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Effect of LHP Nanosilica on Sandstone Wettability and Oil Recovery by Imbibition in Crude Oils with Different API

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ABSTRACT - This study investigates the influence of lipophobic–hydrophilic polysilicon (LHP) nanosilica on wettability alteration and oil recovery performance through spontaneous imbibition in initially neutral-wet sandstone. The novelty of this study lies in its systematic comparative framework using two crude oils with distinct API gravities and SARA compositions to evaluate the role of fluid–rock interactions in depth. Two crude oils with different API gravities were selected to evaluate the role of oil composition in fluid - rock interactions. Crude oil properties were characterized using SARA analysis, while imbibition tests were conducted using 5000 ppm brine and nanosilica dispersions at controlled concentrations. Wettability Index (WI) was determined using the Amott cell method, and Oil Recovery Factor (ORF) was calculated from produced oil volume. Results indicate that LHP nanosilica consistently shifts rock wettability toward more water-wet conditions. The lighter crude oil exhibits a stronger wettability response and higher recovery improvement than the heavier oil. A positive correlation between WI and ORF confirms wettability alteration as the dominant enhanced oil recovery mechanism. These findings provide a significant contribution by establishing crude oil characteristics as a key controlling factor in nanofluid EOR design, which is crucial for field applications with complex fluid variations.

Keywords: LHP nanosilica, wettability alteration, spontaneous imbibition, oil recovery, sandstone.

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INTRODUCTION

The development of nanotechnology has opened new opportunities in the oil and gas industry. Nanoparticles ranging from 1–100 nm possess unique properties including high specific surface area, elevated surface activity, and tunable surface chemistry. These characteristics make nanotechnology a promising candidate for enhanced oil recovery (EOR), influencing mechanisms such as reduction in interfacial tension (IFT), structural disjoining pressure, and wettability alteration, as well as asphaltene precipitation control, which collectively improve microscopic displacement efficiency. Hendraningrat & Torsæter 2016; Li et al., 2015; Eltoum 2021; Daulay et al., 2025. Recent advancements demonstrate that silica-based nanofluids can effectively shift the rock surface toward more water-wet conditions by forming a stable nanoparticle layer that remains resilient against subsequent fluid flow (Al-Anssari et al., 2021). Furthermore, recent studies highlight that rock-fluid interactions at the pore scale strongly govern capillary-controlled recovery performance (Oktaviany et al., 2022). Performance is governed by complex interactions between fluid-flow behavior and rock properties in the field (Syarannamual et al., 2025).

Crude oil is a complex mixture composed of SARA fractions (saturates, aromatics, resins, and asphaltenes). Its composition significantly affects wettability behavior and fluid–rock interactions because polar fractions, particularly resins and asphaltenes, exhibit strong affinity for mineral surfaces Rudyk 2018; Yasin et al., 2013. The fluid chemical composition strongly influences interfacial behavior and oil-mobilization mechanisms in chemical EOR systems (Daulay et al., 2025). Clean quartz-rich sandstone surfaces are generally considered to exhibit water-wet behavior unless altered by adsorption of polar crude oil components Anderson 1986; Denekas et al., 1960. Resins act as peptizing agents that stabilize asphaltenes in crude oil, preventing the formation of large aggregates that strongly adhere to rock surfaces and alter wettability Rudyk 2018; Kokal 2005.

Jumiati (2024) confirmed that chemical alteration of wettability significantly enhances oil recovery by accelerating spontaneous imbibition. However, the study focuses on neutral-wet and water-wet systems on carbonate rocks, leaving a gap in neutral-wet sandstone research. Unlike most previous nanofluid EOR studies, which typically investigate a single crude oil system, this study introduces a comparative framework by systematically evaluating nanosilica performance across two crude oils with distinct API gravity and SARA compositions. This dual-oil approach allows direct assessment of how crude oil characteristics influence nanosilica-induced wettability alteration and imbibition efficiency, a relatively underexplored phenomenon in sandstone systems. This focus provides new mechanistic insight into the coupled effects of oil composition and nanoparticle adsorption on EOR performance, thereby broadening the applicability of LHP nanosilica across a range of reservoir conditions.

Therefore, this study aims to evaluate the effect of LHP nanosilica on sandstone wettability and oil recovery using two crude oils with distinct API gravities. Unlike previous studies that often use a single oil type, this study employs a systematic comparative framework to assess how varying crude oil characteristics influence nanosilica performance. This approach provides new mechanistic insights into the coupled effects of oil composition and nanoparticle adsorption, broadening the practical applicability of LHP nanosilica in diverse reservoir conditions.

METHODOLOGY

The experimental design was developed to investigate the impact of LHP nanosilica on sandstone wettability alteration and oil recovery through spontaneous imbibition tests. The research utilized sandstone, which typically exhibits water-wet behavior in its clean state. Anderson, 1986; Morrow, 1995, A comprehensive characterization of fluids, rock materials, and nanoparticles was conducted to evaluate their influence on recovery performance.

Material

Nanosilica sample particle

The nanosilica used was an LHP-type hydrophilic fumed silica (commercially similar to AEROSIL® 200), with a typical BET specific surface area of around 200 m²/g, a primary particle size of ~12 nm, and a SiO_2 purity of≥99.8 wt%. The powder was dispersed in brine using mechanical stirring and ultrasonication before testing. Characterization was performed using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X - ray Fluorescence (XRF) to confirm its morphology and composition.

Fluids sample

Two light crude oil samples from Sumatra (Riau and Jambi fields) were used. Their properties, including API gravity and SARA composition, are summarized in Table 1 and Table 2. In this study, the crude oil from the Jambi field is referred to as Crude Oil A, while the crude oil from the Riau field is referred to as Crude Oil B. The brine used was saline water with a concentration of 5000 ppm.

Table 1. Oil sample characteristics

	Riau's crude oil (Crude oil B)	Jambi's crude oil (Crude oil A)
^{O} API 60°F	34-35	39-40
Viscosity 25°C		5,71 cP
Density 25°C	0,8106	0,8268 g/cm^3
C5-C100		5,9% wt.

Table 2. Oil report test laboratory results

Oil Composition Data						
No	Sample	Sample Type	Saturate	Aromatic	Resin	Asphaltene
			WR%			
1	Sampel A	Crude Oil	13.67	8.93	77.18	0.22
2	Sampel B	Crude Oil	48.73	17.72	27.57	5.98

The brine used in this study was saline water at 5000 ppm

Figure 1. LHP nanosilica sample

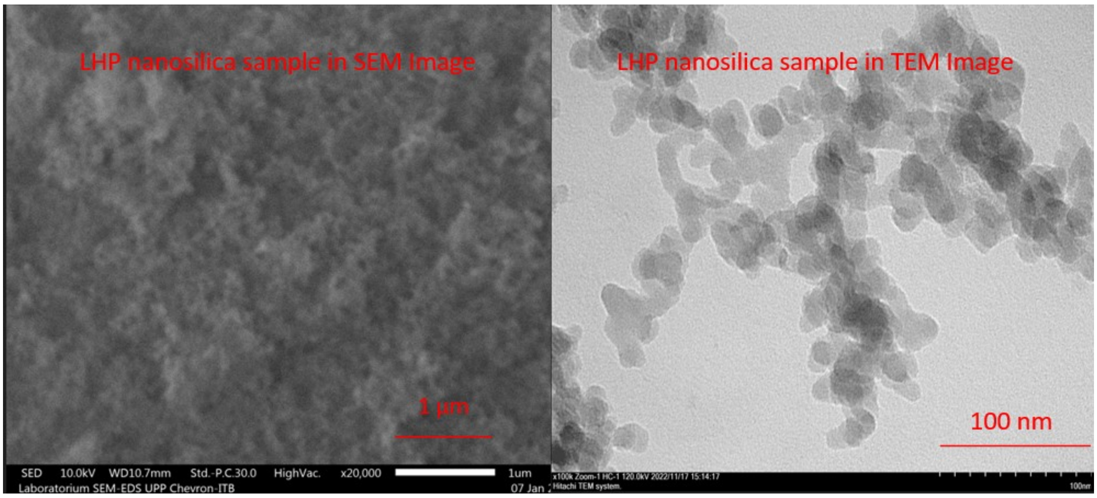

Figure 2. SEM and TEM images of LHP nanosilica

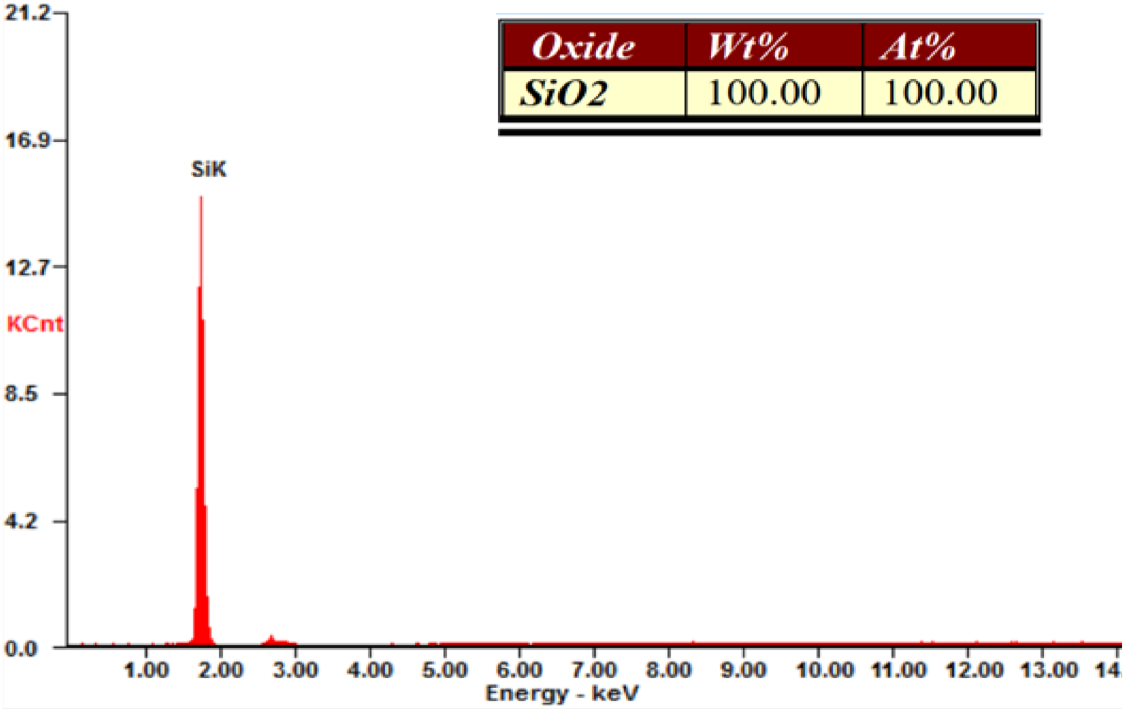

Figure 3. Silica content determined by XRF analysis

SARA analysis determined the composition of saturates, aromatics, resins, and asphaltenes, conducted by an accredited Oil and Gas Testing Center.

Rock sample

Unconsolidated sandstone (−100 mesh) collected from a coastal outcrop in Central Java was packed and prepared as the porous medium. XRF indicated silica-dominated composition (~96 wt.% SiO_2). Pre-conditioning with crude oils yielded initial Amott wettability indices of 0.05 and −0.02 for the two systems, indicating a neutral-wet condition. From Figure 5, the XRF analysis indicates that the oxide composition of the sandstone used in this study is dominated by silica, with a content of approximately 96 wt.% SiO_2.

Wettability measurements

The Amott Cell Wettability Index was used to measure the wettability index, as shown in Figure 5, based on the previous study methodology[2]. Meanwhile, the spinning drop tensiometer with a speed and temperature accuracy of ±3 rpm and ±0.5 °C (T X 500D, KINO, USA) was used to measure IFT at a reservoir temperature of 65 °C, as shown in Figure 6.

Oil recovery measurements

Oil recovery was evaluated using the spontaneous imbibition method. Sandstone samples were saturated with crude oil to determine the initial oil volume within the porous medium. Then, the samples were immersed in imbibition bottles containing a 0.1 wt/wt LHP nanosilica dispersion.

The spontaneous imbibition experiments were conducted under controlled experimental conditions at room temperature (approximately 25°C) and ambient pressure. The imbibition process was monitored for 2–5 days for Crude Oil A (Jambi) and 5–7 days for Crude Oil B (Riau). Each test was terminated when no additional oil or nanosilica fluid was produced from the rock, indicating that the system had reached maximum recovery equilibrium.

Figure 4. XRF Optical Image results of elemental composition in the sandstone sample

Oxide:	Net	Wt%
Al2O3	14.81268	2.866469
SiO2	860.3533	96.99720
K2O	0.87333	0.038036
CaO	0.93333	0.029854
TiO2	2.07333	0.034006
Fe2O3	4.29333	0.019237
Ni2O3	5.08000	0.015200
Total		100.0000

Figure 5. The XRF analysis of the sandstone rock sample

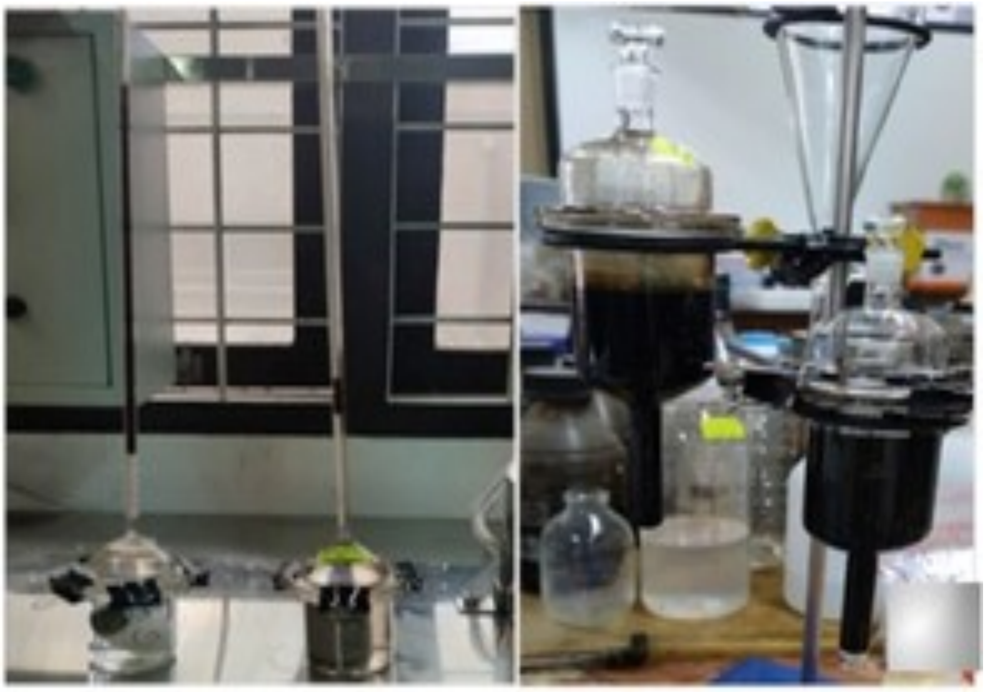

Figure 6. Amott cell measurement for wettability index

The oil recovery factor was calculated using the following Equation 1:

$$\%RF = \frac{V_o}{V_{0i}} x100 \quad (1)$$

where Vo is the volume of oil produced during imbibition (mL), and Voi is the initial oil volume in the porous medium (mL).

RESULT AND DISCUSSION

Figures 7 and 8 illustrate that the interaction between LHP nanosilica and sandstone results in distinct wettability changes depending on the oil's characteristics. Crude Oil A (Jambi) is classified as a lighter oil with a higher API gravity (39–40) and dominant resin content. In contrast, Crude Oil B (Riau) is a medium oil with a lower API gravity (34–35) and a higher saturate fraction.

Mechanisms of wettability alteration

Crude Oil A (light oil) exhibits a stronger wettability response, with the Wettability Index (WI) shifting from an initial 0.05 to 0.30 at a 0.3% nanosilica concentration. This pronounced shift is attributed to its lower viscosity and favorable resin-to-asphaltene ratio. Resins act as stabilizing agents, preventing asphaltenes from forming rigid, large-scale aggregates on rock surfaces. Consequently, the LHP nanosilica particles, rich in surface hydroxyl (–OH) groups, can more effectively penetrate and displace the thin organic oil film through competitive adsorption.

Sandstone saturated with Crude Oil A exhibits a positive initial Wettability Index (WI) value that is relatively close to neutral-wet conditions. This indicates that the rock surface is not completely dominated by oil but still maintains a balanced affinity between water and oil. Although Crude Oil A has a relatively higher resin fraction, its lower viscosity (higher API gravity) contributes to an initial condition that approaches neutral-wet behavior. Resins act as stabilizing agents for asphaltenes in crude oil, preventing the formation of large aggregates that strongly adhere to rock surfaces. The ratio of resins to non-polar fractions plays an important role in maintaining the stability of the oil colloidal system (Rudyk 2018).

In contrast, Crude Oil B shows a more moderate wettability shift, moving from -0.02 to 0.17. The higher heavy-fraction content and viscosity of Crude Oil B led to the formation of more stable, rigid organic films on mineral surfaces, creating a stronger chemical barrier that slows nanoparticle adsorption. This observation is consistent with Al-Anssari et al. (2021), who reported that while silica nanofluids effectively modify sandstone wettability by forming a resilient hydrophilic coating, the efficiency is directly influenced by the stability and thickness of the pre-existing oil film. In Figure 7 (Crude Oil A), the increase in WI from 0.05 → 0.13 → 0.28 → 0.30 demonstrates that higher LHP nanosilica concentrations result in a stronger shift toward water-wet conditions. This indicates the effectiveness of LHP nanosilica in modifying rock surface properties and reducing the oil-wet tendency of the initially neutral-wet system.

Similarly, in Figure 8 (Crude oil B), although the initial WI was in the oil-wet range (−0.02), the LHP nanosilica treatment increased the WI to 0.05, then to 0.15, and finally to 0.17, indicating a clear wettability shift toward water-wet conditions. This suggests that LHP nanosilica nanoparticles can restructure rock surface properties, even when a heavier initial oil saturation strongly influences the initial wettability. Another study has reported similar mechanisms in which silica nanoparticles enhance water-wetness by modifying surface energy and reducing the adhesion of native oil films to rock surfaces (Kazemzadeh 2019).

After treatment with LHP nanosilica, both systems exhibited an increase in WI toward more water-wet conditions. The mechanisms are explained as follows:

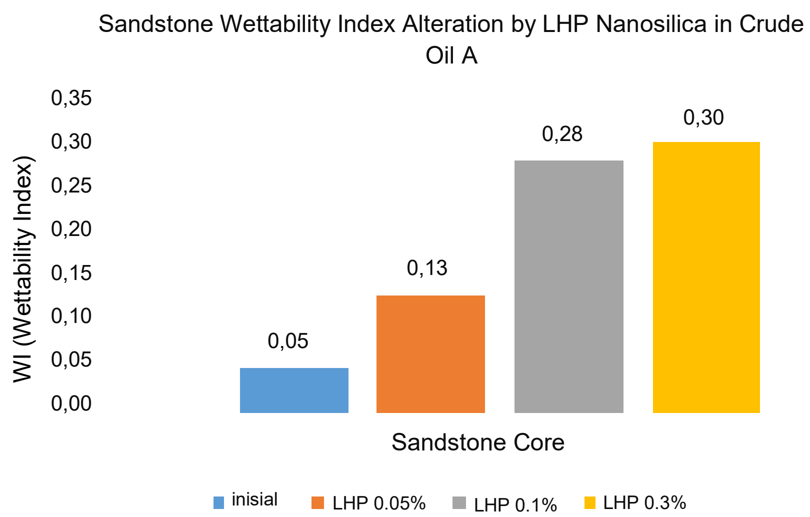

Figure 7. Sandstone wettability index alteration by LHP nanosilica using crude oil A

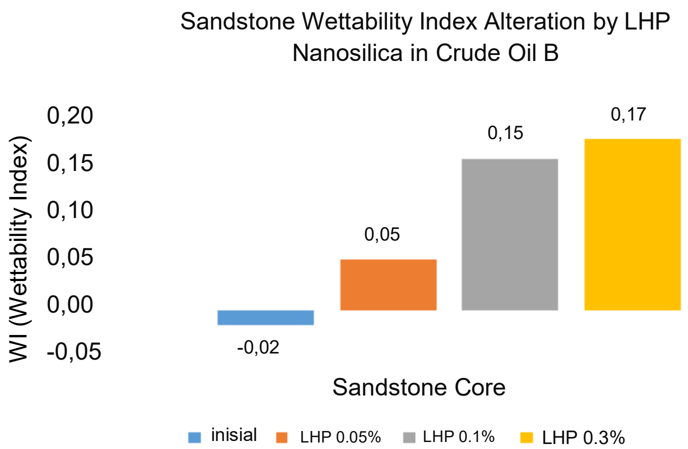

Figure 8. Sandstone wettability index alteration by LHP nanosilica using crude oil B

Silica nanoparticle adsorption

Silica nanoparticles, rich in surface hydroxyl (-OH) groups, adsorb onto rock surfaces and form a hydrophilic coating that replaces oil-wet organic films through competitive adsorption, leading to reduced contact angles and modified surface energy Hendraningrat & Torsæter 2016; Li et al., 2015.

Displacement of organic films

Polar oil components (resins and asphaltenes) previously attached to mineral surfaces can be displaced by nanoparticles through competitive surface adsorption. The effectiveness of chemical agents in modifying interfacial properties and improving displacement efficiency in sandstone reservoirs has also been demonstrated in core-scale studies (Tobing 2016).

Surface energy modification

The nanosilica layer increases the rock's affinity toward water, reduces the oil contact angle, and shifts the system toward water-wet conditions. This phenomenon is consistent with studies on the interaction between heavy oil components and rock surfaces, where a reduction in the adsorption of polar components leads to an increase in water-wetness (Li et al., 2015).

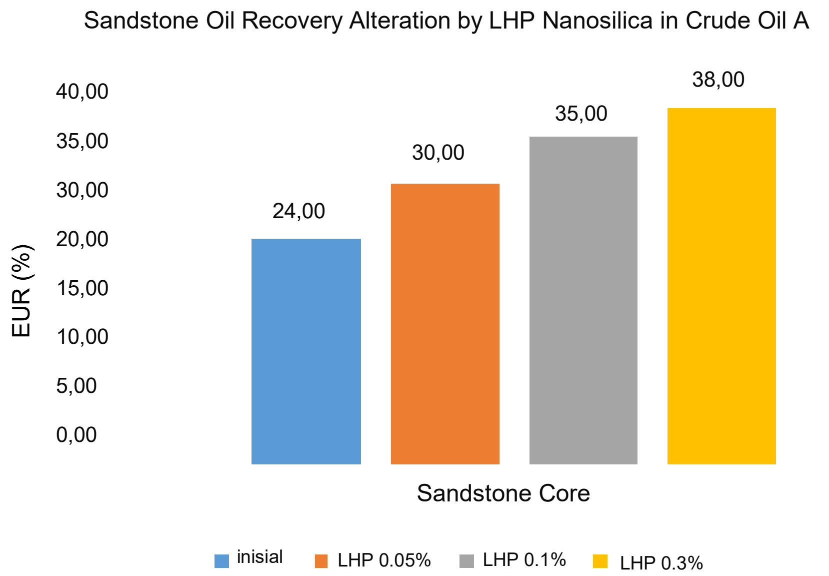

Figure 9. Sandstone oil recovery alteration by LHP nanosilica using crude oil A

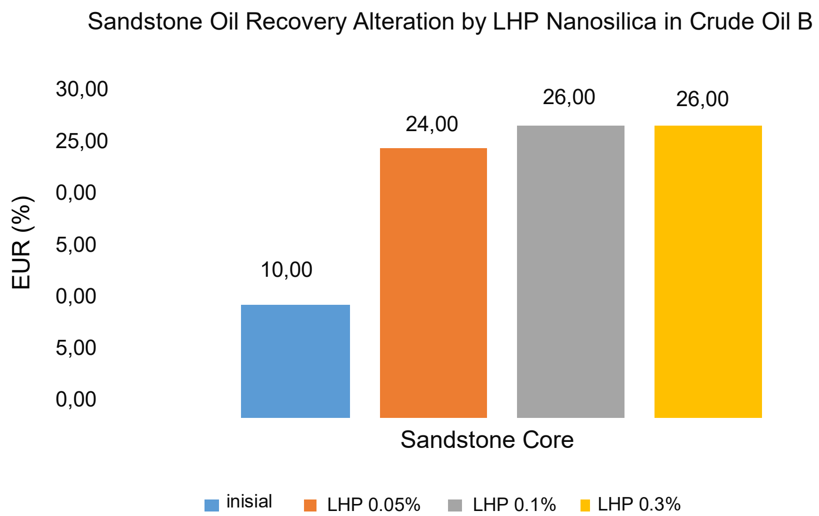

Figure 10. Sandstone oil recovery alteration by LHP nanosilica using crude oil B

Oil recovery performance and imbibition efficiency

The increase in WI is directly proportional to the increase in the Oil Recovery Factor (ORF). Crude Oil A achieved a significantly higher recovery of 38% within a shorter duration of 2 to 5 days. This rapid recovery is driven by the swift transition toward water-wet conditions, which enhances the positive capillary pressure gradients that drive spontaneous imbibition. In water-wet systems, positive capillary pressure gradients drive spontaneous imbibition by allowing water to preferentially enter smaller pores while displacing oil from larger pores (Jadhunandan & Morrow 1995).

Crude Oil B reached a lower maximum recovery of 26% and required a longer duration of 5 to 7 days to reach equilibrium. Even though wettability alteration occurs, the release of trapped oil is slower due to the mechanical and chemical stability of the native oil films in medium-gravity crude. The faster and higher recovery in the lighter oil system confirms that crude oil composition—specifically API gravity and SARA fractions—is a primary controlling factor in nanofluid EOR design.

A direct relationship between wettability alteration and oil recovery has also been reported by Mehrabi and Mohammadzadeh (2021), who demonstrated that Silica nanoparticles reduce crude oil adhesion forces and promote water-wetness by modifying rock surface energy (Mehrabi & Mohammadzadeh 2021).

These findings confirm that crude oil composition is a key controlling factor in the design of nanofluid EOR. In lighter oils, wettability modification occurs more readily, allowing lower nanoparticle concentrations to be effective. In heavier oils, optimizing nanoparticle concentration or using hybrid systems (e.g., with surfactants) may be required to overcome more stable organic films.

Furthermore, these results contribute to a better understanding of neutral-wet sandstone systems, which have previously received limited attention in nanofluid EOR studies.

CONCLUSION

LHP nanosilica treatment effectively shifts sandstone wettability from neutral/oil-wet toward water-wet conditions through nanoparticle adsorption and the displacement of organic oil films.

Crude Oil A (light oil) exhibited a stronger wettability response and greater recovery improvement (38% in 2–5 days) compared to the heavier Crude Oil B (26% in 5–7 days). The increase in oil recovery correlates directly with the increase in wettability index, demonstrating that wettability alteration is the dominant EOR mechanism of nanosilica in this system.

The chemical composition of crude oil is a key parameter in determining the effectiveness of nanofluid-based EOR. Design of nanofluid EOR in sandstone should account for oil composition; lighter oils may require lower nanoparticle dosages, whereas heavier oils may benefit from higher concentrations or hybrid formulations.

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GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
API	American petroleum institute gravity	°API
WI	Wettability index	-
ORF	Oil recovery factor	%
EOR	Enhanced oil recovery	-
IFT	Lipophobic–hydrophilic polysilicon	mN/m

LHP	Lipophobic–hydrophilic polysilicon	-
SARA	Saturates, Aromatics, Resins, and Asphaltenes	-

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