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Performance Evaluation of the Synergetic Effect of *Termialia mantaly* Biopolymer and Silica Nanoparticles for Enhanced Oil Recovery

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Abstract

As at recent, various chemical enhanced oil recovery (CEOR) approaches including nanotechnology have gain global attraction. This is due to their ability to reduce interfacial tension (IFT), reduce crude oil viscosity and effectively yield better mobility ratio. This study explored the effect of silica nanoparticles (SiO₂-NPs) and Terminalia mantaly exudate (TME) hybrid solution in improving oil recovery. Various laboratory investigations were conducted ranging from interfacial tension and zeta potential measurements to core flooding test. From the result, SiO2-NPs presence had great effect on IFT for oil-water interface but caused slight reduction of IFT for oil-polymer interface. The zeta potentials of TME polymer recorded constant potential increase of -35.87 to -26.95mV and at TME polymer concentration range of 0.1% wt to 0.28% wt, a helix with peak point at 0.21% wt was observed. From the core flooding test, TME biopolymer had significant incremental oil recovery with 0.2% wt TME concentration recording the best recovery as it yielded additional 19.44% recovery and displacement efficiency of 58.33%. SiO₂-NPs solutions (nanofluids) at various concentrations also had significant incremental oil recovery with 0.1% wt SiO₂-NPs concentration recording the best recovery as it yielded additional 18.54% oil recovery with displacement efficiency of 63.33%. Comparison of the performance of the SiO₂-NPs-TME biopolymer hybrid solution, showed huge improvement in incremental oil recovery and this was attributed to the synergy that existed between TME biopolymer and SiO₂-NPs.

Keywords: Chemical EOR; Viscosity; Agropolymer; Nanoparticles; Zeta potential.

1. Introduction

Chemical Enhanced Oil Recovery (CEOR) is fast becoming a viable alternative for recovering of entrapped crude ^[1-2] when the supplemental secondary recovery (SR) approach like waterflooding ^[3] becomes ineffective due to unfavorable capillary and viscous forces ^[1-2,4]. This is believed to be due to the CEOR's efficiency and ease of utilization. CEOR involves introduction of certain chemicals into water after secondary oil recovery to improve reservoir displacement and sweep efficiencies. Close to 37% of the initial oil in place (IOIP) could be recovered using CEOR ^[2]. CEOR recovers oil using mechanisms such as interfacial tension reduction, mobility ratio (MR) reduction between reservoir water and oil, capillary pressure reduction, wettability alteration, permeability reduction and polymeric viscoelasticity ^[5].

Several conventional and locally sourced chemicals viz: polymers, surfactant, nanoparticles and alkalis, have been used for CEOR ^[6]. These materials modify the rock-fluid or/and fluidfluid features of the rock formation to improve oil recovery. These interactions improve the sweep efficiency in the reservoir or yields high pore-scale displacement efficiency depending on the type of chemical utilized ^[7-8]. Of the various CEOR processes, surfactants and polymers have exhibited high effectiveness, unique features and prospects. Entrapped oil in the rock formation can be recovered by lowering the IFT between the crude and water in what is called surfactant flooding. In addition to IFT reduction, surfactant also alter the wettability of the reservoir rock from oil-wet to water-wet. These surfactants are plagued with problems such as high adsorption issues and material cost ^[2,5]. The use of viscosity increasing agents called polymers in improving oil recovery is called "polymer flooding". For CEOR methods, polymer flooding is the most widely used, and this is due to its ability to reduce the MR between the mobilized and mobilizing fluid to avoid viscous fingering. In general, polymeric agents exhibit pseudo-plastic fluid behavior with its viscosity categorized as shear thinning ^[9].

Polymer EOR is best suited for oil reservoirs with less than 100cp viscosity, temperature less than 72°C and low to moderate salinity level. Polymers can be in synthetic biological form, though studies have shown biological polysaccharides to be more effective polymers than synthetic polymers [10]. Xanthan gum (biopolymer) and polyacrylamide (PAM) a synthetic polymer are the most used polymer agents for recovering oil from the reservoir owing to their unique properties, low cost and relative abundance. The polymer retention problem, coupled with the high relative cost of importing these chemicals by developing countries like Nigeria has driven the need for alternatives from local sources with the same properties and features. Nanotechnology has also been applied in the petroleum industry and has shown potentials in solving plethora of problems in the gas and oil industry.

The introduction of nanoparticles (NPs) into the porous media, alters certain constraints in the rock and fluid parameters which makes it to be commonly utilized in EOR. NPs enhances recovery by lowering oil-water IFT, modify rock wettability and improve mobility control ^[11]. NPs used for EOR showed positive signs compared to the conventional chemicals, and this was due to their useful features such as ultra-small size, low cost and environmentally friendly nature. NPs are introduced to the formation as nanofluids (NFs) through base fluid like water and NPs mixture with NPs sizes less than 100nm. NFs possess distinctive properties and as such has attracted huge attention due their capacity in modifying thermal conductivity, viscosity and density ^[12-14]. NFs makes use of mechanisms such as mobility control, wettability modification, IFT drop and pore throat plugging. IFT reduction by NPs is critical in EOR as it defines the fluid flow and arrangement in the reservoir rock. The lowering of the permeability of reservoir rock as a result of high adsorption of NPs is the major aim of IFT reduction. NPs reduces the IFT between wetting and non-wetting phase by forming a layer at the interphase when introduced to a mobilizing fluid ^[15].

NPs however, can also cause pore blockage when dispersed into the formation. This can occur due to retention of larger grain sizes and accumulation in the pores of the reservoir rock. As the NPs builds up, it obstructs the pore channels and yields reduction in recovery and permeability. The limitations of polymer and NPs when flooded independently have given rise to the formulation of polymer-NPs hybrid system aimed at maximizing the benefits and mechanism associated with each method. In the last couple of years, EOR using polymer-NP composite design have yielded significant success, particularly in the reduction of trapping efficiency. NPs such as Silica, nano clay and/or modified silica have been introduced to polymer solutions to improve the effectiveness of water-flood for EOR ^[16].

2. Literature review

Recent studies have shown the potentials of biopolymers synthesized from local plants, and NPS in improving oil recovery. Ihebuzor and Onyekonwu ^[17] studied the effectiveness of okra, arabic gum and ogbonno in enhancing oil production. Okra performed better than the other biopolymers as it yielded 63.16% recovery, while gum arabic and ogbonno yielded 53.01% and 47.37% recovery respectively. Abdulraheem *et al.* ^[18] carried out polymer flood study using modified gum arabic, gum arabic, xanthan gum and hengfloc. The modified gum arabic had the best performance of all polymeric materials used for the study as it yielded additional 41% recovery, while natural gum arabic, xanthan gum and henfloc recorded 28.81%, 23.96% and 28.51% recovery respectively.

Uzoho *et al.* ^[5] carried out polymer EOR study with achi, ukpo, natural ogbonno, ofor, modified ogbonno and okro as polymeric agents. Okro performed better than the local agropolymers as it yielded displacement efficiency of 99.1% while achi, ukpo, natural ogbonno, ofor and modified ogbonno yielded 93%, 96%, 93.8%, 85.7% and 95.2% displacement efficiency respectively. Uzoho and Onyekonwu ^[19] conducted a comparative evaluation on two EOR agents, viz: okro and PAM. Okro performed better than PAM as it yielded 99.1% displacement efficiency while PAM had 94.56% displacement efficiency. Obuebite *et al.* ^[20] evaluated

the potentials of TM, PAM and pectin as polymeric EOR agents in both hard and soft brine sandstone formations. TM had the best performance of all the polymers used for the study in both hard and soft brine rocks as it yielded 90% and 89% recovery respectively while PAM and pectin yielded 81% and 79% recovery respectively in soft brine rock, and for hard brine formation, PAM and pectin yielded 79% and 78% recovery respectively. Hendraningrat *et al.* ^[21] conducted an IFT study using lipophobic hydrophilic polysilicon (LHP) NPs at varying concentrations of brine solutions. At 0.01wt%, the LHP-NPs reduced IFT from 14.7mN/m to 9.3mN/m. Further increase in concentration of LHP-NPs from 0.01wt% to 0.05wt% reduced the IFT to 5.2mN/m.

Adeniyi and Olafuyi ^[22] investigated the performance of Teepol-NPs (conventional) and F16-silica- NPs derived from palm kernel on improving oil production in sandstone cores. F16silica- NPs performed better than the conventional Teepol-NPs as it yielded additional 10% recovery of OIIP. Yetunde et al. ^[23] investigated the impact of Hydrophilic Polysilicon (HP) NPs concentrations on enhancing oil production. The study was conducted at HP-NPs varying concentrations of 0.01%, 0.5%, 2.0% and 3.0%. 2.00wt% concentration of HP-NPs performed better than other concentrations as it yielded 36.4% recovery while 0.01%, 0.5% and 3.0% yielded 14.8%, 25.7% and 7.8% recoveries respectively. Odoh et al. ^[2] compared the performance of silicon oxide (SiO₂), magnesium oxide (MgO) and aluminum oxide (Al₂O₃) NPs in improving oil production. From the study, Al_2O_3 performed better than the other NPs as it yielded 97.5% displacement efficiency while SiO₂ and MqO yielded 91.67% and 83.33% respectively. Maghzi et al. ^[24] evaluated the performance of a blend HPAM-silica NPs in high saline brine. The HPAM-silica NPs blend yielded additional 10% recovery of the OIIP while HPAM polymer solution yielded less than 10% recovery. They attributed the increased recovery recorded by HPAM-silica NPs to the silica NPs' hydrophilic nature which altered the oil-wet wettability of the utilized micromodel's to water-wet.

Rueda *et al.* ^[16] conducted a comparative EOR study on silica-NPs, xanthan gum, scleroglucan and xanthan gum-silica-NP blends. The xanthan gum- silica-NP blend yielded better performance than individual performance of the chemical reagent as it yielded 88.3% total recovery. Bila and Torsaeter ^[25] conducted a performance evaluation of polymer-coated silica-NPs as an EOR material in harsh conditions of salinity and temperature. They formulated 4 blends of polymethacrylate with cationic-SiO₂ (38.6%), anionic-SiO₂ (26.0%), SiO₂-Al₂O₃-MOX (21.6%) and SiO₂-Al₂O₃-MOX (25.5%). Catonic-SiO₂-polymer hybrid performed better than other formulations as it yielded 13.74% displacement efficiency in water-wet cores while polymer blends involving anionic-SiO₂, SiO₂-Al₂O₃-MOX (21.6%) and SiO₂-Al₂O₃-MOX (25.5) yielded 7.06%, 12.81% and 4.53% respectively. From the review conducted, it is evident that TM performed better than XG, PAM and some other conventional polymers.

In this work, performance evaluation of silica-NPs assisted TM biopolymer flooding on EOR is conducted. A comparison of FTIR characterization of TM and XG were critically examined to ascertain that TM possesses the required functional groups and necessary features inherent in biopolymer.

3. Materials and methods

3.1. Materials

The materials utilized for the laboratory work were crude, weighing balance, beakers, stirrer, viscometer, borosilicate pipette, pH indicator, methanol, core flood apparatus, glass electrode, density bottle, TM extrudate biopolymer, test tubes, silicon oxide NPs, synthetic brine, tensiometer, toluene, extraction chamber.

3.2. Methods

3.2.1. Crude oil

OKO 1 crude oil of 33.6°API at 29°C from the Niger-Delta OKO reservoir with absolute viscosity of 4.1932cP derived with the aid of cannon u-tube viscometer was used for the laboratory work as depicted in Table 1. Filtration of the crude oil was carried out with filter paper of 1mm.

Table 1. OKO 1 crude oil properties.

Crude oil ID	ρ (g/cm³) @29°C	μ (cP) @29°C	AN (mg KOH/g oil)	BN (mg KOH/g oil)	°API
OKO 1	0.8882	4.1932	2.6536 ± 0.01	0.8714 ± 0.10	33.6

3.2.2. Synthetic brine solution

The synthetic brine (SB) composition which is representative of the brine determined from OKO reservoir shown in Table 2 was prepared using the method outlined by ^[26] and utilized for core saturation and brine-oil IFT derivation. The SB viscosity and density was determined to be 0.931cP and 1.0311g/cm³. The SB has total dissolved solid (TDS) of 36,100 ppm as depicted in Table 2.

Table 2. Con	nposition	of SB.
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S/N	Salt	Composition (1000 ppm)
1	Sodium chloride (NaCl)	29.57
2	Potassium chloride (KCl)	0.88
3	Magnesium chloride (MgCl2)	5.65
4	TDS	36.10

3.2.3. Nanoparticles (NPs)

Silicon oxide NPs (SiO₂-NPs) which was purchased from local supplier was used for the experiment. The SiO₂-NPs has purity (98.2-99.5%) and surface area (130-140m²). The utilized SiO₂-NPs was in compatibility with reservoir conditions as shown by IFT evaluated in Figure 5.

3.2.4. Polymer

TM exudate (TME) was recovered from the incised section of the tree and prepared using Michael *et al.* ^[27] method. The agro biopolymer was extracted from the incised section of the tree and dried for five days. 100g of dried gum was cleansed with deionized water to remove unwanted materials from the body surface. The washed exudate gum was placed in a hot air at 50°C temperature for 50hrs. The gum was hydrated in a solution containing chlorofoam and water for 5 days to allow it to soften. Tedious activity was conducted using a white muslin material to remove viscous phase from the gum before total precipitation was carried out with ethanol. 100ml of dimethyl reagent was utilized for washing of the gum precipitates before it was placed in a hot air for over 10hrs. The precipitated gum was pulverized to powdered form with 50g of the TME powder recovered from air tight container.

3.2.5. Interfacial tension test (IFT)

IFT existing between the wetting (oil) and non-wetting (bulk fluid) phase was derived using the Fisher 20 modelled Scientific Tensiometer. The procedure utilized was as documented in the Fisher Tensiometer Model 20 manual. Experiment was conducted on silica-NFs and TME polymer fluids at different concentration as depicted in Table 3.

	-	
S/N	Samples	Concentration
1	TME	0.1%, 0.2%, 0.3%, 0.4%, 0.5%
2	SiO ₂ -NPs	0.025%wt, 0.05%,0.075%, 0.1%, 0.125%
3	TME- SiO ₂ -NPs	0.1%:0.1%, 0.2%:0.1%, 0.3%:0.1%, 0.4%:0.1% and 0.5%:0.1%

Table 3. Samples concentrations for IFT determination and viscosity test.

3.2.6. Samples' viscosity

The TME viscosity was derived empirically using density data from pyknometer and kinematic viscosity from 150/601B modelled viscometer. The viscometer was used to measure the effluent time and corresponding kinematic viscosity (cS) of the fluid. The absolute or dynamic fluid viscosity was derived by finding the product of the kinematic viscosity and density of the fluids. Table 4 depicts concentration of samples used for viscosity test. Viscosity test was conducted for TME fluid, SiO₂-NPs and TME- SiO₂-NPs solution.

3.2.7. Zeta potential (ZP) measurement

The ZP was measured using a micro-electrophoresis ZP analyzer at ambient temperature. Varying concentrations of TME and TME- SiO2-NPs were introduced into a cell with an electrode distance of 4.88 cm and 49 volt transmitted to the electrodes.

3.2.8. Characterization of samples

Samples characterization are necessary to ascertain the functional groups and necessary features of the samples. The characterization of TM was therefore crucial to ascertain TM's functional groups and confirm whether they have the same functional groups and possible features as XG in order to be appropriate for this study. The characterization of conventional XG was also carried out to obtain the functional groups and necessary features. From the literature, the characterization of TM and XG were carried out by Majoumouo *et al.* ^[28] and Kwabena *et al.* ^[29] respectively with the outcome of these characterization presented in the results section of this work.

3.2.9. Displacement experiment

Core samples of length 5.20 cm and diameter 3.70 cm were used for experimental process. The cores were prepared and cleaned up with toluene and methanol solution in Soxhlet extraction chamber. The rock samples were then oven dried at 90°C moderate temperature for a period of 12 hours. The core dimensions are truly representatives of laboratory scale conventionally utilized. Further drying of cores was carried out at 85°C after 12 hours to constant weight, thereafter the dried cores transferred to saturating unit connected to Enerpac pump.

The Enerpac Pump was utilized to introduced SB into the saturating unit under vacuum. The system was then pressurized for 60hrs at 2500psi to achieve perfect saturation of 100% for the sample. Upon attainment of the 48hrs, pressure was released with the saturated rocks reweighed. The saturated rock samples were placed inside Figure 1 core holders at 1000psi confining pressure with SB introduced at 2cc/sec injection rate. This was carried out to ensure the rock retains 100% saturation and prevent entrapment of air bubbles within the pore spaces. The rock to bine relperm determination was conducted at this point as shown in Table 4 with rock's physical properties as depicted in Table 4.





The OKO 1 crude oil sample then was continuously introduced at 2cc/sec injection rate until the initial water saturation (Swi) was derived. SR was achieved by injecting SB at 2cc/sec injection rate until residual oil saturation (Sor) was achieved. Upon attainment of Sor after water-flood (SB injection), three sets of TR test were carried out on the core samples. The first was polymer flooding (PF), achieved by continuous introduction of TME polymer solution at 2cc/sec, the second was nano-flooding, achieved by continuous introduction SiO₂-NPs solution while the third was SiO₂-NPs-polymer flooding with the SiO₂-NPs-TME polymer solution derived from TME polymer- SiO₂-NPs blend, and then achieved by continuous introduction of nano-polymer solution at 2cc/sec. The incremental oil recoveries from the various flooding operations were measured and recorded. Depicted in Figure 1 is the schematic representation of the experimental setup utilized for the rock sample flood.

4. Results and discussions

4.1. IFT determination

The IFT between oil-polymer and oil-water at different SiO₂-NPs concentrations was determined at laboratory conditions. Figures 2-3 depict the effect of SiO₂-NPs concentrations on IFT between oil-water and that of oil-polymer interfaces. From Figure 2, SiO₂-NPs presence at varying concentrations continued to reduce the IFT between crude oil and water until the least IFT was achieved at 0.1% wt. Further increase in NPs concentrations did not reduce IFT. Evidently, SiO₂-NPs presence has great effect on IFT for oil-water interface. This in agreement with the work of Sun et al. ^[30] in which NPs presence reduced oil-water phase and contributed to significant reduction of Gibbs energy arising from placement of NPs on oil-water interface. In Figure 3, IFT was determined at varying TME concentrations in 0.1% wt silica NPs presence. From Figure 3, silica NPs presence caused slight reduction of IFT at 1%wt-0.3%wt TME concentrations with no reduction of IFT at TME concentrations above 0.3% wt for oil-polymer interface. Figure 3 showed the effect of the NPs presence in reducing the IFT of oil-polymer interface, though TME polymer limited interfacial changes. This is in-line with the study conducted by Rueda et al. [16] which showed that addition of NPs to polymer solution slightly reduces the IFT of the oil-polymer interface. From Figures 2 and 3, 0.1%wt SiO₂-NPs presence is the optimum SiO₂-NPs concentration for IFT reduction in both oil-polymer and oil-water interfaces.

> 40 35

30



Fig. 2. IFT values determined at varying silica NPs concentrations presence in oil-water.



Fig. 3. IFT determination at varying TME concentrations of oil-TME in 0.1% wt Silica NPs presence.

4.2. Viscosity

Figures 4-5 show the viscosities of TME and NPs-TME solutions. As shown in Figure 4, TME recorded increase in viscosity of 0.836cP, 0.842cP, 0.849cP, 0.854cP and 0.859cP with polymer concentration of 0.1%wt, 0.2%wt, 0.3%wt, 0.4%wt and 0.5%wt respectively, and can serve as a mobility control agent for favourable mobility ratio. The increase in thickening effect of the TME agro-polymer with concentration is in line with Ezeh *et al.* ^[31] study, which states that the molecular structure of polymers influences their ability to generate higher intermolecular interaction. From Figure 5, when 0.1%wt concentration of silica-NPs were introduced to TME polymer solutions of various concentrations, the absolute viscosity of the solutions reduced to 0.822cP, 0.831cP, 0.838cP, 0.848cP and 0.855cP for TME concentrations of 0.1%wt, 0.2%wt, 0.3%wt, 0.4%wt and 0.5%wt respectively. These reduction effects due to

silica-NPs introduction, however, became less at TME concentration of 0.4%wt and 0.5%wt. The reduction in viscosity effect of the polymer by the addition of silica-NPs was due to the dispersion effect of NPs in breaking molecular bonds of the polymer and also its ability to reduce colloid formation between the water and polymer.

0.87









4.3. Zeta potential

Figure 6 depicts the Zeta potential of TME and the effect of nanoparticles on TME Zeta potentials. As shown in Figure 6, the zeta potentials of TME polymer recorded constant potential increase of -35.87 to -30.8mV from 0.1%wt-0.21%wt and then a downward trend of -30.8mV to -33.55mV from 0.21%wt up to 0.28%wt. Further increase in TME concentration resulted in increase in zeta potentials of -33.55mV to -26.95mV from 0.29%wt to 0.60%wt. At concentration range of 0.1% wt to 0.28% wt, a helix with peak point at 0.21% wt was observed. Wyatt and Liberatore ^[32] reported that helix transition of polymer starts from around 0.1wt%, though depending on the molecular weight of the polymer, and this lowers the electric repulsive force that exist in the anionic compounds within the chain. TME polymer exhibited this zeta potential behaviours with increase in concentration. This increase is due to the screening of Na⁺ and Cl⁻ on the TME charged monomer units, resulting in a drop in surface charge density. From Figure 6, when silica-NPs was introduced to the TME polymer solution, the zeta potentials of the hybrid solution reduced significantly to -50.72mV to -44.80mV at 0.1% wt to 0.21% wt polymer concentrations, with silica-NPs further reducing the zeta potentials of the hybrid solution at varying polymer concentrations. This decrease in zeta potential could be tied to hydrogen bond formation existing between silica-NPs and TME which caused the formation of stronger structures and networks. The introduction of the silica-NPs into the various polymer concentrations enhanced their stability from moderate to good, reduced force of attraction and mitigated agglomeration.



Fig. 6. Zeta potentials of samples.

4.4. Characterization of samples

The characterization of the samples was obtained to identify the functional groups and necessary features of the samples. This was crucial to ascertain if TM and XG had similar functional groups and possible features that will necessitate the utilization of TM for this study.

From the literature, Majoumouo et al. ^[28] and Kwabena et al. ^[29] characterized TM and XG. The FTIR characterization of TM and XG showed that TM has acetate C=O group at 1048cm⁻¹. 1108cm⁻¹ and 1123cm⁻¹ respectively, methylene and methyl C-H group at 1347cm⁻¹, -COO stretch between 700cm⁻¹-1040cm⁻¹, OH group in alcohol stood at 3717cm⁻¹, 3409cm⁻¹ and 3452cm-1 respectively, aldehyde H-C=O: C-H stretch stood at 2920cm⁻¹-2939cm⁻¹ with β glycoside at 400 cm⁻¹ while XG has acetate C=O group at 1650cm⁻¹, methylene and methyl C-H group between 2500cm⁻¹ - 2900cm⁻¹, -COO stretch between 600cm⁻¹ -1400cm⁻¹, OH group in alcohol stood at 3300, deformation stretch of carbonyl acetate stood at 1050cm⁻¹ -1200cm⁻¹, aldehyde H-C=O: C-H stretch stood at 1643.42cm⁻¹ with β-glycoside around 700cm⁻¹ ¹ to 900cm⁻¹. The result clearly indicates that TM and XG had the same functional group and necessary features and that both are polysaccharides. Thus, TM can fully be utilized for this study.

4.5. Core sample flooding

Figures 7-12 depict the results of core-flood conducted with SiO₂-NPs, TME and SiO₂-NPs-TME hybrid solutions. From Figures 7 and 8, ME biopolymer at 0.1%, 0.2%, 0.3%, 0.4% and 0.5% concentrations had 14.5%, 19.44%, 14.76%, 15.0% and 13.18% incremental oil recovery with displacement efficiencies of 44.62%, 58.33%, 56.36%, 50.00% and 48.33%. 0.2% wt TME concentration recorded the best recovery as it yielded additional 19.44% recovery and displacement efficiency of 58.33%. Further introduction of TME biopolymer at 0.3%wt, 0.4% wt and 0.5% wt concentrations led to reduced volume of recovered oil, showing that there is no longer favourable mobility ratio between mobilizing and mobilized fluids. The performance of 0.2% wt concentration of TME was due to its mobility control feature which caused incremental recovery. From Figures 9 and 10, 0.1wt% SiO₂-NPs concentration yielded the best recovery than the other concentrations as it yielded additional 18.54% recovery with displacement efficiency of 63.33%. The performances of various SiO₂-NPs concentrations in recovering oil were tied to their IFT reduction ability as shown in Figure 2. The introduction 0.1%wt SiO₂-NPs to the respective concentrations of TME polymer solutions as shown in Figure 11, improved recovery of oil with NPs introduction to 0.2%wt-0.3%wt TME concentrations increasing from 19.44% to 20.93% and 14.76% to 21.92% respectively. Comparison of the performance of the SiO₂-NPs-TME with their individual formulations in Figure 9 and Fig 11 showed huge improvement in oil recovery and this was attributed to the synergy that existed between TME biopolymer and SiO₂-NPs. The performance can also be attributed to the NPs' ability to alter or reduce crude oil viscosity and its effective dispersion in the TME solution to form stronger structure and network due to hydrogen ties.





Fig 7. Incremental oil recovery of TME polymer Fig 8. Displacement efficiency of TME polymer. flooding.



Fig 9. Incremental oil recovery of SiO₂-NPs flooding.





Fig 10. Displacement efficiency of the NFs.





Fig 11. Incremental recovery of ${\rm SiO_2\text{-}NPs\text{-}TME}$ blend.

Fig 12. Displacement Efficiency of SiO2-NPs-TME blend.

5. Conclusions

SiO₂-NPs has viscosity reduction effect as its introduction to TME solution reduced the viscosity of the agro-polymer. Optimum concentration of SiO₂-NPs in the nanofluid solution yielded the least possible IFT. Above the optimum concentration, IFT stabilized. The introduction of SiO₂-NPs to the TME solution increased the stability of the TME solution by significantly reducing the zeta potentials of the TME solution due to dispersion effect of the NPs. SiO₂-NPs-TME hybrid solution yielded better EOR performance than the individual TME polymer and nanofluid floods. 0.3%wt TME concentration and 0.1%wt SiO₂-NPs concentrations of the SiO₂-NPs-TME hybrid solution had the greatest EOR performance with incremental recovery of 21.92% and displacement efficiency of 87.38% respectively.

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