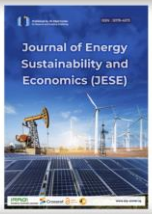
Journal of Energy Sustainability and Economics 1 (2026) 28-46

Al-Sibd Center
for Research and Scholarly Publishing

Journal of Energy Sustainability and Economics (JESE)

Journal Homepage : https://jese.srp-center.iq/



Role of Nanoparticles in EOR: Comparative Efficiency of Al_2O_3 and TiO_2

Murtadha Waheed Khawwam[1], Abdullah Majid Abdulhameed[2], Hussien Ali Kazem[2] , M. Sadeq Adnan[2], Mohammed Jaafar[2]

[1] Oil and Gas Engineering Department, University of Warith Al-Anbiyaa, Kerbala 56001, Iraq.

[2]Department of Petroleum Engineering, University of Kerbala, Kerbala 56001, Iraq.

Corresponding Author : murtadha.wa@uowa.edu.iq

Keywords:

Enhanced Oil Recovery (EOR); Nanoparticles; Interfacial Tension (IFT) Reduction; Nanomaterials; Oil Displacement Efficiency; Wettability Alteration;

Abstract

Nanotechnology has emerged as a promising approach to improve oil recovery by altering rock–fluid interactions and reducing interfacial resistance. This study investigates the effects of aluminum oxide (Al_2O_3) and titanium dioxide (TiO_2) nanoparticles on two critical parameters: wettability alteration and interfacial tension (IFT) reduction. Al_2O_3 nanoparticles were synthesized in the laboratory using the precipitation method, while commercial TiO_2 nanoparticles were employed for comparison. Nanofluids with varying concentrations were prepared and tested under controlled laboratory conditions, with performance evaluated over different exposure times. The results demonstrate that both Al_2O_3 and TiO_2 nanofluids effectively shifted rock surfaces toward more water-wet conditions, enhancing their potential for improved oil displacement. Al_2O_3 nanofluids showed optimal wettability alteration at 400 ppm after 24 hours, although efficiency declined at higher concentrations (1000 ppm) due to nanoparticle agglomeration. TiO_2 nanofluids achieved optimal wettability improvement at 800 ppm after 24 hours and displayed greater consistency across concentrations. In terms of IFT, both nanoparticles reduced interfacial tension significantly, with TiO_2 achieving the lowest value of 15.826 mN/m at 1000 ppm. Overall, TiO_2 nanofluids exhibited more stable and effective behavior, highlighting their suitability for enhanced oil recovery (EOR) applications.

Introduction

Hydrocarbons are poised to remain a cornerstone of the global energy supply chain and are projected to continue as the dominant energy source in the coming decades. However, the majority of oil fields worldwide have already entered—or are approaching—their natural decline phase, despite the fact that a significant portion of the original oil in place (OOIP) remains unrecovered. According to the U.S. Department of Energy, as much as 67% of the total oil in the United States will remain trapped in reservoirs due to the limitations of conventional recovery technologies [1]. In the absence of widely available, low-cost, and reliable renewable energy alternatives, research on enhanced oil recovery (EOR) methods has become increasingly critical to ensure improved recovery factors from hydrocarbon reservoirs. Multiple rate transient analysis (RTA) techniques have proven useful in characterizing unconventional reservoir performance, providing insights that can support more effective EOR strategies [46].

Over the years, a broad range of EOR techniques—thermal, miscible, and chemical methods—have been successfully implemented to enhance recovery efficiency, alongside emerging methods such as microbial and low-salinity flooding, Polymer flooding [49]. More recently, nanoparticles and nanotechnology have gained prominence as promising candidates for EOR applications, given their ability to penetrate pore throats and significantly alter reservoir properties in ways that enhance hydrocarbon recovery [1,2]. Laboratory investigations have demonstrated that surface-modified silica nanoparticles can stabilize emulsions and improve mobility control during flooding processes [3,4]. Furthermore, nanoparticles have been shown to alter rock wettability and reduce interfacial tension, two mechanisms widely recognized as critical for improving displacement efficiency. Parameters such as nanoparticle size, concentration, ionic composition, and type have all been studied with respect to their influence on oil recovery [5,6].

Nanoparticles, generally defined as particles ranging from 1 to 100 nm, can be composed of carbon, metals, metal oxides, or organic materials [7]. At this scale, they exhibit distinctive physical, chemical, and biological properties that differ significantly from their bulk counterparts. These properties—attributable to their high surface area-to-volume ratio, increased chemical reactivity, enhanced stability, and improved mechanical strength—confer nanoparticles with unique advantages in engineering applications [8]. Variations in particle size, shape, and morphology further expand their functional potential [9].

As a rapidly evolving frontier of science and technology, nanotechnology has impacted a wide range of disciplines. Petroleum engineering, like other industries, is compelled to adapt to these advancements in order to optimize efficiency and maximize resource utilization. Given that only 30–50% of the original oil reserves are typically recoverable through primary and secondary recovery mechanisms, the substantial volume of residual oil underscores the critical importance of EOR technologies. The application of nanoparticles for EOR purposes thus emerges as a promising avenue for increasing oil recovery and maximizing the economic return from hydrocarbon reservoirs.

Nanoparticles

2.1 Synthesis of Nanoparticles

A wide range of synthesis methods are currently being developed or optimized to improve nanoparticle A wide range of synthesis methods are currently being developed or optimized to improve nanoparticleproperties while simultaneously reducing production costs. In some cases, these methods are specifically modified to produce application-oriented nanoparticles with enhanced optical, mechanical, physical, and chemical characteristics [9]. Generally, nanoparticle synthesis techniques are classified into two main categories: bottom-up and top-down approaches. A simplified illustration of these processes is provided in Figure 1.

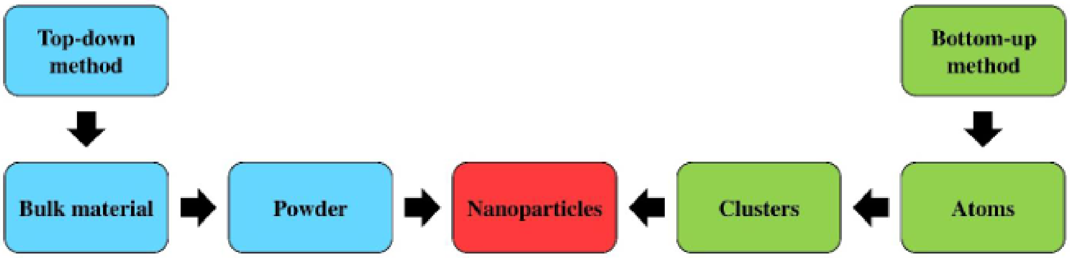


Figure 1: Synthesis Process [43]

Bottom-up method

The bottom-up or constructive method builds nanoparticles from atoms to clusters. Common techniques include sol-gel, spinning, chemical vapor deposition (CVD), pyrolysis, and biosynthesis.

Sol-gel: A widely used wet-chemical process where colloidal solutions act as precursors, typically metal oxides or chlorides. It is favored for its simplicity and versatility [12].

Spinning: Utilizes a spinning disc reactor (SDR) under controlled conditions with inert gases to prevent unwanted reactions [13].

Chemical Vapor Deposition (CVD): Produces uniform, pure, and strong nanoparticles by depositing gaseous reactants onto heated substrates, though it requires specialized equipment and generates toxic by-products [11,14].

Pyrolysis: An industrial-scale process in which precursors are combusted under high pressure to yield nanoparticles; valued for its efficiency, cost-effectiveness, and high yield [15].

Biosynthesis: An eco-friendly approach using biological agents such as bacteria, fungi, or plant extracts for nanoparticle formation, offering non-toxic and biodegradable products [16].

Top-down method

The top-down, or destructive, approach reduces bulk materials into nanoscale particles. Common techniques include mechanical milling, nanolithography, laser ablation, sputtering, and thermal decomposition.

Mechanical Milling: The most widely applied method, involving milling and post-annealing of elements in an inert atmosphere to produce nanoparticles [15].

Nanolithography: A patterning technique on light-sensitive materials that enables precise control of nanoparticle size and shape, though it requires complex and costly equipment [17].

Laser Ablation: Involves irradiating a metal submerged in liquid with a laser beam, generating plasma plumes that condense into nanoparticles [18].

Thermal Decomposition: Uses heat to break chemical bonds at defined decomposition temperatures, producing nanoparticles along with secondary products [10].

Applications of Nanoparticles In Petroleum Industry

Nanoparticles (NPs) have multiple applications in the petroleum industry, including enhanced oil recovery (EOR), drilling improvement, and reservoir tracing. Studies have shown that their use can significantly increase oil production [19]. In EOR, engineered NPs are introduced with injection fluids to enhance recovery efficiency [20]. While their application across different EOR methods presents some challenges, NPs are highly promising due to their unique properties and transport behavior [21]. Moreover, combining NPs with conventional EOR techniques can create synergistic effects that strengthen the performance of the main recovery mechanisms, as illustrated in Figure 2, imilar to recent research in renewable energy, which demonstrated the potential of ground-coupled heat exchangers (GHEs) to enhance photovoltaic system efficiency through design and material optimization, the petroleum industry can likewise benefit from nanotechnology applications to address efficiency challenges [50].

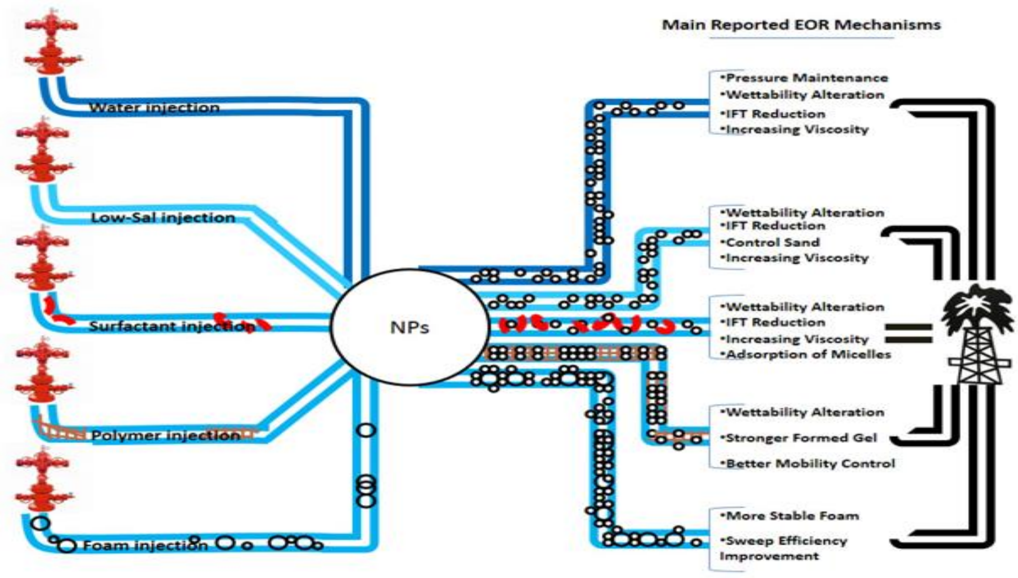


Figure 2: Schematic illustration of the main advantages of using NPs in EOR procedures illustrates some main advantages of using NPs in EOR procedures based on the results of the literature review [44].

In support of these insights, several studies have reported the effective use of nanoparticles and nanocomposites in various EOR applications. A summary of selected research highlighting their mechanisms, experimental conditions, and outcomes is provided in Table 1, which demonstrates the growing potential of nanotechnology in improving oil recovery processes. Furthermore, recent research on unconventional reservoirs has emphasized the importance of advanced EOR methods, such as miscible gas injection, in enhancing oil recovery efficiency, particularly in shale oil formations [48].

Table 1: Summary of studies on the application of nanoparticles and nanocomposites in enhanced oil recovery (EOR)

Author and year	**Type of Nanoparticles (NPs)**	**EOR Mechanism(s) Addressed**
Li et al. 2017 [26]	Silica	Wettability alteration
Jafarn ezhad et al. 2017 [27]	SnO_2	Wettability alteration IFT reduction
Hu et al. 2017 [28]	Synthesized iron oxide	Increase viscosity of injected fluid IFT reduction Stable microemulsions
Kazemzadeh et al. 2018 [29]	(nanocomp-osites) TiO_2/SiO_2 Fe_3O_4/SiO_2	Wettability alteration IFT reduction Lowering viscosity Asphaltene adsorption
Al-Anssari et al. 2018 [30]	Hydrophilic silica	Wettability alteration
Hogeweg et al. 2018 [31]	Al_2O_3, TiO_2	Mobility control IFT reduction
Gomari et al. 2019 [41]	Silica Al_2O_3	Wettability alteration
Dahkaee et al. 2019 [42]	NiO, silica and NiO/SiO_2 (nanocomposites)	Wettability alteration IFT reduction
Kanj et al. 2020 [32]	Carbon nanodots	Wettability alteration
Wu et al. 2020 [33]	Janus silica	Wettability alteration IFT reduction Mobility control (Increase in interfacial shear viscosity)
Ahmed et al. 2020 [34]	Surface-modified silica, pure silica	Wettability alteration IFT reduction Increasing viscosity of injected phase
Zargar et al. 2020 [35]	SiO_2/quartz (nanocomposite)	Wettability alteration IFT reduction
Khademolhosseini et al. 2020 [36]	Synthesized silica (different morphologies)	Wettability alteration IFT reduction
Minakov, A., et al. 2021[37]	silicon and aluminum oxides	Wettability alteration IFT reduction
Jafarbeigi et al. 2021[38]	Modified graphene oxide	Wettability alteration IFT reduction
Ngouangna, E. N., et al. 2022 [39]	hydroxyapatite nanoparticles	Wettability alteration IFT reduction
Nowrouzi, I., et al. 2022 [40]	MgO γ-Al_2O_3 TiO_2	Wettability alteration IFT reduction Spontaneous Imbibition

Mechanisms of Nanoparticles Based EOR

Nanoparticles (NPs) can enhance oil recovery through multiple mechanisms. By leveraging their unique properties, NPs improve both microscopic and macroscopic aspects of EOR, including wettability alteration, interfacial tension (IFT) reduction, pore blockage, flow diversion, dispersion and stabilization, and viscosity modification. Overall, NPs optimize multiphase flow, enabling the mobilization of trapped oil and improving the efficiency of the flooding process. Similar enhancements in system performance have also been demonstrated through innovative material-based cooling applications in energy systems [47].

Wettability Alteration

Wettability is defined as the tendency of a fluid to spread over or adhere to a solid surface in the presence of another immiscible fluid. Generally, it describes the preference of a solid to contact one fluid over another, i.e., wetting versus non-wetting fluid. In the context of EOR, when water preferentially adheres to the reservoir rock in the presence of oil, water and oil are considered the wetting and non-wetting phases, respectively. Reservoir rock can be classified as water-wet, mixed-wet, neutral-wet, or oil-wet depending on factors such as initial hydrocarbon deposition, fluid interactions, rock mineralogy, pore structure, and surface roughness. Contact angle is commonly used to quantify rock wettability: a water contact angle below 90° indicates a water-wet system, above 90° an oil-wet system, and 90° a neutral-wet system. Wettability is a key reservoir property influencing EOR efficiency—particularly chemical EOR—by affecting capillary pressure, relative permeability, dispersion, and irreducible oil saturation.

Recent studies have highlighted the significant role of nanoparticles (NPs) in wettability alteration. Depending on their surface properties, NPs can adsorb onto the rock surface and stabilize a water layer, shifting the rock wettability toward water-wetness [20]. Injection of NP-based fluids can convert oil-wet rock to water-wet or more water-wet conditions, mobilizing adsorbed oil and enhancing recovery. The selection of NPs must consider the reservoir type (sandstone or carbonate) to ensure favorable wettability alteration and effective nanofluid transport with minimal particle loss [22,23].

Furthermore, smaller NPs generate higher disjoining pressure due to stronger repulsive forces, enhancing adsorption and precipitation. Figure 3 schematically illustrates wettability alteration by NPs, showing that adsorption of NPs on rock surfaces creates new interfaces and significantly reduces the water contact angle.

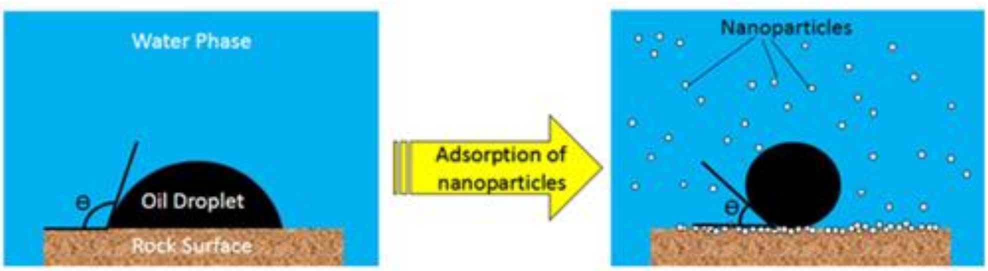


Figure 3: Wettability Alteration Due To Adsorption Of Nanoparticles On The Surface Of Rock [44]

Interfacial Tension Reduction

Interfacial tension (IFT) is the surface free energy existing between two immiscible fluids. Reducing the oil-water IFT increases the capillary number, which is the ratio of viscous to capillary forces and a key requirement for EOR [24]. As shown in Figure 4, at high IFT values, oil droplets cannot pass through pore throats. However, lowering the IFT allows the droplets to move through the pores, mobilizing trapped oil ganglia in the reservoir. In other words, low oil-water IFT is a favorable condition for enhanced oil recovery. Due to their surface-active properties, nanoparticles can adsorb at the oil-water interface, further reducing the system's surface free energy. The degree of NP adsorption at the interface depends on their hydrophobicity and hydrophilicity.

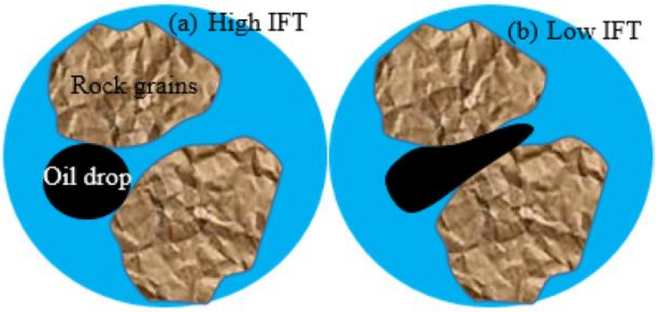


Figure 4: (a) Simple representation of trapped oil at high oil-water IFT and (b) mobilization of that trapped oil at low oil-water IFT [45]

Some studies have shown that the IFT initially increases with rising NP concentration up to a certain point, after which it decreases as the concentration continues to rise. Other findings indicate that IFT in the presence of NPs can be higher than in their absence. Research has also demonstrated that the effectiveness of NPs in reducing IFT can be influenced by the type of base fluid, such as water, surfactant solutions, saline water, or brine, at varying concentrations [25]. Nevertheless, researchers are still working to achieve significant IFT reduction using only NPs by modifying the surface properties of bare nanoparticles, such as with Janus NPs.

Wettability and IFT Modification by Nanoparticles

In this section, the synthesis of nanoparticles using the precipitation method, their properties, and the results of wettability and interfacial tension (IFT) tests are presented and discussed. Nanotechnology has recently emerged as a promising approach in enhancing oil recovery, particularly through the use of nanoparticles to modify rock–fluid interactions. In this study, aluminum oxide (Al_2O_3) nanoparticles were synthesized via the precipitation method and characterized to evaluate their physical and surface properties, while commercial titanium dioxide (TiO_2) nanoparticles were employed for comparative analysis.The prepared nanofluids were tested to examine their influence on two key parameters: contact angle (wettability) and interfacial tension (IFT), across different nanoparticle concentrations. These experiments were conducted under controlled conditions to compare the performance of both nanoparticle types. The results are discussed comparatively to identify which material demonstrates greater efficiency in enhancing oil recovery.

Impact of Nanoparticles on Wettability Alteration

To assess the effect of nanofluids on wettability, the contact angle of a crude oil droplet in deionized water was first measured to establish a baseline. This reference value was then compared with the contact angle obtained when the same oil droplet was immersed in the nanofluid. Such a comparison allows for a clear evaluation of the nanofluid's influence on wettability alteration.

Using the Inverted Sessile Drop Method, the contact angle of a crude oil droplet in deionized water was found to be approximately 91.676°, as shown in Figure 5. This value reflects a nearly neutral wettability state, where the crude oil droplet exhibits no strong affinity toward either the solid surface or the surrounding water. In this intermediate condition, the system lies between water-wet and oil-wet states.

This baseline measurement is critical, as any notable reduction in contact angle after introducing the nanofluid would indicate a shift toward a more water-wet state. Such a change implies enhanced wettability alteration, demonstrating the effectiveness of nanoparticles in modifying rock–fluid interactions.

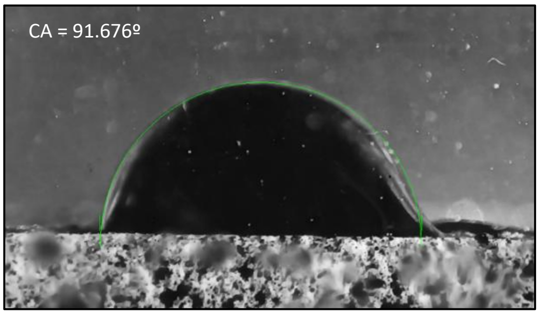


Figure 5: Contact Angle For Crude Oil Droplet In The Deionized Water

Initial Contact Angle Measurements Without Considering Time Effect

Initial contact angle measurements were conducted immediately after placing the oil droplet onto the nanofluid medium, without allowing any interaction time between the fluid and the rock surface. At a concentration of 200 ppm, the Al_2O_3 nanofluid exhibited a contact angle of 60.000°, whereas the TiO_2 nanofluid at the same concentration showed a higher value of 83.621°. These results reflect the initial wettability state, prior to the influence of any time-dependent interactions on contact angle behavior, as illustrated in Figure 6.

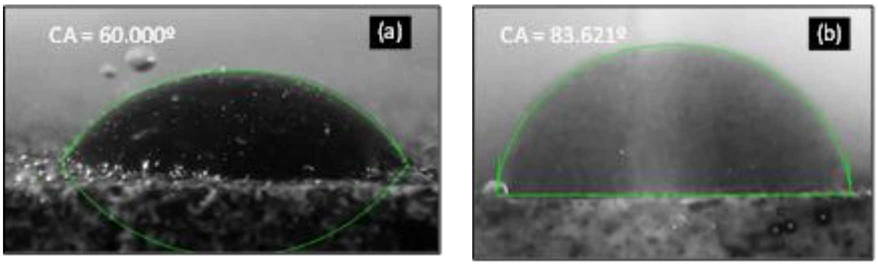


Figure 6: Initial contact angle measurements at 200 ppm: (a) Al_2O_3 nanofluid, (b) TiO_2 nanofluid

After completing all contact angle measurements, the results were summarized in Table 2 for both Al_2O_3 and TiO_2 nanoparticles.

Table 2: Contact Angle Measurement Results for TiO_2 And Al_2O_3

NP types	**Concentration of NP (ppm)**	**Contact angle (degree)**	**Time (hr)**
Al_2O_3	200	53.684°	1
		28.646°	3
		33.528°	6
		28.838°	24
	400	25.693°	24
	600	34.583°	24
	800	35.667°	24
	1000	71.281°	24
TiO_2	200	55.230°	1
		47.289°	3
		62.697°	6
		41.984°	24
	400	51.855°	24
	600	41.819°	24
	800	28.031°	24
	1000	39.325°	24

Contact Angle Behavior of Al_2O_3 Nano-Fluid Over Time

Initial contact angle measurements were performed using an Al_2O_3 nanofluid at a concentration of 200 ppm over different time intervals (1, 3, 6, and 24 hours) to evaluate the progression of wettability alteration. As shown in Figure 7, the most pronounced reduction in contact angle occurred within the first 3 hours, reflecting a rapid transition toward a more water-wet state. The contact angle decreased from 53.684° at 1 hour to 28.646° after 3 hours, confirming a fast and effective wettability shift. A slight increase was observed at 6 hours (33.528°), possibly due to minor variations in nanoparticle distribution on the rock surface or a temporary equilibrium between the fluid and surface. However, after 24 hours the contact angle decreased again to 28.838°, indicating the establishment of a stable water-wet condition induced by the presence of Al_2O_3 nanoparticles.

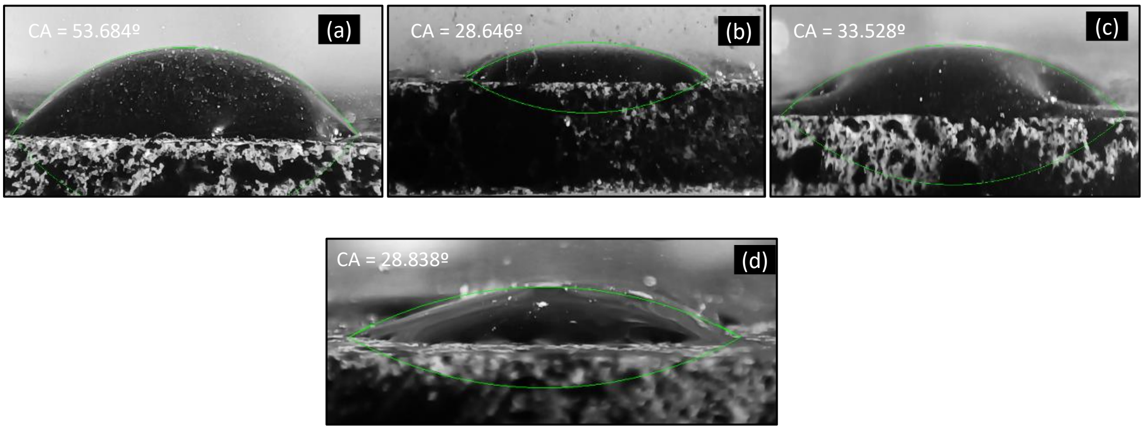


Figure 7: Contact angle of crude oil droplets in Al_2O_3 nanofluid (200 ppm) at different time intervals: (a) 1 hr, (b) 3 hrs, (c) 6 hrs, (d) 24 hrs.

Based on these observations, the 24-hour interval was selected as the standard measurement time for subsequent experiments with higher Al_2O_3 concentrations (400, 600, 800, and 1000 ppm). This period was chosen because it represents a stabilized system, capturing the final influence of nanoparticles on rock wettability and ensuring consistency across different concentrations. When the concentration increased from 200 to 400 ppm, a slight further decrease in contact angle was recorded, indicating improved wettability. However, at 600 and 800 ppm, the contact angle began to rise again, suggesting saturation or agglomeration effects that reduced nanoparticle efficiency. At 1000 ppm, the contact angle increased sharply to 71.281°, indicating a reversal in wettability behavior, likely caused by excessive nanoparticle accumulation on the rock surface, which limited effective interaction or created a barrier layer that hindered water-wet conditions.

Contact Angle Behavior of TiO_2 Nanofluid Over Time

Contact angle measurements were performed using a TiO_2-based nanofluid at a concentration of 200 ppm over time intervals of 1, 3, 6, and 24 hours, as shown in Figure 8. At 1 hour, the initial contact angle was 55.230°, reflecting a moderately water-wet surface. After 3 hours, the contact angle decreased to 47.289°, indicating enhanced water-wettability. Interestingly, a temporary rise in contact angle to 62.697° was observed at 6 hours, which could be associated with the transient redistribution of nanoparticles on the rock surface or temporal variations in the fluid–rock interactions. By 24 hours, the contact angle further decreased to 41.984°, demonstrating a shift toward a more strongly water-wet condition in the long term.

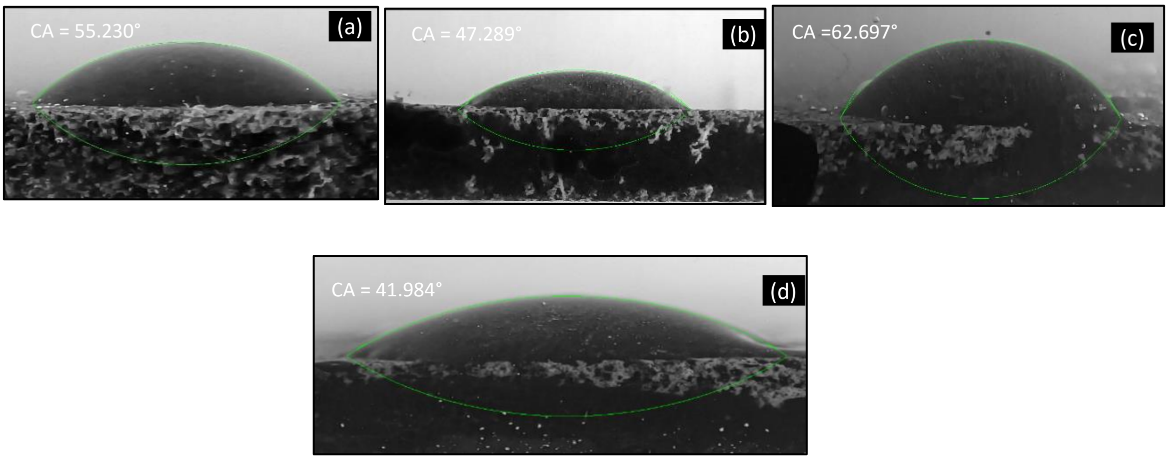


Figure 8: Contact angle of crude oil droplets in TiO_2 nanofluid (200 ppm) at different time intervals: (a) 1 hr, (b) 3 hrs, (c) 6 hrs, (d) 24 hrs.

These observations indicate that the 24-hour interval serves as a reliable reference point for evaluating the final wettability state of TiO_2 nanofluids, ensuring consistency with Al_2O_3-based experiments and capturing the stabilized nanoparticle–rock interactions. The results further show that increasing the concentration from 400 ppm to 800 ppm led to a gradual reduction in contact angle, reaching its lowest value at 800 ppm, which reflects improved nanofluid spreading and stronger surface interactions. At 1000 ppm, however, the contact angle increased to 39.325°, likely due to nanoparticle agglomeration or saturation effects that limit surface efficiency.

Impact of Nanoparticles on interfacial tension (IFT)

To evaluate the influence of the nanofluid on interfacial tension (IFT), an initial measurement was performed between crude oil and deionized water to establish a baseline reference. This value was subsequently compared with the IFT results obtained when crude oil was in contact with the nanofluid. Such a comparison provides a clear indication of the nanofluid's effectiveness in lowering interfacial tension and improving fluid interaction behavior. The baseline IFT of the crude oil droplet in deionized water was measured at 36.432 mN/m, as shown in Figure 8.

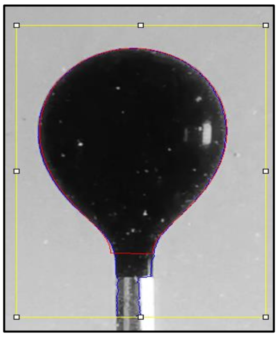


Figure 9: Interfacial tension (IFT) measurement of an oil droplet using the pendant drop method analyzed with ImageJ.

Upon completion of all tests for both Al_2O_3 and TiO_2 nanofluids, the summarized results are presented in Table 3.

Table 3: IFT Measurement Results for TiO_2 And Al_2O_3

NPs type	Concentration of NPs (ppm)	Surface tension(mN/m)
Al_2O_3	200	29.423
	400	24.890
	600	22.178
	800	25.169
	1000	18.558
TiO_2	200	25.754
	400	21.319
	600	23.892
	800	19.130
	1000	15.826

Interfacial Tension Results for Al_2O_3 Nano- Fluid

The interfacial tension (IFT) values of Al_2O_3 nanofluids at various concentrations are summarized in Table 3. Overall, the results demonstrate a general decline in IFT with increasing concentration, accompanied by slight fluctuations at intermediate levels. At 200 ppm, the IFT decreased to 29.423 mN/m compared to the baseline value of 36.432 mN/m. A further reduction was observed at 400 ppm, where the IFT reached 24.890 mN/m. The lowest intermediate value occurred at 600 ppm with 22.178 mN/m. At 800 ppm, a slight increase was recorded, with the IFT rising to 25.169 mN/m. Finally, at 1000 ppm, the IFT decreased significantly to 18.558 mN/m, representing the most effective reduction in interfacial tension. Figure 10 illustrates the changes in oil droplet shape at different nanofluid concentrations, visually reflecting the impact of concentration on interfacial properties and providing supportive evidence for the observed IFT behavior.

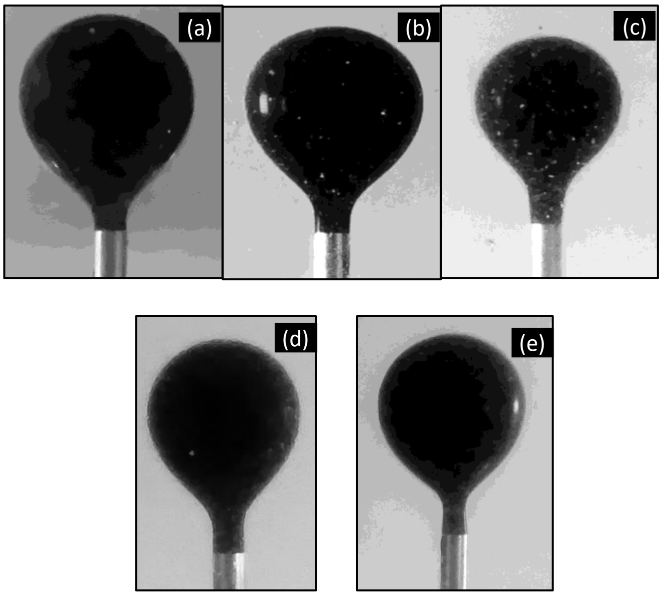


Figure 10: Interfacial tension (IFT) measurements of Al_2O_3 nanofluids at different concentrations: (a) 200 ppm, (b) 400 ppm, (c) 600 ppm, (d) 800 ppm, and (e) 1000 ppm.

These results suggest that Al_2O_3 nanoparticles are effective in lowering IFT, especially at higher concentrations, although some non-linearity in behavior was observed.

Interfacial Tension Results for TiO_2 Nano-Fluid

The IFT values of TiO_2 nanofluids exhibited a more consistent and nearly linear reduction trend with increasing concentration. At 200 ppm, the IFT measured 25.754 mN/m, followed by a further decrease to 21.319 mN/m at 400 ppm. A slight increase was observed at 600 ppm, with a value of 23.892 mN/m, although still lower than the baseline. A notable reduction occurred at 800 ppm, where the IFT dropped to 19.130 mN/m. The lowest value was recorded at 1000 ppm, reaching 15.826 mN/m, indicating that TiO_2 nanofluids were overall more effective than Al_2O_3 in reducing interfacial tension. Figure 11 illustrates the changes in oil droplet shape at different concentrations, visually highlighting the impact of TiO_2 nanofluids on interfacial properties and supporting the observed IFT behavior.

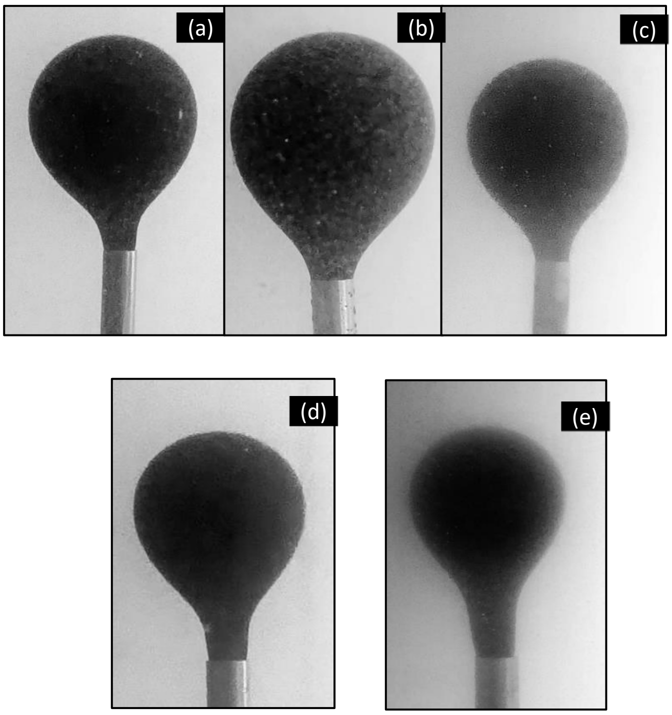


Figure 11: Interfacial tension (IFT) measurements of TiO2 nanofluids at different concentrations: (a) 200 ppm, (b) 400 ppm, (c) 600 ppm, (d) 800 ppm, and (e) 1000 ppm.

This trend highlights the strong performance of TiO_2 nanoparticles in interfacial tension reduction, especially at higher concentrations, with minimal fluctuation.

Conclusions

This research highlights the effectiveness of nanotechnology in enhancing oil recovery by modifying rock–fluid interactions through wettability alteration and interfacial tension (IFT) reduction. The comparative evaluation of laboratory-synthesized aluminum oxide (Al_2O_3) and commercially available titanium dioxide (TiO_2) nanoparticles demonstrated that both nanofluids can improve reservoir conditions, with TiO_2 showing more consistent and efficient behavior. The main conclusions are summarized as follows:

Al_2O_3 nanoparticles were successfully synthesized using the precipitation method, with FE-SEM confirming an average particle size of ~41.8 nm.

Al_2O_3 nanofluids improved rock wettability toward more water-wet conditions, with the best performance at 400 ppm after 24 hours.

At higher concentrations (1000 ppm), Al_2O_3 nanofluids showed reduced efficiency due to nanoparticle agglomeration.

TiO_2 nanofluids enhanced wettability, with optimal results observed at 800 ppm after 24 hours.

Both nanofluids contributed to significant IFT reduction, though TiO_2 achieved superior performance, reaching 15.826 mN/m at 1000 ppm.

Nanoparticle concentration and exposure time were identified as key factors controlling nanofluid efficiency.

TiO_2 nanofluids exhibited more stable and consistent behavior across different concentrations, suggesting higher suitability for field applications.

Nomenclatures

NPs Nano-Particles

EOR Enhanced Oil Recovery

OOIP Original Oil in Place

Nm Nano meter

CNT Carbon Nano Tubes

CVD Chemical Vapour Deposition

IFT Interfacial Tension

IONPs Iron Oxide Nano-Particles

MEs Microemulsions

PEO Poly Ethylene Oxide

PEG Polyethylene Glycol

HAP Hydroxyapatite

SDS Sodium Dodecyl Sulfate

TEM Transmission Electron Microscopy

EDX Energy Dispersive X-ray

CA Contact Angle

Conflicts of interests

There are no identified conflicts of interest associated with this research. Additionally, we confirm that no substantial financial support was received for the completion of this work.

References

[1] Kong, X., & Ohadi, M. M. (2010, November). Applications of micro and nano technologies in the oil and gas industry-an overview of the recent progress. In Abu Dhabi international petroleum exhibition and conference (pp. SPE-138241). SPE. https://doi.org/10.2118/138241-ms

[2] Guo, K., Li, H., & Yu, Z. (2016). In-situ heavy and extra-heavy oil recovery: A review. Fuel, 185, 886-902. https://doi.org/10.1016/j.fuel.2016.08.047

[3] Zhang, T., Roberts, M. R., Bryant, S. L., & Huh, C. (2009, April). Foams and emulsions stabilized with nanoparticles for potential conformance control applications. In SPE International Conference on Oilfield Chemistry? (pp. SPE-121744). SPE. https://doi.org/10.2118/121744-ms

[4] Espinosa, D. R. (2011). Nanoparticle-stabilized supercritical CO_2 foams for potential mobility control applications. https://doi.org/10.2118/129925-ms

[5] Hendraningrat, L., Engeset, B., Suwarno, S., & Torsæter, O. (2012, December). Improved oil recovery by nanofluids flooding: an experimental study. In SPE Kuwait international petroleum conference and exhibition (pp. SPE-163335). SPE. https://doi.org/10.2118/163335-ms

[6] Onyekonwu, M. O., & Ogolo, N. A. (2010, July). Investigating the use of nanoparticles in enhancing oil recovery. In SPE Nigeria annual international conference and exhibition (pp. SPE-140744). SPE. https://doi.org/10.2118/140744-ms

[7] Hasan, S. (2015). A review on nanoparticles: their synthesis and types. Res. J. Recent Sci, 2277, 2502.

[8] Nowack, B., & Bucheli, T. D. (2007). Occurrence, behavior and effects of nanoparticles in the environment. Environmental pollution, 150(1), 5-22. https://doi.org/10.1016/j.envpol.2007.06.006

[9] Cho, E. J., Holback, H., Liu, K. C., Abouelmagd, S. A., Park, J., & Yeo, Y. (2013). Nanoparticle characterization: state of the art, challenges, and emerging technologies. Molecular pharmaceutics, 10(6), 2093-2110. https://doi.org/10.1021/mp300697h

[10] Salavati-Niasari, M., Davar, F., & Mir, N. (2008). Synthesis and characterization of metallic copper nanoparticles via thermal decomposition. Polyhedron, 27(17), 3514-3518. https://doi.org/10.1016/j.poly.2008.08.020

[11] Bhaviripudi, S., Mile, E., Steiner, S. A., Zare, A. T., Dresselhaus, M. S., Belcher, A. M., & Kong, J. (2007). CVD synthesis of single-walled carbon nanotubes from gold nanoparticle catalysts. Journal of the American Chemical Society, 129(6), 1516-1517. https://doi.org/10.1021/ja0673332

[12] Ramesh, S. (2013). Sol-Gel Synthesis and Characterization of Ag3 (2+ x) AlxTi4− xO11+ δ (0.0≤ x≤ 1.0) Nanoparticles. Journal of Nanoscience, 2013(1), 929321. https://doi.org/10.1155/2013/929321

[13] Tai, C. Y., Tai, C. T., Chang, M. H., & Liu, H. S. (2007). Synthesis of magnesium hydroxide and oxide nanoparticles using a spinning disk reactor. Industrial & engineering chemistry research, 46(17), 5536-5541. https://doi.org/10.1021/ie060869b
[14] Adachi, M., Tsukui, S., & Okuyama, K. (2003). Nanoparticle synthesis by ionizing source gas in chemical vapor deposition. Japanese journal of applied physics, 42(1A), L77. https://doi.org/10.1143/jjap.42.l77
[15] Yadav, T. P., Yadav, R. M., & Singh, D. P. (2012). Mechanical milling: a top down approach for the synthesis of nanomaterials and nanocomposites. Nanoscience and Nanotechnology, 2(3), 22-48. https://doi.org/10.5923/j.nn.20120203.01
[16] Kuppusamy, P., Yusoff, M. M., Maniam, G. P., & Govindan, N. (2016). Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications–An updated report. Saudi Pharmaceutical Journal, 24(4), 473-484. https://doi.org/10.1016/j.jsps.2014.11.013
[17] Hulteen, J. C., Treichel, D. A., Smith, M. T., Duval, M. L., Jensen, T. R., & Van Duyne, R. P. (1999). Nanosphere lithography: size-tunable silver nanoparticle and surface cluster arrays. The Journal of Physical Chemistry B, 103(19), 3854-3863. https://doi.org/10.1021/jp9904771
[18] Amendola, V., & Meneghetti, M. (2009). Laser ablation synthesis in solution and size manipulation of noble metal nanoparticles. Physical chemistry chemical physics, 11(20), 3805-3821. https://doi.org/10.1039/b900654k
[19] Sun, X., Zhang, Y., Chen, G., & Gai, Z. (2017). Application of nanoparticles in enhanced oil recovery: a critical review of recent progress. Energies, 10(3), 345. https://doi.org/10.3390/en10030345
[20] Foroozesh, J., & Kumar, S. (2020). Nanoparticles behaviors in porous media: Application to enhanced oil recovery. Journal of Molecular Liquids, 316, 113876. https://doi.org/10.1016/j.molliq.2020.113876
[21] Sandeep, R., Jain, S., & Agrawal, A. (2020). Application of nanoparticles-based technologies in the oil and gas industry. In Nanotechnology for Energy and Environmental Engineering (pp. 257-277). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-33774-2_11
[22] Esfandyari Bayat, A., Junin, R., Samsuri, A., Piroozian, A., & Hokmabadi, M. (2014). Impact of metal oxide nanoparticles on enhanced oil recovery from limestone media at several temperatures. Energy & fuels, 28(10), 6255-6266. https://doi.org/10.1021/ef5013616
[23] Hendraningrat, L., & Torsæter, O. (2015). Metal oxide-based nanoparticles: Revealing their potential to enhance oil recovery in different wettability systems. Applied Nanoscience, 5(2), 181-199. https://doi.org/10.1007/s13204-014-0305-6
[24] Green, D. W., & Willhite, G. P. (1998). Enhanced Oil Recovery, vol. 6. Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers, Richardson, TX, pp. 143e154.
[25] Joonaki, E., & Ghanaatian, S. J. P. S. (2014). The application of nanofluids for enhanced oil recovery: effects on interfacial tension and coreflooding process. Petroleum Science and Technology, 32(21), 2599-2607. https://doi.org/10.1080/10916466.2013.855228
[26] Li, R., Jiang, P., Gao, C., Huang, F., Xu, R., & Chen, X. (2017). Experimental investigation of silica-based nanofluid enhanced oil recovery: the effect of wettability alteration. Energy & Fuels, 31(1), 188-197. https://doi.org/10.1021/acs.energyfuels.6b02001
[27] Jafarnezhad, M., Giri, M. S., & Alizadeh, M. (2017). Impact of SnO_2 nanoparticles on enhanced oil recovery from carbonate media. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 39(1), 121-128. https://doi.org/10.1080/15567036.2016.1163439
[28] Hu, Z., Nourafkan, E., Gao, H., & Wen, D. (2017). Microemulsions stabilized by in-situ synthesized nanoparticles for enhanced oil recovery. Fuel, 210, 272-281. https://doi.org/10.1016/j.fuel.2017.08.004
[29] Kazemzadeh, Y., Sharifi, M., Riazi, M., Rezvani, H., & Tabaei, M. (2018). Potential effects of metal oxide/SiO_2 nanocomposites in EOR processes at different pressures. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 559, 372-384. https://doi.org/10.1016/j.colsurfa.2018.09.068
[30] Al-Anssari, S., Arif, M., Wang, S., Barifcani, A., Lebedev, M., & Iglauer, S. (2018). Wettability of nanofluid-modified oil-wet calcite at reservoir conditions. Fuel, 211, 405-414. https://doi.org/10.1016/j.fuel.2017.08.111
[31] Hogeweg, A. S., Hincapie, R. E., Foedisch, H., & Ganzer, L. (2018, June). Evaluation of aluminium oxide and titanium dioxide nanoparticles for EOR applications. In SPE Europec featured at EAGE Conference and Exhibition? (p. D041S009R005). SPE. https://doi.org/10.2118/190872-ms
[32] Al-Anssari, S., Arain, Z. U. A., Shanshool, H. A., Ali, M., Keshavarz, A., Iglauer, S., & Sarmadivaleh, M. (2020, November). Effect of nanoparticles on the interfacial tension of CO_2-oil system at high pressure and temperature: an

experimental approach. In SPE Asia Pacific Oil and Gas Conference and Exhibition (p. D013S101R009). SPE. https://doi.org/10.2118/202231-ms

[33] Wu, H., Gao, K., Lu, Y., Meng, Z., Gou, C., Li, Z., ... & Kang, W. (2020). Silica-based amphiphilic Janus nanofluid with improved interfacial properties for enhanced oil recovery. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 586, 124162. https://doi.org/10.1016/j.colsurfa.2019.124162

[34] Ahmed, A., Saaid, I. M., Ahmed, A. A., Pilus, R. M., & Baig, M. K. (2020). Evaluating the potential of surface-modified silica nanoparticles using internal olefin sulfonate for enhanced oil recovery. Petroleum Science, 17(3), 722-733. https://doi.org/10.1007/s12182-019-00404-1

[35] Zargar, G., Arabpour, T., Manshad, A. K., Ali, J. A., Sajadi, S. M., Keshavarz, A., & Mohammadi, A. H. (2020). Experimental investigation of the effect of green TiO2/Quartz nanocomposite on interfacial tension reduction, wettability alteration, and oil recovery improvement. Fuel, 263, 116599. https://doi.org/10.1016/j.fuel.2019.116599

[36] Khademolhosseini, R., Jafari, A., Mousavi, S. M., Manteghian, M., & Fakhroueian, Z. (2020). Synthesis of silica nanoparticles with different morphologies and their effects on enhanced oil recovery. Applied Nanoscience, 10(4), 1105-1114. https://doi.org/10.1007/s13204-019-01222-y

[37] Minakov, A. V., Pryazhnikov, M. I., Suleymana, Y. N., Meshkova, V. D., & Guzei, D. V. (2021). Experimental study of nanoparticle size and material effect on the oil wettability characteristics of various rock types. Journal of Molecular Liquids, 327, 114906. https://doi.org/10.1016/j.molliq.2020.114906

[38] Jafarbeigi, E., Salimi, F., Kamari, E., & Mansouri, M. (2022). Effects of modified graphene oxide (GO) nanofluid on wettability and IFT changes: Experimental study for EOR applications. Petroleum Science, 19(4), 1779-1792. https://doi.org/10.1016/j.petsci.2021.12.022

[39] Ngouangna, E. N., Jaafar, M. Z., Norddin, M. N. A. M., Agi, A., Risal, A. R., Mamah, S. C., & Oseh, J. O. (2022). The effect of hydroxyapatite nanoparticles on wettability and brine-oil interfacial tension as enhance oil recovery mechanisms. Journal of Petroleum Science and Engineering, 218, 110941. https://doi.org/10.1016/j.petrol.2022.110941

[40] Nowrouzi, I., Khaksar Manshad, A., & Mohammadi, A. H. (2022). Effects of MgO, γ-Al2O3, and TiO2 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. ACS omega, 7(26), 22161-22172. https://doi.org/10.1021/acsomega.1c07134

[41] Gomari, S. R., Omar, Y. G. D., Amrouche, F., Islam, M., & Xu, D. (2019). New insights into application of nanoparticles for water-based enhanced oil recovery in carbonate reservoirs. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 568, 164-172. https://doi.org/10.1016/j.colsurfa.2019.01.037

[42] Dahkaee, K. P., Sadeghi, M. T., Fakhroueian, Z., & Esmaeilzadeh, P. (2019). Effect of NiO/SiO2 nanofluids on the ultra interfacial tension reduction between heavy oil and aqueous solution and their use for wettability alteration of carbonate rocks. Journal of Petroleum Science and Engineering, 176, 11-26. https://doi.org/10.1016/j.petrol.2019.01.024

[43] Ealia, S. A. M., & Saravanakumar, M. P. (2017, November). A review on the classification, characterisation, synthesis of nanoparticles and their application. In IOP conference series: materials science and engineering (Vol. 263, No. 3, p. 032019). IOP Publishing. https://doi.org/10.1088/1757-899x/263/3/032019

[44] Iravani, M., Khalilnezhad, Z., & Khalilnezhad, A. (2023). A review on application of nanoparticles for EOR purposes: history and current challenges. Journal of Petroleum Exploration and Production Technology, 13(4), 959-994. https://doi.org/10.1007/s13202-022-01606-x

[45] Foroozesh, J., & Kumar, S. (2020). Nanoparticles behaviors in porous media: Application to enhanced oil recovery. Journal of Molecular Liquids, 316, 113876. https://doi.org/10.1016/j.molliq.2020.113876

[46] Dheyauldeen, A., Alfarge, D., Alkhafaji, H., & Aljarah, A. M. (2025). A generic method for diagnosing flow regimes based on dynamic gas in place in unconventional gas reservoirs. Modeling Earth Systems and Environment, 11(5), 1-17 https://doi.org/10.1007/s40808-025-02520-x

[47] Ahmed Ameen Ali, Hind Lafta Tubena, Zahra'a Aamer Oudah, Dheiaa Alfarge, Sajad W. Noori, Firas Abdulamir. (2025). Enhancing photovoltaic performance and efficiency by innovative cooling system of sawdust: Experimental investigation. https://doi.org/10.1002/ep.14640

[48] Dheiaa Alfarge, Ahmed M. Aljarah, Najeh Alali, Insights from field applications of miscible gases based EOR for unconventional oil reservoirs: A review, Unconventional Resources, Volume 5, 2025, 100132, ISSN 2666-5190, https://doi.org/10.1016/j.uncres.2024.100132

[49] Shakir, H.A., Abdulhameed, R.F., Hilal, H.A.A. et al. Factors impacting the performance of polymer-based EOR in oil reservoirs. Chem. Pap. 77, 4859–4875 (2023) https://doi.org/10.1007/s11696-023-02824-1
[50] Ali, A. A., Alfarge, D., lafta Rashid, F., Ugla, A. A., Kareem, A. K., & Mohammed, H. I. (2025). Improving photovoltaic Panels by utilizing ground-coupled heat exchangers: Insights and technological advances. Geothermics, 130, 103335 https://doi.org/10.1016/j.geothermics.2025.103335