. Figure 2 showed oil recovery performance with a peak of 85.71 % at 2500 ppm, followed by 81.82 % at 2000 ppm and 77.27 % at 1000, 1500, and 3000 ppm. The highest recovery at 2500 ppm indicates that this concentration optimizes the mobilization of trapped oil, likely due to effective IFT reduction and wettability changes driven by cocoa-pod waste's elemental and phytochemical properties. The consistent recovery across other concentrations highlights its robust performance for EOR. Table 3 presents the cash-out costs for cocoa-pod waste, ranging from ₦0.8 (1000 ppm, 1.0 g) to ₦2.4 (3000 ppm, 3.0 g) at ₦0.8/g. The linear increase in cost with concentration reflects higher material usage. The low preparation cost (₦800/kg) compared to synthetic surfactants (\$2–5/kg) indicates that cocoa-pod waste is a cost-effective option for EOR, leveraging Nigeria's abundant cocoa production to minimize expenses in sandstone reservoir applications.

Table 1: Major Elements and its Oxide in Local Materials

Sample ID	Local Material	P %	K %	Ca %	Mg %	Na %	P ₂ O ₅ %	K ₂ O %	SO ₃ %	CaO %	MgO %	Na ₂ O %	S %
SA 1	Cocoa pod waste	3.42	0.004	0.21	N/D	0.012	5.38	0.28	1.18	0	N/D	0.34	1.26
SA 2	PBM (Unpurified)	1.95	46.50	11.60	N/D	2.64	4.47	56.03	3.15	16.22	N/D	3.55	1.26
SA 3	Ukpo	7.62	41.80	9.56	N/D	0.74	17.48	50.37	4.55	13.37	N/D	0.997	1.82
SA 4	Akanwu (potash)	<0.001	10.50	15.90	N/D	4.36	<0.001	12.65	1.15	22.24	N/D	5.877	0.46
SA 5	Okpo	2.57	48.50	13.5	N/D	3.24	5.895	54.44	3.25	18.89	N/D	4.38	1.30
SA 6	Akanwu (sediment)	<0.001	6.80	25.5	N/D	2.32	<0.001	8.19	0.15	35.67	N/D	3.13	0.06
SA 7	Bitter leaf	1.86	44.1	19.5	N/D	4.21	4.27	53.14	2.37	27.28	N/D	5.68	0.948
SA 8	PPA	1.1	44.94	4.94	N/D	1.96	2.52	54.15	1.30	6.91	N/D	2.64	0.52
SA 9	Paw-Paw leaf	2.23	47.0	16.20	N/D	1.02	5.12	56.64	4.95	22.66	N/D	1.37	1.98
SA 10	Ogbonno	4.50	37.30	23.20	N/D	2.32	10.323	44.95	10.03	32.46	N/D	3.13	4.01
SA 11	Ofor	8.86	20.60	30.20	N/D	0.26	20.32	24.82	<0.001	42.25	N/D	0.35	<0.001
SA 12	Achi	4.00	10.40	50.20	N/D	0.23	9.176	12.53	<0.001	70.23	N/D	0.31	<0.001
SA 13	SDA	1.60	18.60	46.33	N/D	0.38	3.67	22.41	3.15	64.82	N/D	N	1.26

**Figure 1:** the displacement efficiency of different proportion of cocoa-pod waste on fossil fuel reclamation

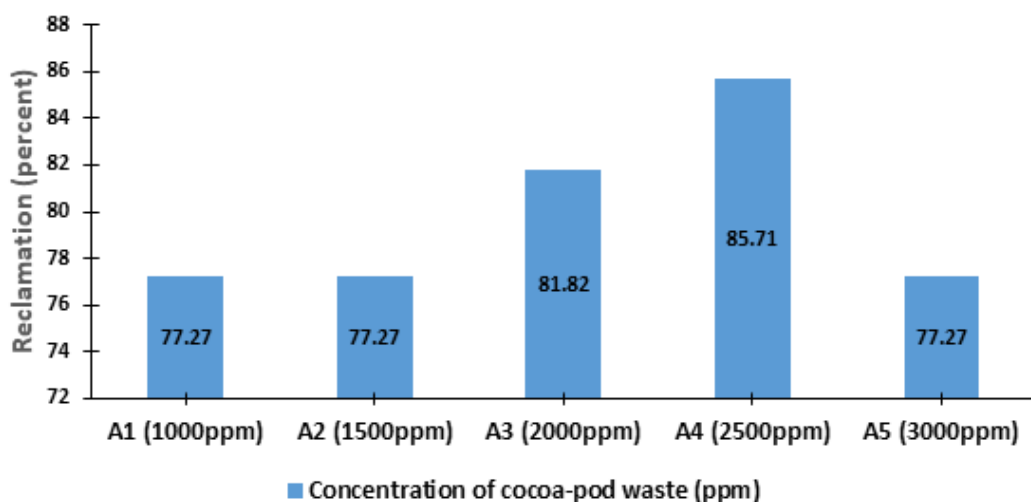


Figure 2: Performance of Oil Reclamation from the Use of Cocoa-Pod Waste

Table 3: Cash-Out Analysis

Item (Cocoa-pod waste)	Conc.(ppm)	Quantity (g)	Cost per gram (₦/g)	Cash out expenditure (₦)
A1	1000	1	0.8	0.8
A2	1500	1.5	0.8	1.2
A3	2000	2	0.8	1.6
A4	2500	2.5	0.8	2.0
A5	3000	3	0.8	2.4

Table 4 showed the cash-in values based on a crude oil price of \$75/bbl and an exchange rate of ₦411.33/\$, yielding ₦194/mL. Cash-in ranges from ₦388 (2 mL recovered at 1000, 2500, 3000 ppm) to ₦582 (3 mL recovered at 1500, 2000 ppm). The higher cash-in at 1500 and 2000 ppm corresponds to greater oil recovery (3 mL), reflecting higher displacement efficiencies. These results demonstrate the economic potential of cocoa-pod waste, particularly at intermediate concentrations, for generating revenue in EOR operations. Table 5 presented Net Cash Flow

(NCF) and Net Present Value (NPV) at a 10% discount rate, with NCF ranging from ₦385.6 to ₦580.8 and NPV from ₦350 to ₦528. The highest NPV (₦528) at 1500 ppm reflects the best economic performance, driven by high cash-in (₦582) and low cash-out (₦1.2). The slightly lower NPV at 2000 ppm (₦527) is due to increased cash-out. Lower NPVs at 1000, 2500, and 3000 ppm (₦350–352) result from lower oil recovery or higher costs, highlighting the economic advantage of 1500–2000 ppm for EOR applications.

Table 4: Cash-In Analysis

Item (Cocoa-pod waste)	Fossil fuel Price (\$/bbl)	Exchange (₦/\$)	Fossil fuel Cost per mL (₦/ mL)	Fossil fuel Recovered by Inundating (mL)	Cash-In (₦)
A1	75	411.33	194	2	388
A2	75	411.33	194	3	582
A3	75	411.33	194	3	582
A4	75	411.33	194	2	388
A5	75	411.33	194	2	388

Table 5: NCF and NPV Analysis

Item (Cocoa-pod waste)	NCF	NPV@10percent
A1	387.2	352
A2	580.8	528
A3	580.4	527
A4	386.0	350
A5	385.6	350

Discussion

The experimental results of this study, which evaluated cocoa-pod waste as a bio-surfactant for enhanced oil recovery (EOR) in Niger Delta sandstone reservoirs, demonstrate significant potential, with oil recovery rates of 77.27 – 85.71 % and displacement efficiencies of 9.09 – 13.63 % across concentrations of 1000 – 3000 ppm. The core flooding experiments showed a peak oil recovery of 85.71 % at 2500 ppm, with maximum displacement efficiencies (13.63 %) at 1500 and 2000 ppm, driven by cocoa-pod waste's elemental (potassium: 2.45 mg/g, calcium: 1.82 mg/g) and phytochemical (saponins, alkaloids) properties that reduce interfacial tension (IFT) and alter wettability. These results aligned with Mohammed et al. (2019), who reported that cocoa-pod husk extract enhances oil recovery in sandstone reservoirs through IFT reduction, consistent with Green and Willhite (1998), who emphasized low IFT for improving displacement efficiency. The increased capillary number, as per Taber et al. (1997), supports oil mobilization, with 1500 – 2000 ppm optimizing this effect. Comparatively, ASP flooding in Daqing Oilfield achieved 10 – 20 % additional recovery (Pu & Xu, 2009; Qu *et al.*, 1998), and SP flooding yields 7 – 10 % (Sheng, 2010, 2015), aligning with the 9.09 – 13.63 % displacement efficiencies here. Natural polymers like guar gum (Taha *et al.*, 2019; Zhang *et al.*, 2019), chitosan (Liu *et al.*, 2019), and wheat straw extract (Qiu *et al.*, 2021) show similar IFT reduction, with wheat straw achieving up to 15 % additional recovery due to higher polysaccharide

content. The sandstone cores (porosity: 22.5%, permeability: 150 mD) and crude oil (API 32°, viscosity: 4.2 cP) meet chemical flooding criteria (Taber *et al.*, 1997), supporting cocoa-pod waste's applicability.

Contrary findings highlighted bio-surfactant challenges. Mohammed et al. (2013) and Hakiki et al. (2015) noted surfactant adsorption reduces efficiency, observed here at 3000 ppm (9.90 % displacement efficiency) due to increased viscosity (1.5 cP) or rock adsorption. Synthetic surfactants in ASP flooding maintain performance at higher concentrations (Pitts et al., 2004, 2006) but are costlier (\$2–5/kg vs. ₦800/kg). Microbial EOR (Patil *et al.*, 2021) achieved high recovery but requires expensive cultivation, unlike cocoa-pod waste (Ofori-Boateng *et al.*, 2020). Nanoparticle EOR (Song *et al.*, 2021; Vukovic *et al.*, 2022) offers up to 20% additional recovery but faces scalability issues due to cost and aggregation, contrasting with cocoa-pod waste's affordability. Differences arise from material properties and reservoir conditions; synthetic options are engineered for high-salinity reservoirs (Zhiwei *et al.*, 2014), while cocoa-pod waste may be less stable in extreme conditions (Zhang *et al.*, 2019).

The economic analysis showed cash-out costs of ₦0.8 – 2.4 and NPVs of ₦350 – 528, with the highest NPV (₦528) at 1500 ppm due to high recovery (3 mL) and low cost (₦1.2). This aligns with Hebert (2015), who noted EOR viability at oil prices above \$70/bbl. Compared to synthetic

surfactants (\$2 – 5/kg), cocoa-pod waste's low cost (₦800/kg) is a significant advantage (Mohammed *et al.*, 2019), supported by studies on local materials like palm wine (Nyah & Onyekonwu, 2012) and alkaline agents (Obot & Onyekonwu, 2014). Contrary findings from ASP projects (Pitts *et al.*, 2004; Qu *et al.*, 1998) show higher costs due to chemical procurement, highlighting cocoa-pod waste's economic edge due to local availability (Ofori-Boateng *et al.*, 2020; Vasquez *et al.*, 2019).

Cocoa-pod waste reduced landfill methane emissions (Oddoye *et al.*, 2013; Lu *et al.*, 2018) and is biodegradable, unlike synthetic surfactants (Igunnu & Chen, 2012). This aligned with green EOR agents like scleroglucan (Rani *et al.*, 2019) and soybean polysaccharides (Wang *et al.*, 2021). Contrary findings from CO₂ flooding (Manrique & Pereira, 2007; Moritis, 2008) showed higher environmental costs, emphasizing cocoa-pod waste's sustainability (Vasquez *et al.*, 2019; Rojo-Poveda *et al.*, 2020). Its environmental advantage stems from its circular economy integration, though stability under reservoir conditions needs further study (Zhang *et al.*, 2019).

4.0 Conclusion and Recommendations

Conclusion

This study reveals that cocoa-pod waste is an effective and sustainable bio-surfactant for enhanced oil recovery in Niger Delta sandstone reservoirs, achieving oil recovery rates of 77.27 – 85.71 % and displacement efficiencies of 9.09 – 13.63 % across concentrations of 1000 – 3000 ppm. The highest oil recovery at 2500 ppm and peak displacement efficiencies at 1500 and 2000 ppm demonstrate its ability to reduce interfacial tension and mobilize residual oil, driven by its elemental and phytochemical properties. Economically, cocoa-pod waste is highly viable, with a low preparation cost of ₦800/kg and a maximum NPV of ₦528 at 1500 ppm, offering a

cost-effective alternative to synthetic surfactants. Environmentally, it repurposes agricultural waste, reducing landfill pollution and providing a biodegradable solution. These results support the study's objectives to characterize cocoa-pod waste, evaluate its EOR performance, and assess its economic feasibility, highlighting its potential to enhance oil production while promoting sustainability and supporting Nigeria's agricultural sector.

Limitations of the Study

- i. The experiments used controlled core plugs, which may not fully capture the heterogeneity of Niger Delta sandstone reservoirs, potentially limiting the applicability of the results in field conditions.
- ii. The reduced displacement efficiency at 3000 ppm (9.90%) suggests possible adsorption of cocoa-pod waste onto reservoir rock or increased viscosity, which could hinder field-scale performance.
- iii. The study did not assess cocoa-pod waste's stability under high-temperature or high-salinity conditions, which are common in some Niger Delta reservoirs and could affect its efficacy.
- iv. The economic analysis relies on fixed crude oil prices (\$75/bbl) and exchange rates (₦411.33/\$), which may fluctuate, impacting the projected viability.
- v. The long-term stability of cocoa-pod waste solutions in reservoir environments was not evaluated, posing a potential challenge for sustained field applications.

Recommendations

From the study findings, the following recommendations were made:

- i. Performance of pilot tests in Niger Delta reservoirs to validate laboratory results and assess performance under real-world conditions.

- ii. Improvement on the extraction methods to increase the yield of surfactant-active compounds and reduce adsorption losses.
- iii. Evaluate cocoa-pod waste's stability in high-temperature and high-salinity environments to ensure broader applicability.
- iv. Combine cocoa-pod waste with polymers or low-salinity water to enhance sweep efficiency and mitigate adsorption issues.
- v. Quantify the environmental benefits, such as reduced carbon footprint and waste management, to strengthen its sustainability profile.
- vi. Analyze the impact of oil price and exchange rate variations to ensure robust economic planning for field implementation.
- vii. Partner with Nigeria's cocoa industry to scale up waste collection and processing, creating jobs and supporting agriculture.

Acknowledgements

The authors thank Prof. M. Horsfall and Usiayo, Afoke Victor for their guidance, and the University of Port Harcourt for laboratory facilities.

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