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HYDROPHILIC NANOSILICA DERIVED FROM FLY ASH AND BOTTOM ASH: A SUSTAINABLE APPROACH FOR ENHANCED OIL RECOVERY

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Abstract. *Silica-based nanoparticles synthesized from fly ash and bottom ash (FABA) have been investigated as potential agents for Enhanced Oil Recovery (EOR). The utilization of solid waste generated from coal-fired power plants not only mitigates environmental impacts but also provides value-added functional materials. This article examines the strategic potential of fly ash and bottom ash (FABA)-derived nanosilica as a low-cost and environmentally sustainable alternative material for EOR applications. The discussion integrates sustainability perspectives with EOR performance by positioning FABA-based nanosilica as a technically feasible and environmentally viable green material. By synthesizing key findings from recent literature, this paper highlights the relationship between the physicochemical properties of nanosilica, nanofluid stability, and the dominant EOR mechanisms, including wettability alteration, interfacial tension reduction, contact angle measurement, viscosity factor, porosity modification, and structural disjoining pressure. These findings indicate that silica nanofluids derived from FABA exhibit significant potential for practical implementation in Enhanced Oil Recovery (EOR), while simultaneously offering a sustainable approach to industrial waste management and long-term energy resilience.*

Keywords: *enhanced oil recovery, fly ash and bottom ash, nanofluids silica, nano-eor, nano flooding*

INTRODUCTION

In petroleum engineering operations, nanomaterials offer a variety of integrated solutions, such as improving well cementing quality, optimizing drilling fluid rheology, and better controlling chemical compatibility. These nanomaterials significantly improve recovery efficiency in tertiary oil recovery processes by reducing interfacial tension and altering rock moisture, especially in old wells (Zadeh et al, 2024).

Most old oil fields, which were previously almost abandoned, still hold about 50% of the total original oil in place (OOIP) that has not been produced (Afolabi, 2019). With declining production from old wells and increasing costs of developing new projects, petroleum engineers are now focusing on maximizing the final yield from existing fields. One method used is Enhanced Oil Recovery (EOR), or tertiary recovery, which is a technique to increase the amount of oil that can be extracted from reservoirs by modifying the interaction between fluids and rocks below the surface.

In mature oil fields, the injected fluid typically has a lower viscosity than the resident oil, resulting in an unfavorable mobility ratio. This condition leads to viscous fingering, where the injected fluid forms irregular flow paths and bypasses the oil, thereby reducing sweep efficiency (Alvarado & Manrique, 2010; Sheng, 2013). In Indonesia, the implementation of Enhanced Oil Recovery (EOR) in mature fields faces significant challenges, including declining reservoir pressure, high water cut, limited reservoir data, and aging infrastructure. Most oil fields in Indonesia are classified as mature, with production declining by 5–20% annually, rendering conventional recovery methods increasingly ineffective. Furthermore, many EOR techniques remain at the pilot or laboratory scale, limiting their large-scale field application (Abdurrahman et al., 2017; Abdurrahman et al., 2016; Pasarai, 2020).

Fly ash and bottom ash (FABA), by-products of coal combustion, contain significant amounts of silica (SiO_2), with fly ash typically comprising 50–70% SiO_2, making it a promising precursor for silica-based nanomaterials (Blissett & Rowson, 2012; Yao et al., 2015). Silica nanoparticles have been widely studied in Enhanced Oil Recovery (EOR) applications due to their ability to alter rock wettability, reduce interfacial tension (IFT), and improve oil displacement efficiency, particularly in mature reservoirs (Alvarado & Manrique, 2010; Sheng, 2013).

On the other hand, the coal combustion process produces waste in the form of 80% fly ash and 20% bottom ash, collectively known as FABA (Kartika, 2010). With coal demand projected to reach 162 million

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tons by 2027, FABA production potential is estimated to reach 16.2 million tons, assuming 10% of coal consumption (KESDM, 2018). In 2019 alone, ash production from steam power plants (PLTU) reached 9.7 million tons and is estimated to increase to 13.5 million tons by 2028 (Puslitbang ESDM, 2020). If not managed optimally, this waste can cause air pollution that has the potential to cause respiratory tract infections in communities around PLTU.The alternative solution we offer to solve these two problems, which can support Net Zero Emissions 2060 and the Sustainable Development Goals (SDGs), is a futuristic idea of utilizing FABA waste into nanosilica from the synthesis of FABA as a well productivity enhancer in EOR techniques to support national energy security.

EOR techniques can increase oil recovery rates by 30–60% of total reserves, which is much higher than primary and secondary methods, which only range from 20–40% (Turta et al., 2010). This is achieved by increasing fluid viscosity, changing rock wettability, and reducing interfacial tension (Cheraghian et al., 2013). Various methods have been used, ranging from gas injection, water injection, to a combination of both, such as water alternating gas (WAG) or foam-assisted WAG (Kharrat et al., 2010).

Wettability is defined as the ability of a fluid to wet a rock surface in the presence of another fluid. This property greatly determines the initial distribution of the fluid, its flow pattern in the reservoir, and ultimately affects oil and gas production. Hydrophilic reservoir rocks are generally more advantageous than oleophilic ones, because in oleophilic rocks oil tends to adhere, reducing production efficiency. During well operations, formation damage can make rocks more oleophilic. This condition can be improved by adding nanoparticles.

Several studies have shown that nanofluids can improve the wettability of carbonate rocks, which is an important factor in Enhanced Oil Recovery (EOR). Commonly used types of nanoparticles include ZnO_2, TiO_2, $CaCO_3$, and SiO_2 (Nazari Moghaddam et al., 2015).

Advances in nanotechnology have brought new approaches to EOR by utilizing nano-assisted EOR (Muggeridge et al., 2014) (Sun et al., 2014). This technology focuses on improving particle characteristics down to the nanometer scale, which provides unique and more effective properties compared to materials in micro or millimeter sizes (Fakoya et al., 2017). At the nanoscale, changes in material properties can significantly affect performance in various applications, including in the petroleum industry (Kamyshny et al., 2010) (Fletcher et al., 2010).

Based on this background, this paper aims to examine the potential of fly ash and bottom ash (FABA) as sustainable alternative sources of nanosilica for Enhanced Oil Recovery (EOR) applications. The discussion is focused on a critical analysis of the literature concerning the conversion of FABA into nanosilica, the relevant physicochemical characteristics, and the principal mechanisms by which nanosilica enhances oil recovery, particularly through rock wettability alteration and interfacial tension reduction.

METHODOLOGY AND EXPERIMENTAL APPROACH

This section outlines the methodological approaches and experimental configurations commonly employed in previous studies concerning the application of nanosilica for Enhanced Oil Recovery (EOR).

Fabrication of FABA into Silica

Silica nanoparticles derived from fly ash and bottom ash (FABA) were synthesized by initially dissolving FABA, previously sieved through a 200-mesh screen, in hydrochloric acid (HCl) to remove metallic impurities such as Fe. The mixture was subsequently filtered and oven-dried. The Fe-free FABA was then re-dissolved in sodium hydroxide (NaOH) and heated on a hot plate stirrer at 80 °C for 120 minutes, followed by filtration to obtain a sodium silicate (Na_2SiO_3) solution as the filtrate.

The Na_2SiO_3 solution was transferred into a beaker, and 8 M HCl was added dropwise until a white gel formed at pH 7. The resulting silica gel was allowed to precipitate for 24 hours, then filtered using filter paper, washed with distilled water, and finally dried.

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Figure 1. The fly ash was first dried and ground, then reacted with 3 M NaOH at 100 °C for 4 hours. The resulting mixture was subsequently precipitated using 6 M HCl and calcined at 800 °C for 3 hours. The obtained product was then further reacted with 6 M NaOH for 24 hours to produce sodium silicate

Figure 2. Silica–alumina catalysts were synthesized from fly ash-derived silica using a hydrothermal method through the reaction of sodium silicate and sodium aluminate at a 1:1 ratio in an autoclave at 100 °C for 3 days. The resulting mixture was then aged for 24 hours, followed by filtration, neutralization, and drying. The obtained solid product was identified as a silica–alumina catalyst.

A study conducted by Meliyana (2011) demonstrated that silica synthesized using the sol–gel method yielded nanosilica with a purity of 89.17%, and particle sizes ranging from 92 ± 25 nm to 98 ± 25 nm. Meanwhile, research by Wibowo (2018) reported that silica extracted from rice straw via the sol–gel method exhibited an average pore size of 45.3869 nm.

Contact Angle Measurements

The contact angle measurement method was adopted and adapted from the approach reported by Chandio et al. (2021), employing a KRÜSS DSA25E drop shape analyzer to characterize the nanofluid–oil–solid interfacial system. The sessile drop technique was applied with a modified configuration to represent fluid–rock interaction conditions relevant to Enhanced Oil Recovery (EOR) applications.

As described by Chandio et al. (2021), the conventional sample holder of the instrument was replaced with a transparent glass container filled with silica-based nanofluid. A flat glass substrate was positioned horizontally above the container, ensuring that its entire surface was immersed in the nanofluid medium. Subsequently, a paraffin oil droplet with a volume of approximately 1 μL was carefully injected beneath the substrate using a modified U-shaped syringe needle.

To ensure accurate image acquisition, a collimated light source was directed from one side of the system, while a high-resolution camera was positioned on the opposite side to record the droplet profile in real time. The entire process, including droplet formation, image capture, and contact angle analysis, was conducted using integrated software, as detailed by Chandio et al. (2021). This approach enables consistent and reproducible contact angle evaluation, making it suitable for analyzing wettability alteration induced by nanofluids in the context of EOR.

Interfacial Tension Measurements

The interfacial tension (IFT) measurements in this study were adopted and adapted from the work of Chandio et al. (2021), by evaluating the interaction between the oleic phase and the nanofluid to examine the physical interactions between them. The procedure employed a KRÜSS K20 tensiometer at room temperature using the standard Wilhelmy plate method. In the study conducted by Chandio et al. (2021), paraffin oil served

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as the oil phase; therefore, the IFT measurements were specifically focused on the interaction between paraffin oil and the nanofluid at varying concentrations.

Core Flooding Tersier

Core flooding tests were conducted using a high-pressure, low-temperature (HPLT) core flooding apparatus. The FARS-EOR core flooding system was employed in this study, which presents the basic schematic configuration of the experimental setup consisting of three core-flooding accumulators, along with their labeled components.

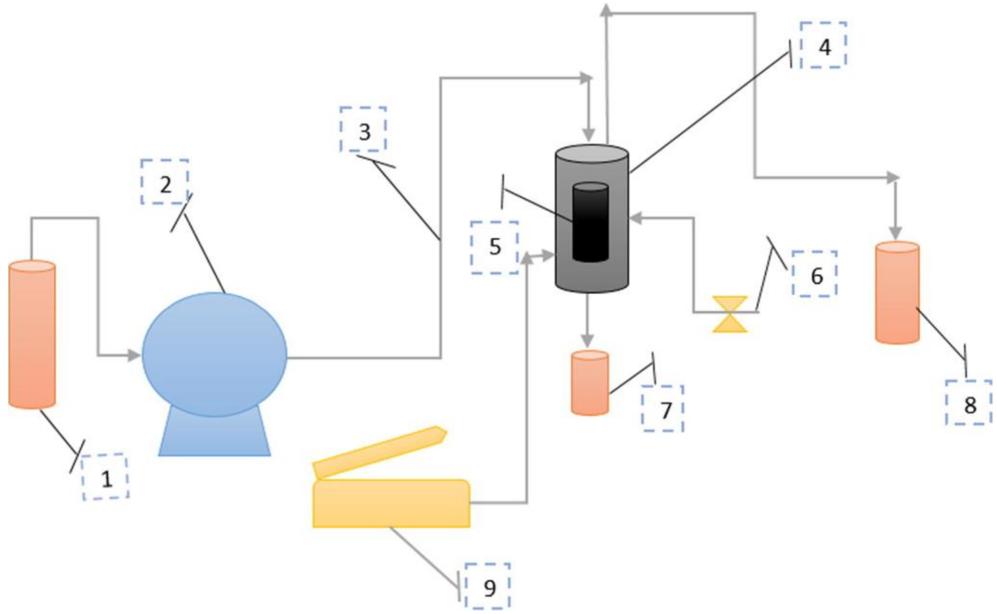

Figure 3. Experimental set up schematic: (1) Graduated tube. (2) Prep Pump. (3) Injection pipe. (4) Core holder. (5) Core plug. (6) Sleeve pressure. (7) Fluid accumulator. (8) Carry over fluid accumulator. (9) Hydraulic pump (Yousif et all, 2017)

Porosity Disorder

Prior to fluid injection into the rock cores, porosity measurements were performed on all core samples. The procedure began with cleaning the cores to remove residual fluids using a Soxhlet extraction apparatus with toluene for 24 hours. Subsequently, the cores were oven-dried at 100 °C for an additional 24 hours.

After confirming that the rock cores were clean and completely dry, porosity was measured using a helium porosimeter. This measurement was conducted to evaluate potential changes in porosity following the nanoflooding process. The study assumed that porosity reduction due to clay swelling would not occur, as the sandstone samples used were classified as clean, with minimal clay content.

LITERATURE REVIEW

This section discusses the principal theories underlying the understanding of the topic, defines the key concepts and their relevance, and critically analyzes previous studies.

Fly Ash

FABA is a byproduct of coal combustion, primarily generated in coal- fired power plants that are equipped with collection facilities for combustion residues. The finer fraction of this waste is commonly known as fly ash, while the coarser fraction is referred to as bottom ash. Fly ash particles are typically spherical in shape and very small in size, generally ranging from 1 µm to 150 µm. According to ASTM (2010), fly ash is classified into two categories: Class F and Class C. These classifications are distinguished by their compositional differences, which result from variations in the coal source. Class C fly ash is derived from the combustion of lignite or sub-bituminous coal, whereas Class F fly ash originates from the combustion of bituminous coal. Furthermore, the utilization of fly ash as a pozzolanic material offers advantages such as improved

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mixture flowability and reduced water demand. The chemical composition of fly ash is presented in Table 1.

Table 1. Comparison of Fly Ash Chemical Composition

Properties	Class	
	F	C
Silicon dioxide ($SiO2$) plus aluminum oxide $Al2O3$) plus iron oxide ($Fe2O3$), min, %	70	50
Sulfur trioxide ($SO3$), max, %	5	5
Moisture content, max, %	3	3
Loss on ignition, max, %	6	6

Bottom Ash

Coal bottom ash is a waste product generated from coal combustion in power plants. Compared to fly ash, it contains larger and denser particles, which settle at the bottom of the combustion furnace and are collected in a dust collector. The material is then removed from the furnace by spraying with water before being either disposed of or utilized as an additive in road pavement. The chemical composition of bottom ash primarily consists of Si, Al, Fe, Ca, Mg, S, Na, and other trace elements. Research by Moulton (1973) indicated that the low salt content and acidic nature of bottom ash may lead to corrosion in steel structures exposed to mixtures containing this material. The low pH values, caused by the high concentration of dissolved sulfates, also point to significant amounts of pyrite (iron sulfide) present in bottom ash.

The utilization of coal bottom ash remains limited, as its application is largely confined to use as an additive in artificial aggregates for concrete production, with a maximum proportion of only 2.4%. Consequently, its use is considered far from optimal. This concern is further highlighted by the Director General of Waste, Waste Management, and Hazardous Waste, who emphasized that bottom ash poses health and environmental risks. Prolonged inhalation can lead to severe respiratory problems, while rainfall can generate acidic leachate that contaminates the surrounding environment and reduces soil fertility.

Nanofluids Silica

Gbadamosi et al. (2019) reported that nanomaterials such as SiO_2 improve fluid stability and enhance flow behavior through mechanisms such as adsorption and precipitation. In a review published in 2020, Eltoum et al. discussed the role of SiO_2 and ZnO nanoparticles in altering rock wettability and reducing interfacial tension (IFT), while also emphasizing the significance of surface functionalization in sustaining nanofluid stability. Later, Al-Yaari et al. (2022) provided experimental evidence that SiO_2 and Al_2O_3 nanofluids markedly increase oil recovery in porous media and highlighted that their thermal conductivity contributes to more efficient energy transfer. In the same year, Dahlam et al. investigated ionically stabilized nanofluids for heavy oil reservoirs, whereas Wang et al. examined the potential application of nanocomposites in complex geological environments. Overall, the use of nanofluids in enhanced oil recovery (EOR) has progressed beyond early exploratory stages, supported by a clearer understanding of the governing mechanisms and improvements in technology. Nevertheless, continuing studies are aimed at further optimization. Extensive research consistently shows that certain nanomaterials provide high oil displacement efficiency while maintaining economic feasibility.

Silica is characterized by low impurity levels and low density, which facilitates its dispersion during oil transport while also reducing environmental impact (Obinna et al., 2017). In addition, its relatively low production cost enhances its potential for large-scale application (Omairi et al., 2024). Previous studies have demonstrated that SiO_2 nanoparticles are capable of lowering interfacial tension, promoting the formation of multiphase emulsions, and altering wettability, all of which significantly contribute to improving hydrocarbon recovery. In the context of EOR, Wu et al. (2020) introduced a silica-based amphiphilic Janus nanofluid system that achieved an incremental oil recovery of 5.74% at a concentration of 100 mg/L. Similarly, Yin et al. (2019)

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found that hydrophilic carboxyl/alkyl silica Janus nanosheets enhanced sweep efficiency by 18.31%. Lan et al. (2019) further developed both water-in- oil (W/O) and oil-in-water (O/W) emulsions by adjusting the hydrophilic– hydrophobic domain ratio of Janus particles. However, investigations into Janus nanoparticle-stabilized O/W/O three-phase Pickering emulsions in relation to EOR remain scarce, and the underlying mechanisms involving silica nanoparticle-driven conformational regulation and capillary-assisted oil mobilization are still insufficiently understood.

Expanded EOR techniques rely on the injection of nanomaterials into reservoirs to enhance recovery performance. By influencing fluid interactions, nanomaterials facilitate the release and migration of residual oil within porous networks, offering opportunities for improved exploitation of low-permeability reservoirs. However, challenges persist in such reservoirs, including rising injection wellhead pressure, reduced fluid intake capacity, suboptimal performance of production wells, significant reservoir pressure decline, and severe productivity losses. These issues collectively result in lower waterflooding efficiency, diminished hydrocarbon yields, reduced production rates, and overall recovery factor decline (He et al., 2022; Liu et al., 2021; Su et al., 2021).

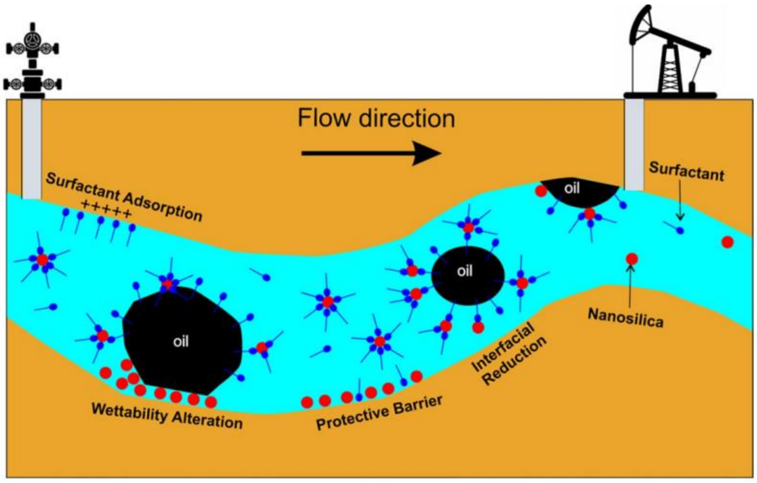

Figure 4.The synergistic interaction between surfactants and nanosilica reduces surfactant adsorption, stabilizes micelle formation, and enhances interfacial tension (IFT) reduction as well as wettability alteration. Consequently, this leads to improved oil displacement efficiency and greater economic feasibility (Rahman et al., 2024).

NANOSILICA-BASED EOR MECHANISMS

Enhanced oil recovery through silica nanofluid injection in Enhanced Oil Recovery (EOR) applications is governed by a series of interacting physicochemical mechanisms within the fluid–rock–oil system. Numerous laboratory investigations have confirmed the transformative potential of nanoparticles (NPs) for EOR processes. In particular, SiO_2 nanoparticles have attracted considerable attention for both sandstone and carbonate reservoirs due to their broad applicability and stability, as reported by Hendraningrat et al. (2013). In high-temperature reservoirs, mixtures of SiO_2 nanoparticles and surfactants have been demonstrated to yield an additional oil recovery increase of approximately 10–15%. The principal mechanisms widely reported in the literature include rock wettability alteration, interfacial tension reduction, contact angle modification, viscosity control of the displacing fluid, and modification of rock petrophysical properties, such as porosity changes resulting from nanoparticle retention.

Wettability Alteration

Wettability is defined as the tendency of one fluid to spread over or adhere to a solid surface in the presence of another immiscible fluid, reflecting the interfacial energy balance within the fluid–oil–solid system, as described by Bera et al. (2016) and Cheragian et al. (2015). This property is governed by rock characteristics, including mineral composition, pore size distribution and geometry, and specific surface area, and is also influenced by fluid composition and temperature conditions Cheragian et al. (2015).

Wettability plays a crucial role in controlling multiphase flow during hydrocarbon accumulation and production processes, as it directly affects capillary pressure, relative permeability, and spontaneous imbibition mechanisms that promote oil displacement from the rock matrix, as reported by Wang et al. (2011), Morrow (1990), Giraldo et al. (2013), and Bera et al. (2016).

The primary objective of wettability alteration in EOR applications is to shift the reservoir rock toward a more strongly water-wet state, thereby enhancing the displacement of trapped oil, as noted by Kandiel et al. (2025). Although surfactants have long been utilized as wettability-altering agents, economic limitations at the field scale have encouraged the development of nanoparticles as a more effective and sustainable alternative for Enhanced Oil Recovery, as discussed by Maerker et al. (1992).

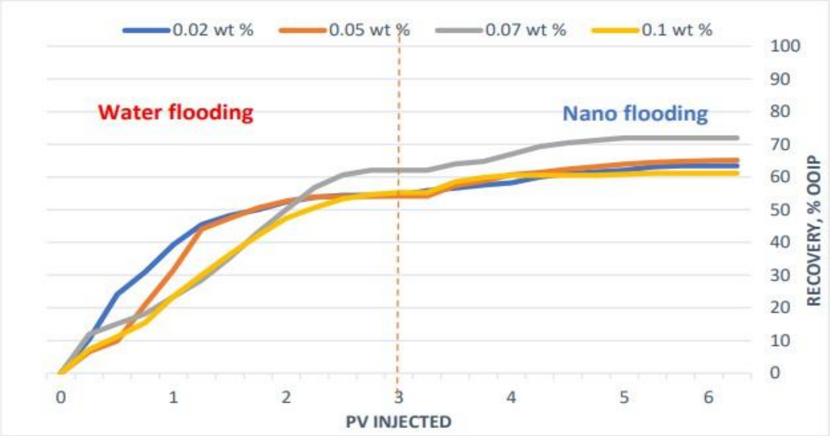

Figure 5. *Oil Recovery (%OOIP) versus Injected Pore Volume (Chandio et al., 2021)*

Chandio et al. (2021) reported that the injection of silica nanofluid as a tertiary nanoflooding mechanism at a salinity of 20,000 ppm was able to enhance oil recovery following the waterflooding stage, as illustrated in Figure 5; however, its performance was strongly dependent on nanoparticle concentration. Among the tested concentrations of 0.02, 0.05, 0.07, and 0.10 wt.%, the 0.05 wt.% concentration exhibited the highest incremental recovery and displacement efficiency, which was attributed to optimal wettability alteration and interfacial tension reduction under these conditions.

Conversely, increasing the concentration beyond this value resulted in a decline in oil recovery performance due to reduced nanofluid stability and the potential for nanoparticle agglomeration, as shown in Figure 6. These findings indicate that the effectiveness of silica nanofluids in Enhanced Oil Recovery (EOR) is not linearly proportional to concentration, but rather governed by the presence of an optimum concentration.

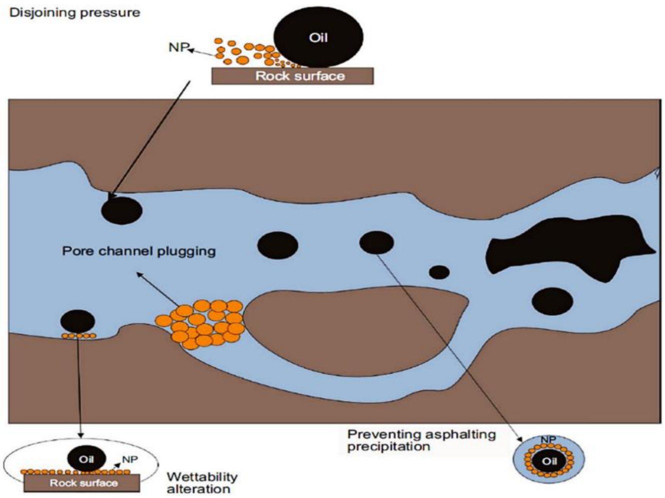

Figure 6. EOR mechanisms of nanofluids in porous media (Eltoum et al. 2021)

Similar findings were reported by Hendraningrat et al., who investigated the effect of low–high pressure (LHP) silica nanofluids through core flooding experiments on Berea sandstone cores. The nanoparticle concentrations ranged from 0.01 to 0.1 wt.% dispersed in 3.0 wt.% NaCl brine. The results demonstrated that increasing nanoparticle concentration reduced the contact angle and enhanced rock wettability; however, at higher concentrations, a tendency toward pore plugging was observed, as illustrated in Figure 7, particularly in low-permeability cores.

Furthermore, nanofluid injection at the initial stage proved to be more effective than post-waterflood injection or sequential water–nanofluid injection, as it resulted in higher ultimate oil recovery. In addition, Jafarnezhad et al. (2017) reported an improvement in heavy oil recovery ranging from 39% to 61% in carbonate core samples.

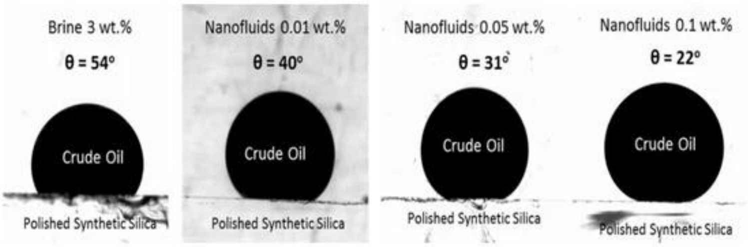

Figure 7. Variation of Oil–Brine System Contact Angle at Different Concentrations (Somasundaran et al., 1967)

A study conducted by Hu et al. (2023) reported that in high-permeability core flooding experiments, SiO_2 nanoparticles formed wedge-like structures that generated structural disjoining pressure, thereby promoting crude oil mobilization. Simultaneously, the nanoparticles adsorbed onto the rock surface, altering wettability from oil-wet to strongly water-wet conditions. This transition was evidenced by a reduction in contact angle from 110° to 18°, which significantly decreased oil adhesion and enhanced oil recovery through the synergistic effect of these mechanisms. Hydrophilic SiO_2 nanofluids reduced the contact angle to as low as 10° without substantially increasing oil recovery, whereas hydrophobic SiO_2 nanofluids shifted the rock wettability toward a neutral state (approximately 90°) and significantly improved oil recovery, underscoring wettability as a key parameter in EOR.

Nilsson et al. (1997) reported that more than half of global reservoirs consist of carbonate formations, and approximately 90% of these are classified as oil-wet or intermediate-wet. Therefore, shifting wettability toward more water-wet conditions represents a promising strategy for enhancing oil recovery. One of the extensively investigated approaches involves the use of nanoparticles that adsorb onto rock surfaces and modify their surface energy, as illustrated in Figure 8.

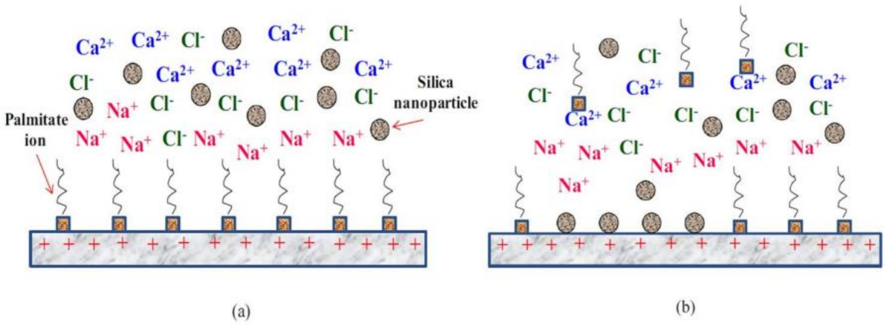

Figure 8. Mechanism of Wettability Alteration in Oil-Wet Carbonate Surfaces Induced by SiO_2 Nanofluids (Hou et al., 2019)

Interfacial Tension Reduction and Contact Angle Measurement

Capillary forces constitute one of the primary factors limiting oil recovery in reservoir systems, where their magnitude is governed by interfacial tension (IFT) and rock wettability, as described by Towler et al.

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(2017) and Chatzis et al. (1984). Reductions in IFT and alterations in wettability directly decrease capillary pressure, thereby enhancing oil mobility and recovery efficiency, as reported by Melrose (1974). Experimentally, IFT is commonly measured using the pendant drop and spinning drop methods, as documented by Ju et al. (2006) and Suleimanov et al. (2011).

The use of surfactants has long been recognized as an effective mechanism for mobilizing residual oil through IFT reduction; however, nanoparticles are increasingly proposed as alternative or synergistic agents in EOR processes. The presence of nanoparticles, either independently or within surfactant systems, can reduce IFT through adsorption at the fluid interface and enhance the rheological properties of the solution, thereby strengthening the overall effectiveness of IFT reduction, as discussed by Munshi et al. (2008), Towler et al. (2017), and Suleimanov et al. (2011).

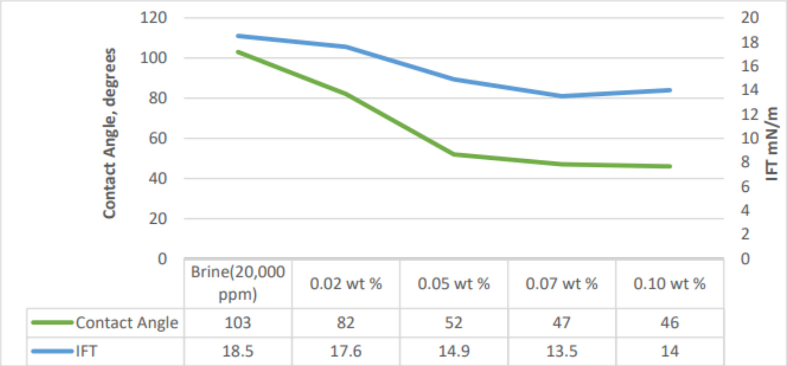

Figure 9. Contact Angle (Nanofluid–Oil–Solid) and Interfacial Tension (Oil–Nanofluid) at Various Nanomaterial Concentrations (wt.%) (Chandio et al., 2021)

Chandio et al. (2021), as illustrated in Figure 9, reported that increasing the concentration of silica nanofluid resulted in a reduction in both contact angle and interfacial tension (IFT), with the most pronounced changes observed at the optimum concentration of 0.05 wt.%. This behavior was attributed to the structural disjoining pressure mechanism and the wedge film effect, which promote rock wettability alteration.

At higher concentrations, however, the change in contact angle became insignificant and the IFT tended to increase again, indicating a shift in the fluid–rock interaction mechanism. This trend correlates with the decline in oil recovery performance, as shown in Figure 10.

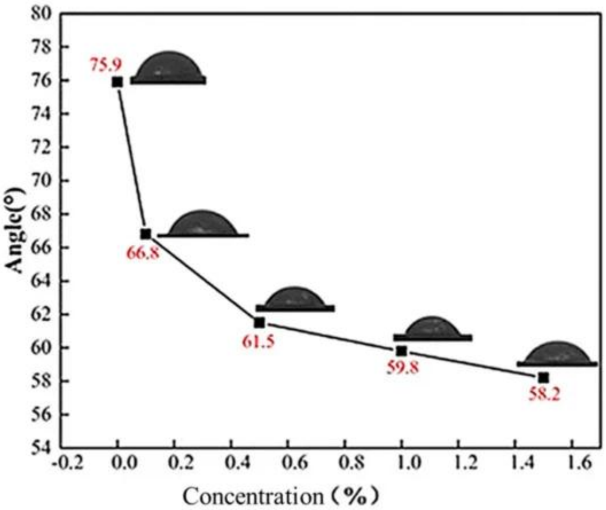

Figure 10. Effect of Nano Oil-Displacement Agent Concentration on Contact Angle (Deng et al., 2024)

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Sharma et al. (2015) investigated the use of silica nanoparticles dispersed within a polymer–surfactant system for chemical EOR applications and reported that the presence of silica nanoparticles reduced and stabilized interfacial tension through the formation of Pickering emulsions, resulting in an additional oil recovery of approximately 21% compared to conventional surfactant–polymer injection. Furthermore, while the performance of polymer and surfactant–polymer injection declined at elevated temperatures, the nanofluid system exhibited superior thermal stability, confirming its potential as a chemical EOR solution under high-temperature reservoir conditions, as further discussed by Sharma et al. (2016). The presence of nanoparticles in surfactant mixtures can also enhance solution rheology and strengthen the surfactant effect in reducing IFT, as reported by Munshi et al. (2008).

Joonaki et al. (2014) demonstrated that higher concentrations of nanosilica were capable of reducing the contact angle from 134° to 82°, indicating superior performance in wettability alteration. In addition, Xu et al. (2018) developed hydrophilic silica-based nanocomposites for crude oil interfacial regulation and investigated their mechanisms at the molecular scale using a microfluidic system. The results showed that hydrophilic silica nanoparticles induced significant swelling of oil droplets within the aqueous phase, particularly at low salinity and high nanoparticle concentrations, as illustrated in Figure 11. This phenomenon increased flow resistance, reduced the mobility ratio, and improved sweep efficiency, leading to an incremental oil recovery of approximately 11%.

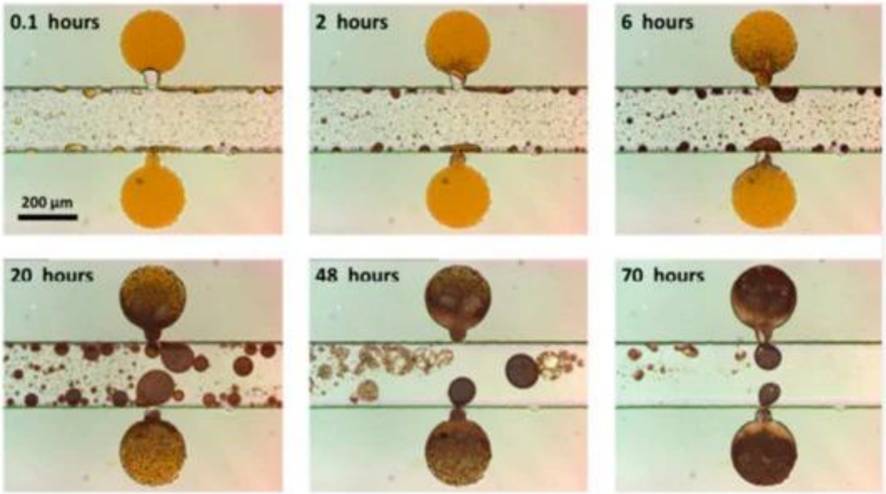

Figure 11. Schematic Diagram of Closed-Loop Crude Oil Expansion at Different Time Intervals (Xu et al., 2018)

Viscosity Control

During Enhanced Oil Recovery (EOR) processes, excessively high mobility of the displacing fluid can trigger viscous fingering, leading to poor sweep efficiency and unfavorable flow conformance, as reported by Sun et al. (2017). Therefore, controlling the mobility of the injection fluid is crucial for improving sweep efficiency and overall oil recovery. Polymer injection has been widely implemented as a viscosity control agent; however, under extreme reservoir conditions such as high temperature, pressure, and salinity, polymer solutions are susceptible to degradation, resulting in reduced viscosity and performance, as discussed by Wang et al. (2009) and Sheng (2010). In this context, nanoparticles have been proposed as additives to enhance the thermal stability of polymer solutions, thereby maintaining injection fluid viscosity and improving sweep efficiency, as suggested by Ramsden et al. (1986).

Maghzi et al. (2014) investigated the effect of silica nanoparticle addition on polymer injection performance through pore-scale visualization experiments and core flooding tests, as shown in Figure 12. The results demonstrated that the presence of silica nanoparticles enhanced polymer solution stability, improved the mobility ratio, and reduced the occurrence of viscous fingering, thereby promoting more uniform oil displacement and reducing residual oil saturation. Additionally, silica nanoparticles contributed to preventing polymer degradation and reinforcing flow structure at the pore scale, which directly supported improved oil recovery efficiency.

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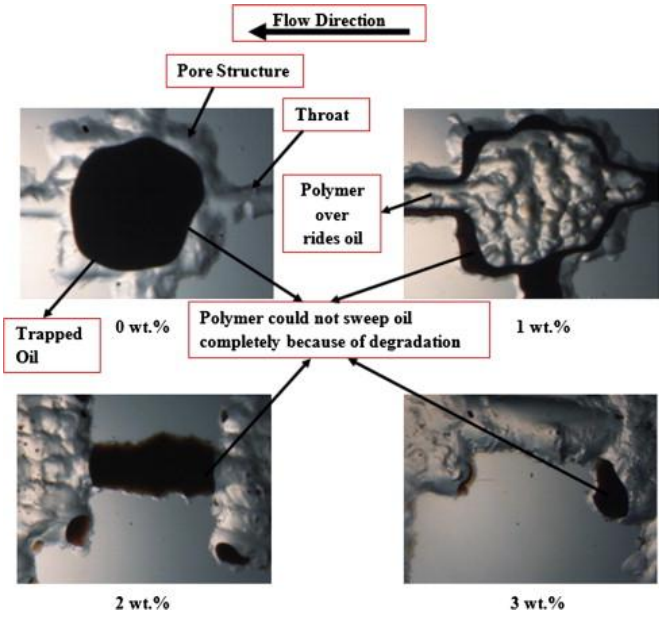

Figure 12. The addition of silica nanoparticles to polymer solutions enhances flow stability at the pore scale, reduces viscous fingering, and mobilizes residual oil more effectively compared to polymer solutions without nanoparticles (Maghzi, 2014).

Porosity and Permeability Alteration After Nano-Flooding

Reservoir permeability is a critical factor in the effectiveness of nanoparticle-assisted EOR. In low-permeability reservoirs with restricted pore throat sizes, nanoparticle transport and distribution tend to be limited, thereby increasing the risk of pore plugging and reduced fluid flow. This performance decline is commonly associated with formation damage, where nanoparticle agglomeration becomes a primary challenge, particularly in low- to medium-permeability reservoirs (>50 mD). Nevertheless, several studies have reported that nanofluids can still operate effectively across a wide range of reservoir permeabilities, as documented by Hogeweg et al. (2018) and Kazemzadeh et al. (2018, 2019).

Chandio et al. (2021) reported that post–silica nano-flooding porosity measurements using a helium porosimeter indicated a reduction in porosity due to nanomaterial retention within the rock cores. The smallest reduction was observed at a concentration of 0.02 wt.%, while similar reductions of approximately 5.5–6% were recorded at concentrations of 0.05–0.07 wt.%. At 0.07 wt.%, injection pressure initially increased before stabilizing to a pattern comparable to lower concentrations after approximately 1.5 pore volumes (PV) of injection. This behavior suggests temporary pore blockage (log-jamming), which gradually diminished as the injected fluid displaced the obstruction. The greatest porosity reduction occurred at a concentration of 0.10 wt.%, which was attributed to decreased nanofluid stability and increased nanoparticle agglomeration, leading to pore plugging and adsorption onto the rock surface.

Recovery Factor

Numerous studies indicate that silica (SiO_2) nanoparticles have the potential to enhance oil recovery through wettability alteration and modification of fluid–rock interactions, with performance strongly influenced by concentration, salinity, temperature, and reservoir rock type. Bayat et al. (2014) reported that the injection of low-concentration SiO_2 nanoparticles (0.005 wt%) in 0.3 wt% NaCl solution into limestone cores resulted in an incremental oil recovery of 2–2.9% compared to waterflooding, with performance improving as temperature increased from 26 to 60 °C.

Hendraningrat and Torsæter (2014) conducted controlled experiments on Berea sandstone using 0.05 wt% SiO_2 nanoparticles dispersed in 3 wt% NaCl at temperatures ranging from 25 to 80 °C. They reported an increase in recovery factor of up to 6.62% at the highest temperature, with positive responses also observed at lower temperatures. The influence of salinity was further emphasized by Hou et al. (2019) and Jiang et al. (2022), who demonstrated that injection of 0.05 wt% SiO_2 in low-salinity brine (0.05–0.1 wt% NaCl) led to a significant oil recovery increase of up to 17.79%, compared to a baseline recovery of 2.43%.

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In carbonate systems, Jiang et al. (2017) reported an 8.7% improvement in oil recovery through injection of 0.01 wt% SiO_2 in deionized water at room temperature. Subsequent studies explored synergistic formulations combining SiO_2 with chemical agents. Rezaei et al. (2022) reported incremental recoveries of approximately 4% to more than 7% in carbonate cores using 0.01–0.2 wt% SiO_2 in combination with 0.03 wt% LABSA, while Zhang et al. (2014) demonstrated a substantial recovery increase of up to 53% in sandstone using 0.1 wt% SiO_2 dispersed in deionized water at 25 °C.

Overall, these findings indicate that SiO_2 performance is highly dependent on concentration and salinity, tends to improve at elevated temperatures, and exhibits strong synergistic effects when combined with surfactants.

CONCLUSIONS AND SUGGESTION

Based on the reviewed literature, silica nanofluids have demonstrated significant potential to enhance oil recovery through multiple Enhanced Oil Recovery (EOR) mechanisms, particularly rock wettability alteration, interfacial tension reduction, viscosity control, and modification of fluid flow behavior at the pore scale. The effectiveness of these mechanisms is strongly influenced by nanoparticle concentration, salinity, temperature, and reservoir rock characteristics, indicating that the performance of silica nanofluids is not linear but governed by the existence of optimum operating conditions.

Furthermore, this review confirms that silica derived from fly ash and bottom ash (FABA) represents a promising and sustainable alternative source of nanoparticles for EOR applications. The utilization of FABA not only enables the production of nanosilica with physicochemical properties relevant to enhanced oil recovery, but also provides environmental added value through industrial waste reduction and the implementation of circular economy principles. Compared to commercial silica, FABA-based nanosilica offers an opportunity to integrate increased energy production with more environmentally responsible waste management practices.

Nevertheless, major challenges in the application of silica nanofluids, particularly those derived from FABA, remain associated with dispersion stability, potential agglomeration, nanoparticle retention, and the risk of formation damage in low- to medium-permeability reservoirs. Therefore, further development is required in fabrication processes, surface modification strategies, and performance evaluation under representative reservoir conditions. Overall, FABA-based silica nanofluids constitute a promising candidate for sustainable EOR, with strong field-scale application prospects provided that these technical challenges are systematically addressed.

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