



TiO₂ Nanoparticles in Low-Salinity Waterflooding: An Experimental Study on Wettability Alteration and Oil Recovery

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Abstract

Low-salinity waterflooding combined with titanium dioxide (TiO₂) nanoparticles can improve microscopic oil displacement by modifying oil-brine and rock-fluid interactions. This study presents a preliminary experimental evaluation of TiO₂-assisted low-salinity waterflooding using Berea sandstone and crude oil from a mature oil field in Indonesia. Synthetic NaCl brines with salinities of 500–32,000 ppm were prepared, while TiO₂ concentrations of 100, 250, and 500 ppm were evaluated. Interfacial tension (IFT) was measured using a spinning-drop tensiometer, wettability was assessed through contact-angle measurements, and selected formulations were subsequently evaluated by coreflooding at 68°C. The measured IFT values ranged approximately from 1.4 to 7.5 mN/m, with 100 ppm TiO₂ producing the lowest IFT under most tested salinity conditions. Contact-angle measurements also shifted toward more water-wet conditions, with the largest decrease from approximately 29.5° to 14.5° after adding 100 ppm TiO₂. Coreflooding at 8,000 ppm brine showed that 100 ppm TiO₂ increased the recovery factor from 9.26% to 30.42% ROIP, corresponding to an incremental recovery of 21.16 percentage points. These preliminary results identify 100 ppm TiO₂ as the most favorable tested concentration. Nevertheless, the optimum formulation remains specific to the investigated rock-brine-oil system because nanoparticle stability, retention, and surface charge were not independently measured.

Keywords: *Low Salinity Waterflooding, Tio₂ Nanoparticles, Interfacial Tension, Wettability Alteration, Enhanced Oil Recovery*

INTRODUCTION

Enhanced oil recovery (EOR) is crucial for extracting oil remaining in mature reservoirs after primary and secondary recovery. Chemical EOR (cEOR) methods typically involve alkaline, polymer, and surfactant flooding. Alkaline methods generate in situ surfactants, polymers improve sweep efficiency by increasing water viscosity, and surfactants reduce oil-water interfacial tension (IFT) to mobilize trapped oil.

However, these methods face challenges such as thermal and chemical degradation, salinity sensitivity, and injectivity issues in low-permeability formations. In recent years, nanotechnology has emerged as a promising approach. In particular, titanium dioxide (TiO₂) nanoparticles offer high surface area, chemical stability, and the ability to modify interfacial tension (Mumbere et al., 2025).

When dispersed in injection low-salinity water, TiO₂ nanoparticles enhance oil recovery by reducing IFT and shifting rock wettability toward a more water-wet state. TiO₂ nanoparticles are inexpensive and environmentally friendly materials widely used in photocatalysis, sunscreen, and the coating industry for surface modification.

Previous studies show that TiO₂ nanoparticles have significant potential for EOR

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applications. [Megayanti et al. \(2023\)](#) experimentally investigated adding TiO₂ nanoparticles to a surfactant solution in contact with crude oil and sandstone rock. Their findings confirmed that TiO₂ nanoparticles can substantially reduce oil-brine interfacial tension and shift rock wettability toward a more water-wet condition, both favorable mechanisms for enhancing oil recovery.

Several studies have proposed different explanations for how low-salinity water alters rock wettability, though the underlying driver remains debated. According to [Lyu et al. \(2022\)](#), the mechanisms behind the low-salinity effect can be broadly classified into solid-liquid and liquid-liquid interactions, with several solid-liquid mechanisms including electric double-layer (EDL) expansion, multicomponent ion exchange (MIE), and fines migration, all converging on wettability alteration as the primary outcome.

One line of evidence points to particle-scale transport: as low-salinity water flows through the pore network, it mobilizes clay and fine mineral particles, redistributing flow channels and opening new displacement pathways that improve sweep efficiency. A separate body of work focuses on surface chemistry at the mineral-crude oil interface.

Under this view, injected low-salinity brine expands the electric double layer surrounding clay and mineral surfaces, weakening the electrostatic attraction that binds polar organic compounds from the crude oil, and this expansion is often accompanied by a local pH rise that further destabilizes these bonds and releases the adsorbed organics, shifting the surface toward a more water-wet state.

An alternative, more specific explanation for sandstone reservoirs centers on multicomponent ion exchange (MIE), in which polyvalent cations such as Ca²⁺ in the formation water anchor acidic crude oil components onto the sandstone surface. When low-salinity water is introduced, its ions exchange with these surface-bound cations, releasing the organic complexes and altering wettability.

Taken together, these studies suggest that LSW-induced wettability alteration in sandstone can arise from at least three interacting pathways: fines migration that reshapes flow geometry, EDL-driven bond weakening that releases adsorbed organics, and cation exchange (MIE) that displaces oil components from mineral surfaces ([Lyu et al., 2022](#)).

Therefore, this study investigates the effect of adding TiO₂ nanoparticles to low-salinity water on interfacial tension (IFT), rock wettability, and oil recovery performance for EOR applications. Specifically, this study aims to (1) evaluate the change in IFT between crude oil and brine as a function of salinity and TiO₂ nanoparticle concentration using a spinning drop tensiometer, (2) assess the resulting wettability alteration of Berea sandstone through contact angle measurements, and (3) determine the incremental oil recovery achieved by TiO₂-nanoparticle-dispersed low-salinity water through coreflooding experiments.

NaCl-based synthetic brine with varying salinities and TiO₂ nanoparticles at different concentrations were used, together with crude oil from the Oil Field, Indonesia, to identify the optimum formulation for enhancing oil recovery in sandstone reservoirs.

LITERATURE REVIEW

The Stability of TiO₂ nanoparticles in Low-Salinity Water

The nanoparticle used in this study is Titanium Dioxide, which is composed of titanium and oxygen. TiO₂ nanoparticles form a wedge-shaped nanofilm at the oil-water interface, generating a high structural disjoining pressure that displaces oil from the pore surface and shifts the rock from oil-wet toward water-wet conditions ([Davoodi et al., 2022](#)).

These effects depend on nanofluid stability, which is primarily controlled by zeta potential and nanoparticle concentration. [Ehtesabi et al. \(2014\)](#) demonstrated that this metal oxide-based nanoparticle, composed predominantly of titanium and oxygen at approximately 90%, exhibited an

average pore diameter of 13.27 nm and a specific surface area of 52.32 m²/g.

Zeta potential (ζ -potential) is the potential between the liquid layer immediately next to the surface, which is strongly bound to the particle, and the continuous phase (Wang et al., 2023). In practice, zeta potential can predict emulsion stability (Wang et al., 2023).

Emulsions with a high zeta potential, either negative or positive, are electrically stabilized, while emulsions with low zeta potentials tend to coagulate or flocculate, eventually leading to phase separation (Wang et al., 2023).

Mechanism of Interfacial Tension (IFT) Reduction by TiO₂

Interfacial tension, commonly referred to as IFT, is the force required to expand the interface between two immiscible liquids over a certain area (Sun et al., 2023). Surface tension refers to the force acting on the surface of a single liquid. In contrast, interfacial tension refers to the energy acting at the interface between two liquids of different phases. This force arises from direct contact between two fluids with different physical and chemical properties.

In the International System of Units (SI), interfacial tension is expressed in units of mN/m or dyne/cm. Reducing interfacial tension weakens cohesive forces while strengthening adhesive forces. Cohesive forces are the attractive forces between molecules of the same kind, whereas adhesive forces are the forces between molecules of different kinds.

Interfacial tension is calculated using the Vonnegut equation, which is based on the width of an oil droplet. The equation is as follows:

$$\gamma = \frac{1}{4} r^3 \Delta \rho \omega^2$$

- γ : interfacial tension value
- $\Delta \rho$: fluid density difference between oil and brine
- r : radius of oil droplet
- ω : rotational speed

The TiO₂ reduces IFT by several mechanisms. Nanoparticles like TiO₂ adsorb at the oil-water interface, forming a thin layered structure that lowers IFT, with the reduction becoming more pronounced as nanoparticle concentration rises within a certain range (Sun et al., 2023). This adsorption behavior can also be described through a surface pressure mechanism, in which particle adsorption at the oil-water interface generates an effective surface pressure that corresponds to the decrease in interfacial tension (Nowrouzi et al., 2022).

The interfacial adsorption mechanism was further demonstrated by Ahmadi, Y, et al. (2025), who evaluated a green nanocomposite combined with low-salinity brine and reported consistent IFT reduction alongside favorable wettability alteration and improved spontaneous imbibition performance, reinforcing that nanoparticle-brine synergy rather than salinity or nanoparticle concentration alone governs the extent of interfacial tension reduction.

Brine salinity also governs the effectiveness of TiO₂ through electrical double layer (EDL) interactions. In high-salinity brine, dissolved ions compress the EDL around TiO₂ nanoparticles, weakening the repulsive force between them and causing aggregation. In contrast, in low-salinity brine, the EDL expands, keeping particles well dispersed and stable.

Jafarbeigi and Kamari (2026) confirmed that their TiO₂ nanofluid was most stable in low-salinity brine, reaching a zeta potential of -58.46 mV at the optimal concentration, and this stability corresponded to the lowest IFT achieved (1.16 mN/m, down from 24.45 mN/m). The low-salinity brine also expanded the EDL at the rock surface itself, weakening the bond between oil and rock

and further promoting nanoparticle adsorption.

Mechanism of Wettability Alteration by TiO_2

Wettability refers to a fluid's tendency to spread on or adhere to a solid surface in the presence of immiscible fluids. In natural porous media, the wettability varies from point to point depending on surface roughness, immobile adsorbed liquid layers, and the adsorptive properties of the mineral constituents (Falode & Manuel, 2014). Coal, graphite, sulfur, talc, talc-like silicates, and many sulfides are probably neutrally wet to oil-wet (Anderson, 1986).

In contrast, most common minerals such as quartz, carbonates, and sulfates are strongly water-wet (Falode & Manuel, 2014). Wettability alteration is the process of shifting the rock surface from an oil-wet toward a more water-wet condition. Therefore, it is recognized as one of the most effective EOR mechanisms because it reduces oil adhesion to the rock surface, improves water imbibition into the pore network, and enhances overall displacement efficiency.

Ehtesabi et al. (2015) studied the transport and retention behavior of low-concentration TiO_2 nanoparticles in core-plug porous media and their effect on heavy oil recovery. They measured nanoparticle deposition along the core, viscosity, IFT, and contact angle. The results showed that flooding with 0.01% TiO_2 nanoparticles improved heavy oil sweeping from 41% to 55%. Contact angle measurements showed that the main mechanism for increasing oil sweeping was changing the wettability of the rock surface rather than reducing IFT or viscosity.

Several interrelated mechanisms explain TiO_2 's ability to alter wettability. Wasan and Nikolov (2003) defined structural disjoining pressure as the additional pressure generated by nanoparticle self-assembly within a confined thin liquid film. At the oil-water-rock contact, this pressure pushes the nanoparticle film to spread over the rock surface, helping to lift and displace the oil from the rock.

McElfresh et al. (2012) built on this, showing that the propagating nanofilm separates oil, paraffin, and other hydrophobic residues from the rock, exposing a cleaner, more hydrophilic surface and reducing its oil-wet character.

More specifically for TiO_2 nanoparticles, Nowrouzi et al. (2019) reported that the adsorption of TiO_2 onto the rock surface was proportional to nanoparticle concentration, with smaller particles (10 nm) exhibiting greater adsorption capacity than larger ones (30 nm), indicating that particle size plays a critical role in the efficiency of wettability alteration.

Summary of Literature Review

The literature study in this research collects information about the latest developments in TiO_2 addition in low-salinity waterflooding for enhanced oil recovery (EOR), particularly focusing on IFT reduction, wettability alteration, and increase in recovery factor in coreflood tests. Table 1 summarizes relevant studies.

Table 1. Summary of Literature Studies

Title	Author (Year)	Description
Enhanced Heavy Oil Recovery in Sandstone Cores Using TiO_2 Nanofluids	Ehtesabi, H., Ahadian, M. M., Taghikhani, V., & Ghazanfari, M. H. (2014)	TiO_2 nanoparticles improved heavy oil recovery from sandstone cores from 49% to 80% at 0.01% concentration; contact angle confirmed a shift from oil-wet to water-wet.

Enhanced Heavy Oil Recovery Using TiO ₂ Nanoparticles: Investigation of Deposition during Transport in Core Plug	Ehtesabi, H., Ahadian, M. M., & Taghikhani, V. (2015)	Investigated transport/retention behavior of low-concentration TiO ₂ in porous media. Flooding with 0.01% TiO ₂ improved heavy oil sweep efficiency from 41% to 55%, primarily via wettability alteration.
Effects of Concentration and Size of TiO ₂ Nano-Particles on the Performance of Smart Water in Wettability Alteration and Oil Production under Spontaneous Imbibition	Nowrouzi, I., Khaksar Manshad, A., & Mohammadi, A. H. (2019)	TiO ₂ adsorption onto rock is proportional to concentration; smaller particles (10 nm) adsorb more than larger ones (30 nm).
Effects of MgO, γ -Al ₂ O ₃ , and TiO ₂ Nanoparticles at Low Concentrations on Interfacial Tension (IFT), Rock Wettability, and Oil Recovery by Spontaneous Imbibition in the Process of Smart Nanofluid Injection into Carbonate Reservoirs	Nowrouzi, I., Khaksar Manshad, A., & Mohammadi, A. H. (2022)	Combining smart water with nanoparticles reduced IFT and contact angle more than either method alone; MgO gave the largest IFT reduction, TiO ₂ the strongest wettability alteration.
Experimental Investigation of the Effect of Green TiO ₂ /Quartz Nanocomposite on Interfacial Tension Reduction, Wettability Alteration, and Oil Recovery Improvement	Zargar, G., Arabpour, T., Khaksar Manshad, A., Ali, J. A., Mohammad Sajadi, S., Keshavarz, A., & Mohammadi, A. H. (2020)	Lowest IFT recorded in distilled water (2.65 mN/m, down from 36.42 mN/m); IFT reduction more gradual once nanoparticle concentration exceeded 500–1000 ppm.
A Complete Experimental Study of Oil/Water Interfacial Properties in the Presence of TiO ₂ Nanoparticles and Different Ions	Khalilnezhad, A., Rezvani, H., Ganji, P., & Kazemzadeh, Y. (2019)	Systematically evaluated TiO ₂ nanoparticles dispersed in formation water with varying ion types/concentrations, pressure, and temperature, establishing key links between ionic composition and interfacial behavior.
Exploring the Effects of Salinity and Ionic Composition on Wettability Alteration and Interfacial Properties in Carbonate Oil Reservoirs	Ahmadi, B., Molaei, A. H., Sahraei, E., & Mohammadi, A. H. (2025)	Coupled diffusion-EDL expansion model; reduced brine salinity expands EDL and shifts zeta potential toward more negative values.
Evaluating the Role of Monovalent and Divalent Salts on Interfacial Tension	Gholamzadeh, Y., Sharifi, M., & Hemmati-	At higher ionic strength, a shorter Debye screening length weakens electrostatic attraction of asphaltenes/resins toward

Reduction Using Nitrogen-Doped Carbon Dots for Enhanced Oil Recovery	Sarapardeh, A. (2025)	the interface.
Spreading of Nanofluids on Solids	Wasan, D. T., & Nikolov, A. D. (2003)	Introduced structural disjoining pressure: nanoparticles self-assemble into a wedge-shaped film that drives oil displacement from a solid surface.
The Application of Nanoparticle Dispersions to Remove Paraffin and Polymer Filter Cake Damage	McElfresh, P. M., & Ector, D. (2012)	Propagating nanofilm separates oil, paraffin, and hydrophobic residues from the rock, exposing a cleaner, more hydrophilic mineral surface.
Investigation of Crude Oil-Brine-Rock Interaction using Low Salinity Water and TiO ₂ Nanoparticles: Implications on the Surface Charge and the Interfacial Properties	Kusuma, S. I. T., Hidayat, M., Sagita, F., Kadja, G. T. M., & Marhaendrajana, T. (2025)	Identified interactions in Crude Oil-Brine-Rock (COBR) systems; salinity and TiO ₂ concentration jointly affect surface charge and interfacial properties.
A Synergistic Nano-Brine Formulation for Enhanced Oil Recovery through Interfacial Engineering in Carbonate Reservoirs	Jafarbeigi, E., & Kamari, E. (2026)	Surface-modified TiO ₂ in low-salinity brine; high salinity destabilizes particles by neutralizing surface charge, lowering zeta potential and IFT-reduction efficacy.

RESEARCH METHOD

Materials and Experimental Scope

The experimental materials consisted of TiO₂ nanoparticles, analytical-grade sodium chloride, demineralized water, Berea sandstone, and crude oil obtained from the Oil Field, Indonesia. The crude oil had an API gravity of 43.45°, a viscosity of 0.90 cP at 68 °C, and a SARA composition of 71.60% saturates, 25.49% aromatics, 2.14% resins, and 0.78% asphaltenes.

Synthetic NaCl brines representing high- and low-salinity conditions were prepared, and TiO₂ was dispersed at concentrations within the range of 100–500 ppm. The experimental program included interfacial tension, contact-angle, and coreflood measurements.

This conference paper reports the principal results obtained from the nanoparticle-free brines and the selected 100 ppm TiO₂ formulation. Other tested formulations were used for preliminary screening, but are outside the reporting scope of this paper.

Nanofluid Preparation

Synthetic brines were prepared by dissolving NaCl in demineralized water and stirring for 15 min. TiO₂ nanoparticles were subsequently added to the selected brines and sonicated for 32 min. The same preparation procedure was applied consistently to all reported fluids. Because the sonication duration was not independently optimized and zeta potential was not measured, the stability of the resulting nanofluids could not be quantitatively established.

Interfacial Tension (IFT) Measurement

Oil–brine interfacial tension was measured using a TX-500D spinning-drop tensiometer at $68 \pm 0.3^\circ\text{C}$. A 2 μL crude-oil droplet was introduced into a capillary tube containing the test fluid

and rotated at 3,000 rpm for 30 min. IFT was determined from the equilibrium droplet geometry using the density difference between the oil and aqueous phases. This paper reports results for the nanoparticle-free brines and the selected 100 ppm TiO₂ formulation. Each reported condition was measured once; therefore, standard deviations could not be determined.

Contact Angle Measurement

Contact-angle measurements were performed using a Theta Lite TL-100 optical tensiometer at $68 \pm 0.3^\circ\text{C}$. Berea sandstone sections were aged in crude oil for 24 h and subsequently submerged in the selected brine or TiO₂ nanofluid. A crude-oil droplet was placed on the submerged rock surface, and the contact angle was recorded after the droplet geometry had stabilized. This paper compares only nanoparticle-free brine with the selected 100 ppm TiO₂ formulation.

Preliminary Coreflood Evaluation

Berea sandstone cores were characterized by measuring their dimensions, porosity, and gas permeability following API RP 40. The cores were vacuum-saturated with 8,000 ppm NaCl brine, flooded with crude oil, and aged for 24 hours at $68 \pm 0.3^\circ\text{C}$. The selected injection fluid was then injected at 0.3 cm³/min for up to 10 pore volumes under 100 psia. Produced oil was measured volumetrically, and recovery was calculated relative to the original oil in place.

Although several formulations were screened during the broader experimental program, this conference paper reports only the comparison between the nanoparticle-free 8,000 ppm brine and the selected formulation containing 100 ppm TiO₂. This comparison aimed to provide an initial verification of the interfacial and wettability observations rather than a comprehensive evaluation of concentration-dependent displacement performance. The reported coreflood comparison was based on individual experiments; consequently, statistical significance could not be evaluated.

Table 2. Reporting Scope of the Preliminary Experimental Evaluation

Measurement	0 ppm TiO ₂	100 ppm TiO ₂	Other TiO ₂ Concentrations
Interfacial tension	Reported	Reported	Screening only
Contact angle	Reported	Reported	Not reported
Coreflooding	Reported	Reported	Not reported

FINDINGS AND DISCUSSION

Preliminary Performance of TiO₂-Assisted Low Salinity Waterflooding

Table 3 summarizes the principal experimental findings reported in this conference paper. The discussion compares the case without nanoparticles with the selected formulation containing 100 ppm TiO₂. This comparison evaluated whether the interfacial and wettability responses were accompanied by improved oil displacement.

Table 3. Summary of the Principal Experimental Findings

Indicator	0 ppm TiO ₂	100 ppm TiO ₂	Observed response
Minimum measured IFT	2.60 mN/m	1.33 mN/m	IFT reduction
Contact angle at 4,000 ppm	29.43°	15.09°	More water-wet
Recovery factor at 8,000 ppm	9.26% ROIP	30.42% ROIP	+21.16 percentage points

Interfacial Response

Adding 100 ppm TiO_2 reduced the IFT relative to the corresponding brine without nanoparticles under most reported salinity conditions. The lowest measured IFT was 1.33 mN/m at a brine salinity of 8,000 ppm, compared with 2.60 mN/m without TiO_2 under the same salinity condition.

The reduction suggests that TiO_2 modified the oil–brine interface, potentially through nanoparticle accumulation at the interface and the resulting change in interfacial free energy. Similar interfacial responses have been reported for TiO_2 -containing brines, although their magnitude depends on nanoparticle concentration, salinity, crude-oil composition, and dispersion stability (Khalilnezhad et al., 2019; Nowrouzi et al., 2022).

Brine without nanoparticles did not show a monotonic reduction in IFT with decreasing salinity. Consequently, these results do not support the assumption that lower NaCl concentration necessarily produces lower IFT. Because zeta potential, particle-size distribution, and interfacial charge were not measured, the origin of this response could not be conclusively established. The observed trend should therefore be regarded as specific to the investigated crude-oil–NaCl–brine system.

Wettability Response

Contact-angle measurements provided supporting evidence of wettability alteration. At 4,000 ppm brine salinity, adding 100 ppm TiO_2 decreased the contact angle from 29.43° to 15.09°. Based on the measurement convention applied in this study, this decrease indicates that the Berea sandstone surface shifted toward a more water-wet condition.

This change is consistent with previous studies reporting that TiO_2 nanoparticles can promote aqueous-phase spreading over sandstone surfaces through nanoparticle–mineral interactions and structural disjoining pressure (Ehtesabi et al., 2014; Davoodi et al., 2022). A more water-wet surface can weaken oil adhesion and facilitate oil displacement from pore walls.

Nevertheless, nanoparticle deposition and surface-charge modification were not measured directly. Wettability alteration is therefore interpreted as an experimentally observed response rather than definitive evidence of a particular molecular mechanism. The relatively short 24-h aging period may also have influenced the initial wettability condition and limits direct comparison with reservoir-aged sandstone.

Preliminary Oil-Recovery Response

The selected formulation was evaluated through a preliminary coreflood comparison at 8,000 ppm brine salinity. Brine without nanoparticles produced a recovery factor of 9.26% ROIP, whereas adding 100 ppm TiO_2 increased recovery to 30.42% ROIP. This represents an incremental recovery of 21.16 percentage points relative to the without-nanoparticle condition.

The higher recovery was consistent with the lower IFT and reduced contact angle observed after TiO_2 addition. IFT reduction can increase the capillary number and help mobilize capillary-trapped oil. At the same time, a shift toward more water-wet conditions can improve aqueous-phase spreading and displace oil from the pore surface. These complementary effects plausibly explain the observed recovery improvement.

However, the coreflood experiments were not replicated, and the influence of core-to-core variability could not be separated from the effect of the injection fluid. Therefore, the increase should not be described as “statistically significant.” Furthermore, nanoparticle retention and pore plugging cannot be confirmed because effluent nanoparticle concentration and spatial deposition were not measured.

Contribution and Limitations

The main contribution of this preliminary study is identifying 100 ppm TiO_2 as a potentially favorable low-dose formulation for modifying interfacial behavior, wettability, and oil displacement in the investigated Berea sandstone–crude oil system. Unlike studies that evaluate only interfacial properties, this work provides an initial connection between IFT reduction, contact-angle alteration, and core-scale recovery response under a consistent experimental temperature.

The results should nevertheless be interpreted within the experimental boundaries. The study used Berea sandstone, one crude-oil sample, NaCl-only synthetic brine, a single temperature, and a limited number of coreflood experiments.

The study did not include divalent ions representative of reservoir brine, and it did not measure nanofluid stability, surface charge, nanoparticle retention, or effluent concentration. Consequently, the selected 100 ppm concentration should be regarded as specific to the tested system and not as a universally optimum field dosage.

CONCLUSIONS

This preliminary study shows that adding TiO_2 nanoparticles can modify oil–brine and rock–fluid interactions under the investigated experimental conditions. Among the formulations reported in this conference paper, 100 ppm TiO_2 produced the most favorable response, indicated by reduced interfacial tension and a shift of Berea sandstone toward a more water-wet condition.

The corresponding coreflood experiment at 8,000 ppm brine salinity increased the recovery factor from 9.26% to 30.42% ROIP, representing an incremental recovery of 21.16 percentage points relative to the nanoparticle-free brine.

These findings provide preliminary evidence that a relatively low TiO_2 dosage may enhance oil displacement without requiring a high nanoparticle concentration. Nevertheless, the identified formulation is specific to the investigated Berea sandstone–crude oil–NaCl brine system and should not be interpreted as a universal optimum for field application.

The study was limited by using a single rock type and crude-oil sample, NaCl-only synthetic brine, a single test temperature, a 24-h aging period, and non-replicated coreflood experiments. In addition, the authors did not measure zeta potential, particle-size distribution, nanoparticle retention, or effluent concentration. Future work should therefore evaluate nanofluid stability, repeatability, nanoparticle transport and retention, and the effects of divalent ions under representative reservoir conditions before considering the formulation for scale-up.

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