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Performance assessment of metal oxide nanoparticles for interfacial tension reduction in high-salinity environments: Implications for enhanced oil recovery

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Abstract
Interfacial tension **(**IFT) measurement is a critical diagnostic and optimization tool in high-salinity reservoirs for developing efficient EOR methods and increasing oil production. This study aims to determine the best nanoparticle types and concentrations for enhanced oil recovery (EOR) by examining the impact of SiO_2 and Al_2O_3 nanoparticles on interfacial tension (IFT) between crude oil and brine under high-salinity conditions. With just brine and crude oil, the baseline IFT was 16.47 dyne/cm. When SiO_2 nanoparticles were added, the IFT dropped dramatically to 7.80 dyne/cm at 0.01 wt%. However, as the concentration was increased further, the results fluctuated, peaking at 10.73 dyne/cm (0.05 wt%) and then falling again to 7.61 dyne/cm (2 wt%). Aggregation effects and fluctuating adsorption efficiencies are suggested by this non-linear behavior. Al_2O_3 nanoparticles, on the other hand, showed a more consistent and effective IFT reduction, reaching 5.77 dyne/cm at 0.01 wt% and sustaining low values (5.89-6.09 dyne/cm) up to 1 wt%. The ideal concentration was found at 3wt% Al_2O_3, which had the lowest IFT (4.22 dyne/cm).
Surface charge, morphology, and hydrophilicity are some of the physicochemical characteristics of Al_2O_3 that improve its interfacial activity and are responsible for its superior performance. According to these results, AlO_3 nanoparticles reduce IFT more effectively than SiO_2 in high-salinity environments, which makes them better candidates for EOR applications.

Keywords: Al_2O_3 nanoparticles, enhanced oil recovery, high-salinity reservoirs, interfacial tension, nanofluids, SiO_2 nanoparticles

1. Introductions

The oil extraction sector in the energy industry is becoming increasingly aware of novel techniques to maximize the extraction of oil from existing reservoirs because of escalating energy requirements, the depletion of easily accessible reservoirs, and economic considerations (Fu & He, 2024) [3]. A recovery method's primary and secondary form traditional techniques recover over 30 to 40 percent of the original oil in place (OOIP) has routinely been observed (Hosny *et al*., 2023) [4]. To further increase these recovery ratios, Enhanced Oil Recovery (EOR) techniques are used to extract additional oil which is left behind in oil reservoir rocks pore spaces. Chemical oil recovery utilizes lower-cost materials while thermal, gas injection, and chemical flooding are among the EOR methods applied the most (Shakeel *et al*., 2024) [10].

Surfactant and polymer based chemical EOR methods change flow characteristics by decreasing interfacial tension (IFT) and viscosity. This assists in overcoming capillary forces and enhancing effective displacement leading to the increased capture and production of oil (Jain *et al*., 2022) [5]. Nevertheless, these conventional chemical agents suffer high-salinity reservoirs. Large amounts of dissolved salts lead to the destabilization of surfactants and polymers which precipitate, lose activity, and become less capable of altering fluid properties. This represents a fundamental problem in mature fields and offshore regions where salinity is high and conditions are extreme (Majeed *et al*., 2021) [7].

Nanotechnology is a promising new technology for enhancing the efficiency and efficacy of EOR methods (Sharma *et al*., 2024) [11]. Ultra-small particles, known as Nanoparticles (NPs) sized between 1 and 100 nm, have unique properties owing to their high surface area to volume ratio. These NPs can improve oil recovery by overcoming the stability limitations associated with traditional chemicals (Pang *et al*., 2024) [9].

When submerged in brine, NPs have the capability to change the oil-water interface, alter wettability, reduce the tension between fluids, and improve oil recovery (Tangparitkul *et al*., 2024) [13].

The performance of nanofluids in EOR applications is directly linked with the concentration of nanoparticles. Low concentration of nanoparticles entails weak bonds with the interface boundary (Sun *et al*., 2020) [12]. As a consequence, minimal recovery is achieved. On the contrary, higher concentration brings former barrier blockages in pore throats leading to increased fluid viscosity and particle aggregation damage (Shakeel *et al*., 2024) [10]. This contributes to the formation of barriers in pore throats, leading to increased fluid viscosity and aggregating particles. Ensuring optimal nanoparticle dosage is key to striking balance between risks while ensuring the best yield obtainable from the oil while ensuring safe operations (Davoodi *et al*., 2024) [1].

A significant parameter when examining the impact of nanoparticles on EOR is the oil-fluid interfacial tension (IFT) (Lashari *et al*., 2022) [6]. IFT describes the force that must be applied to separate oil from water, and is fundamental to oil retention and associated capillary forces within a reservoir (Deng *et al*., 2021) [2]. By measuring interfacial tension (IFT) at varying nanoparticle concentrations, researchers can identify the concentration that yields the greatest enhancement in oil recovery and displacement efficiency through optimal IFT reduction. (Ben-Awuah *et al*., 2017) [8].

This research will investigate how the concentration of nanoparticles influences oil recovery when injected into the reservoir, with a primary focus on silicon dioxide and Aluminum oxide nanoparticles. The study aims to determine the optimal nanoparticle type and concentration that enhance oil recovery under saline conditions by preparing nanofluids and conducting interfacial tension (IFT) testing in the laboratory. The goal is to provide reliable data using IFT measurements as an analytical tool to support enhanced oil recovery (EOR) in high-salinity reservoirs

2. Methodology

2.1 Sourcing and preparation

In this research, two available commercial NPs namely, silicon dioxide NP (SiO_2, with 99.9% purity, size of 20nm-30nm, specific surface area of 100-500m^2/g and Aluminium oxide NP (Al_2O_3, with 99% purity, size of 20-30nm and specific surface area of 50m^2/g to 150m^2/g),were purchased from Guangdong GuanghuaSci-Tech Co., Ltd China. Brine with concentration of 8wt% will be used in the formulation of nanoparticles solutions. The crude oil samples were obtained from the chevron laboratory warri, Delta state. Sodium chloride (NaCl) and Distilled water was obtained from chemistry laboratory Bayero university, Kano Nigeria.

The physical properties of the nanoparticles are summarized in Table 1.

Apparatus: Tensiometer, Du Nouy Ring, sample container, Beakers (100-250 mL), ultrasonic bath (for dispersion), stirrer, Digital scale (accuracy ±0.01 g), Volumetric cylinder, sample bottles, Ethanol (for cleaning equipment) and Labeling materials.

Table 1: Properties of nanoparticles

Properties	SiO_2	Al_2O_3
Appearance	Dispersion	White powder
Particle size	20nm-30nm	20nm-30nm
Specific Surface area	100-500 m^2/g	50 m^2/g-150m/g
Purity	99.9%	99%
Density	0.25g/cm^3	0.2-0.6g/ cm^3

2.1.1 Sample preparation

The 8 wt.% sodium chloride brine solution was prepared by accurately weighing 8.0 grams of NaCl, adding 80 mL of distilled water, and stirring continuously until completely dissolved.

The NaCl solution was adjusted to 100 mL with distilled water, ensuring the correct concentration of 8wt.% NaCl. This procedure was repeated 14 times for each nanofluid sample, ensuring uniformity.

Dispersions of silicon dioxide and aluminum oxide nanoparticles were prepared for enhanced oil recovery studies, with each sample prepared separately to maintain uniformity and prevent cross-contamination.

Solutions of SiO_2 and Al_2O_3 were prepared at seven concentrations using a fixed volume of 100 mL of an 8wt.% brine solution.

The preparation process began with accurately weighing the mass of nanoparticles corresponding to each target concentration.

The nanoparticles' mass was measured using a precision analytical balance (±0.01 g) for 0.01wt% samples and 3.0wt% samples, respectively.

A beaker filled with weighed nanoparticles was stirred for 20 minutes, then placed in an ultrasonic bath for 30-minute sonication to break up agglomerates and improve the stability and homogeneity of the nanofluids.

Fourteen samples were created, seven for SiO_2 (S01 to S07) and seven for Al_2O_3 (A01 to A07), each labeled with a matching identification code after sonication.

The nanofluid samples were then prepared for interfacial tension measurements.

2.2. Experiments

Details of experiments are exactly as those described in previous report (Ben-Awuah *et al*., 2017) [8]. The experiment was designed to find out how different concentrations of nanoparticles could enhance oil recovery in a highly salinized reservoir. The propose concentrations that were chosen for SiO_2 and Al_2O_3 were 0.01wt%, 0.05wt%, 0.1wt%, 0.5wt%, 1.0wt%, 2.0wt%, and 3.0wt%. The optimal nanoparticle concentration will be selected based on the results and analysis of the interfacial tension measurement. Prior to this The API gravity of the crude oil to be used in the experiment will be measured to determine its suitability in the subsequent experiment., viscosity and density of the crude oil will also be measured.

2.2.1 Setting Up

To investigate the interfacial behavior of nanoparticle-enhanced fluids for enhanced oil recovery (EOR), interfacial tension (IFT) was measured between crude oil and various nanoparticle solutions using a calibrated Du Noüy ring tensiometer. The integrity of the measurements relied on the proper maintenance of the platinum ring, which was thoroughly cleaned using ethanol and flame it to ensure it remained free from any contaminants. All measurements were conducted under controlled room temperature conditions, typically maintained 25°C, to ensure repeatability and accuracy.

2.3 Method

The prepared nanofluids are dispersed in an 8 wt.% NaCl brine solution to obtain various concentrations: 0.01 wt%, 0.05 wt%, 0.1 wt%, 0.5 wt%, 1.0 wt%, 2.0 wt%, and 3.0 wt%. These concentrations are selected to determine the optimal nanoparticle dosage for reducing interfacial tension (IFT) in high-salinity environments.

For each measurement, a clean beaker was filled with the nanoparticle solution corresponding to the target concentration. Approximately 15 mL of crude oil was then carefully added to the surface of the nanofluid using a pipette, taking care not to disturb the interface. The beaker was placed on the tensiometer platform, and the platinum ring was slowly lowered until it gently rested at the interface between the oil and aqueous phases.

The tensiometer was then operated to lift the ring through the interface at a controlled rate. The maximum force required to detach the ring from the interface was measured and used to determine the interfacial tension, reported in dyne/cm (equivalent to mN/m).

Initially, a baseline IFT was measured between crude oil and the 8 wt.% brine solution without nanoparticles. This served as a control for evaluating the influence of nanoparticle addition. Subsequently, each nanofluid sample at varying concentrations was tested under identical conditions. Each measurement was repeated three times per sample to ensure precision, and the average IFT value was recorded. Between tests, the platinum ring was cleaned and dried to avoid cross-contamination between samples.

The IFT values obtained for each test are summarized in a results table and will be used to assess the effectiveness of each nanoparticle type and concentration in reducing interfacial tension, which is critical for enhancing oil recovery performance in high-salinity environments.

3. Results and Discussion

3.1. Fluid Measurement

The API gravity, viscosity, and density of the crude oil were first measured to evaluate its category and compatibility for EOR studies. The results are summarized in Table 2.

Table 2: Properties of Crude Oil

Property	Value
Viscosity	1.333Cp
API	43.11
Density	0.80g/mL

By comparing the results obtained in the experiment to the standard API classification of crude oil shown in table 2, it can be seen clearly that the crude oil used in the experiment, falls in the light category with an API of 43.11.

3.2 IFT measurement

Interfacial tension (IFT) plays a critical role in enhanced oil recovery (EOR) as it directly influences the capillary number a key parameter that governs fluid displacement in porous media. A lower IFT causes capillary forces to decrease, which raises the capillary number. This increase is preferable because it improves the injected fluids' capacity to release trapped oil. Reduced oil retention in the reservoir's pores due to lower IFT values eventually results in less residual oil saturation and increased recovery efficiency. In this study, the Du Noüy ring method was used to measure the IFT between crude oil and different nanoparticle solutions. This method, which offers a quantitative assessment of interfacial forces, is frequently used to determine how well additives like nanoparticles reduce IFT for EOR applications. The results of the measurement were summarized in the Table 3 and Fig. 1.

Table 3: Results of IFT measurement of crude oil and NP solution Using Hu-Mason correction factor

S/N	Solution	IFT (dyene/cm)
1	Brine solution with crude oil	16.47
2	Np solution (0.01wt% SiO_2)	7.80
3	Np solution (0.05wt% SiO_2)	10.73
4	Np solution (0.1wt% SiO_2)	9.01
5	Np solution (0.5wt% SiO_2)	9.17
6	Np solution (1wt% SiO_2)	12.52
7	Np solution (2wt% SiO_2)	7.61
8	Np solution (3wt% SiO_2)	8.22
9	Np solution(0.01wt%Al_2O_3)	5.77
10	Np solution (0.05wt% Al_2O_3)	6.02
11	Np solution (0.1wt% Al_2O_3)	9.87
12	Np solution (0.5wt% Al_2O_3)	5.89
13	Np solution (1wt% Al_2O_3)	6.09
14	Np solution (2wt% Al_2O_3)	6.58
15	Np solution (3wt% Al_2O_3)	4.22

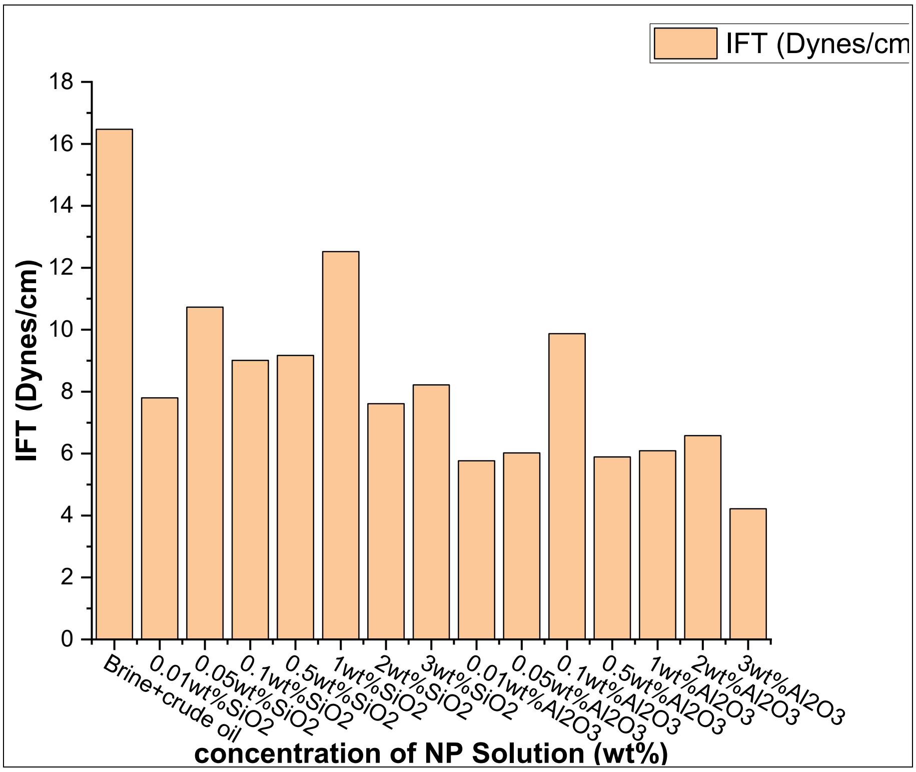

Fig 1: Graphical representation of IFT measurement

The interfacial tension between the crude oil and nanoparticle solutions were measured in dynes/cm which is equivalent to mN/M as shown in Table 3. Initially, the base solution which consisted of only brine solution with crude oil was used to measure the interfacial tension which serve as a control line for comparative assessment. From the result, the IFT value obtained using only brine solution was 16.47 dynes/cm. Upon the introduction of SiO_2 nanoparticles, a substantial decrease in IFT was observed at 0.01 wt%, with a value of 7.80 dyne/cm. However, as the concentration increased to 0.05 wt%, the IFT unexpectedly rose to 10.73 dyne/cm, followed by moderate reductions at 0.1 wt% (9.01 dyne/cm) and 0.5 wt% (9.17 dyne/cm). The increase in IFT at intermediate concentrations may be due to a combination of nanoparticle aggregation and reduced interfacial adsorption efficiency. The IFT values decreased once more to 7.61 dyne/cm and 8.22 dyne/cm at higher concentrations of 2 wt% and 3 wt%, respectively. This implies that when particle concentrations increase, particles settle more neatly at the interface.

Despite this partial performance recovery, SiO_2 nanoparticles' lowest IFT value stayed at the lowest tested concentration (0.01 wt%), exhibiting a concentration-dependent response that deviates from linearity as shown in Figure 1.

In contrast, Al_2O_3 nanoparticles exhibited a more consistent and superior performance in reducing IFT. At 0.01 wt%, Al_2O_3 reduced the IFT to 5.77 dyne/cm, outperforming SiO_2 at the same concentration. The IFT values remained relatively low and stable across 0.05 to 1 wt% concentrations, ranging from 5.89 to 6.09 dyne/cm. Notably, the most significant reduction was recorded at 3 wt%, where the IFT reached a minimum of 4.22 dyne/cm the lowest among all tested formulations. Thus, it can be concluded that this concentration is considered as the optimum concentration that could be used to improve enhanced oil recovery. From the results obtained, it can be inferred that Al_2O_3 nanoparticles are more suitable in enhancing oil recovery in high salinity reservoir compared to SiO_2 nanoparticles as clearly shown in Figure 1.

The observed differences between SiO_2 and Al_2O_3 can be attributed to their distinct physicochemical properties, including surface charge, particle morphology, and degree of hydrophilicity. These properties influence nanoparticle adsorption and alignment at the oil-water interface. Although both nanoparticle types have potential for EOR applications, Al_2O_3 nanoparticles were found to be more efficient in reducing IFT under the experimental conditions used.

In summary, the best nanoparticle formulation for lowering interfacial tension in high-salinity reservoirs was determined to be 3 wt% Al_2O_3, with an IFT of 4.22 dyne/cm.

4. Conclusion

For this particular research, the different concentrations of SiO_2 and Al_2O_3 NP were formulated and their properties have been measured in terms of their application in enhancing oil recovery. The results shows that SiO_2 and Al_2O_3 nanoparticles can reduce IFT in high-salinity conditions, boosting oil recovery. SiO_2 nanoparticles exhibited non-linear, concentration-dependent behavior, with the lowest IFT value of 7.80 dyne/cm at the lowest concentration (0.01wt%). However, efficacy varied at intermediate concentrations, most likely due to aggregation or inefficient interfacial adsorption, and increased only minimally at higher concentrations.

Al_2O_3 nanoparticles had a consistent and improved IFT reduction profile across all investigated doses. At 0.01 wt%, the IFT was 5.77 dyne/cm, with little fluctuation across concentrations up to 1 wt%. At 3 wt%, the IFT attained a low of 4.22 dyne/cm, showing significant surface activity and effective interfacial packing of Al_2O_3 particles.

Overall, the results highlight the impact of nanoparticle type and concentration on interfacial behavior. Al_2O_3

nanoparticles, especially at 3 wt%, were shown to be the most effective formulation for lowering IFT. This makes them a suitable choice for further exploration in core flooding tests and field-scale enhanced oil recovery (EOR) applications under high salinity circumstances.

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6. Disclosure statement

6.1 Conflict of Interest: The authors declare that there are no conflicts of interest.

6.2 Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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