

Original Research Article

Graphene-Ferrite Quantum Dots Nanohybrid Nanofluids: Stability, Density, and Application in Enhanced Oil Recovery

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ABSTRACT

This study addresses the common challenges of nanoparticle agglomeration and low stability in nanofluids used for enhanced oil recovery (EOR). Graphene-ferrite quantum dots (G-FQDs) were synthesized and characterized using various techniques, and then dispersed in high-salinity brine at different concentrations. The G-FQDs nanofluids showed strong stability under harsh conditions and significantly reduced oil-brine interfacial tension from 46.6 to 24.3 mN/m. More importantly, they caused a pronounced change in rock surface wettability from oil-wet to water-wet. This wettability alteration was found to be more crucial than interfacial tension reduction in improving oil recovery, even at very low G-FQDs concentrations. Overall, G-FQDs-based nanofluids appear to be a promising, and cost-effective method for enhancing the mobility of residual oil in porous reservoirs.

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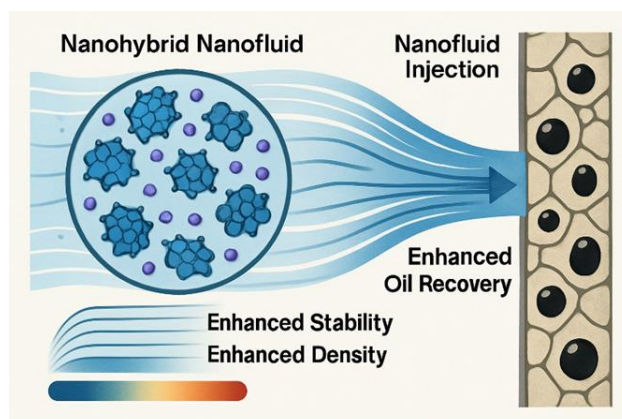
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GRAPHICAL ABSTRACT



Introduction

Oil production from existing fields declines due to reservoir depletion, prompting the use of secondary and tertiary recovery techniques to increase the oil production rate. One effective tertiary method is Chemical Enhanced Oil Recovery (CEOR), which involves injecting chemicals such as polymers, surfactants, and alkalis into the reservoir. These chemicals improve oil recovery by altering reservoir properties to reduce interfacial tension, increase sweep efficiency, and enhance the mobility ratio between oil and injected fluids. CEOR methods such as alkaline-surfactant-polymer (ASP) flooding combine these chemicals to synergistically enhance recovery efficiency, especially in heavy oil reservoirs and challenging conditions. These techniques are widely applied worldwide in various projects to maximize the extraction of residual oil after primary and secondary methods have been exhausted [1-5]. These chemicals improve oil recovery by modifying crucial factors that influence capillary forces, including interfacial tension and wettability.

However, two primary problems in the CEOR method are the expensive nature of the chemicals and the considerable loss of these chemicals within the porous media caused by adsorption and retention [6]. Therefore, new, effective, and

more affordable CEOR techniques are being explored using nanotechnology. Due to their tiny dimensions and large surface area relative to volume, nanofluids are being investigated as innovative agents for CEOR [7,8]. Aboahmed *et al.* [9], investigate the application of graphene quantum dot (GQD)-stabilized foam as a mobility control agent in enhanced oil recovery (EOR) processes. It demonstrates that incorporating graphene quantum dots into a cocamidopropyl hydroxysultaine amphoteric surfactant solution significantly enhances the stability of the resulting foam under challenging reservoir conditions, namely 3,500 psi, 115 °C, and 200,000 ppm brine salinity.

Wei *et al.* [10], examined the effect of graphene oxide (GO) nanosheet concentration, asphaltene concentration in synthetic oil, and NaCl concentration was reported on the stability of Pickering emulsions. They conveyed that the increase in the GO nanosheet concentration enhanced the stability of the emulsions; the increase in the asphaltene concentration improved the stability of the emulsions due to the formation of an interfacial film surrounding the dispersed water droplets. Finally, increasing the salinity up to the optimal concentration improved the stability of the emulsions; however, at higher concentrations, the stability decreased due to suppression of the electric

double layer, which caused the aggregation of GO nanosheets. Lashari *et al.* [11] used HPAM/GO-SiO₂ nanocomposites were employed for wettability alteration. At a concentration of 0.05 wt.%, the incremental oil recovery increased to 30.82% [8]. The injection of nanofluids enhances sweep efficiency in reservoirs through mechanisms including wettability alteration and the reduction of interfacial tension [12-16]. The elevated surface energy of the nanostructures confers outstanding electrical, rheological, thermal, and interfacial properties [17].

Luo *et al.* [18], reported that a nanofluid consisting of graphene amphiphilic Janus nanosheets was prepared by modifying the surface of graphene oxide (GO) with alkylamine. The study demonstrated that this nanofluid effectively reduces IFT even at low concentrations (0.005 wt%). The enhanced oil recovery efficiency is likely due to the accumulation of nanosheets at the oil/water interface. In a separate investigation, the colloidal stability of these amphiphilic graphene nanosheets was assessed under high-salinity, high-temperature (HSHT) conditions [19,20]. However, the experimental results revealed that the amphiphilic nanofluid becomes unstable after 5 hours of exposure to very low NaCl salinity (0.05844 wt%).

Parmar *et al.* [21] studied the superparamagnetic and perfect paramagnetic zinc ferrite quantum dots from microwave-assisted tunable synthesis, which focuses on the synthesis and characterization of zinc ferrite quantum dots (QDs) through a microwave-assisted method. This research demonstrates that the microwave-assisted synthesis technique enables precise control over both the size and magnetic properties of the zinc ferrite quantum dots. By adjusting various synthesis parameters, including microwave power and reaction time, the researchers were able to tailor the QDs' characteristics to achieve specific superparamagnetic and paramagnetic behaviors. The findings indicate that the tunable magnetic properties of these zinc ferrite quantum dots can be effectively utilized in applications such as oil recovery,

catalysis, and environmental remediation, underscoring their versatility and potential for future research and development. One of the major problems in deploying nanofluids for enhanced oil recovery (EOR) is maintaining the stability of the nanoparticle suspension, especially under harsh reservoir conditions characterized by high salinity and elevated temperatures [22].

In high-salinity environments, the elevated ionic strength from dissolved salts suppresses the electrostatic double-layer repulsion that typically keeps nanoparticles apart, which reduces their ability to remain evenly dispersed. Additionally, nanoparticles naturally tend to cluster due to their high surface area-to-volume ratio and the attractive van der Waals forces acting between them [23]. This agglomeration is problematic, as it can lead to the formation of larger aggregates that risk clogging the pore throats within the reservoir rock, thereby reducing both porosity and permeability of the porous media. These effects can hinder fluid flow and ultimately decrease the effectiveness and efficiency of the EOR process [23,24]. As a result, this phenomenon reduces the amount of trapped oil recovered and lowers the sweep efficiency. These challenges can be significantly mitigated by using self-stabilized nanoparticles that resist agglomeration and sedimentation under HSHT conditions, ensuring efficient displacement of the trapped oil.

Therefore, the primary aim of this study is to synthesize G-FQDs using an economical and environmentally friendly sol-gel method. The goals are to enhance their dispersion stability in high-salinity brine over extended periods and to evaluate their potential as a cost-effective agent for C-EOR at ultra-low concentrations. Additionally, this study investigates the optimization of the effective concentration of FQDs-G to improve both stability and viscosity. The G-FQDs nanofluids leverage the large adsorption ability and structural support of graphene, as well as the magnetic responsivity and surface reactivity of ferrite QDs to deliver enhanced EOR performance through several upgraded mechanisms simultaneously. The mixture

distinguishes this research from other previous work that studies only single-component graphene oxide or ferrite nanoparticle nanofluids.

Experimental

Materials

The materials utilized in the synthesis of ferrite quantum dot-graphene nanohybrids comprised iron(III) chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) with 99% purity, sodium hydroxide (NaOH), and ethanol ($\text{C}_2\text{H}_5\text{OH}$), all of which were commercially obtained. These chemicals were used as received, without further purification, and were dried in an oven before use. A 0.22 μm filter paper was employed to filter the extracts during experiments. Deionized distilled water was used throughout the study for all processes. Additional equipment and supplies included a hot plate, gloves, a 10 mL syringe, a water disperser, spatulas, petri dishes, forceps, aluminum foil, and plastic weighing trays. the N-decane was sourced from Merck Co., Germany. Carbonate and sandstone rock samples were collected from outcrops of two reservoirs located in the eastern region of Nigeria.

Preparation Ricinus Communis Plant Extract.

The leaves of *Ricinus communis* were collected from the LAUTECH botanical garden. The leaves were thoroughly rinsed and washed with deionized water to remove any impurities, and then sun-dried to eliminate all moisture. 50 g of the dried leaves were ground into a fine powder using a pestle and mortar. The powdered leaves were then boiled in 100 ml of deionized water at 60 °C for 2 hours. During boiling, the water initially turned green and was continuously heated until the color changed to brown. After boiling, the mixture was allowed to cool at room temperature for 10 to 15 minutes. The residue was discarded, and the aqueous plant extract was collected by filtration through 22 μm Whatman filter paper into a clean beaker. The aqueous extract was subsequently stored in a refrigerator until further use.

This synthesis method is consistent with the procedure reported by Azeez *et al.* [26].

Synthesis of Carbon Quantum Dots (CQDs)

50 mL of *Ricinus communis* extract was placed into a Teflon-lined stainless-steel autoclave and subjected to hydrothermal treatment at temperatures ranging from 120 °C to 280 °C for 12 hours. After the reaction, the autoclave was allowed to cool naturally to room temperature. During this process, the solution changed to a dark brown color, indicating the formation of carbon dots (C-dots). These C-dots were then purified by filtering through a 2 μm filter paper to remove larger nanoparticles. The microstructure and particle size distribution of the C-dots were characterized using HRTEM and dynamic light scattering (DLS). This synthesis method is consistent with Castañeda-Serna *et al.* [27].

Synthesis of FQDs Nanocomposite

The FQD nanocomposite was synthesized via the co-precipitation method using a weight ratio of 2:1. Specifically, 2 mmol (0.02 g) of CoFe_2O_4 and 1 mmol (0.01 g) of gelatin-CQDs were dispersed in 10 mL of ethanol and stirred for 15 minutes to obtain a uniform mixture. The solution was then heated to 70 °C in an oil bath under an argon atmosphere, with magnetic stirring maintained for 4 hours. Following the reaction, the brown precipitate was collected using a strong external magnet, washed alternately with distilled water and ethanol in a 2:1 ratio, and finally dried overnight in an oven at 40 °C [28].

Synthesis of Graphene Oxide (GO)

The synthesized GO was prepared from graphite pencil lead using a modified Hummers' method. 2 g of finely powdered graphite were added to 50 mL of H_2SO_4 and stirred thoroughly with a magnetic stirrer for 60 minutes in an ice bath. While maintaining stirring, 7 g of KMnO_4 were gradually introduced to the mixture. The reaction mixture was then transferred to an oil bath, where it was

stirred continuously at 500 revolutions per minute (RPM) for 40 minutes. Next, 150 mL of reverse osmosis (RO) water was added, and stirring continued for about 20 minutes, after which 400 mL more water was added. Hydrogen peroxide was then slowly introduced to the mixture to ensure complete removal of residual oxidants, leading to an observable color change from brown to yellowish. The resulting suspension was filtered and washed with 250 mL of dilute HCl (1:10 dilution). The product was dried and subsequently dispersed in 500 mL of water. The GO solution was washed repeatedly to eliminate residual salts and acids. After neutralization, the GO dispersion was stirred overnight, and then sonicated to exfoliate graphite oxide into graphene oxide sheets. The final GO dispersion was stored for later reduction. This synthesis method is consistent with the results reported by Azeez *et al.* [29].

Synthesis of G-FQDs Nanohybrids

In typical synthesis, G-FQDs nanohybrid was prepared by a sol-gel process with a weight ratio of 2:1. Specifically, 2 mmol (0.02 g) of ferrite quantum dots and 1 mmol (0.01 g) of graphene were mixed thoroughly in 10 mL of ethanol for 15 minutes to achieve uniform dispersion. The solution was then heated to 80 °C in an oil bath and stirred magnetically under an argon atmosphere for 5 hours to ensure complete integration. Finally, the resulting mixture was dried overnight in an oven at 40 °C. The ratio agrees with the result reported by Hussein Talib *et al.* [30].

Characterization

The crystalline structures and other structural characteristics of the G-FQDs nanohybrid were analyzed using a Rigaku SmartLab X-ray diffractometer, with an X-ray generator operating at 40 kV and 30 mA for X-ray powder diffraction. To investigate its chemical composition and functional groups, Fourier Transform Infrared (FTIR) spectroscopy was conducted using a Perkin Elmer FTIR spectrometer over the range of 4,000 to 400

cm⁻¹. Additionally, Raman spectroscopy was employed to examine a material's chemical composition, crystal structure, polymorphism (different crystal structures of the same compound), crystallinity, and the presence of impurities or defects. The contact angle was measured using an optical goniometer after subjecting the samples to hydrothermal carbonization for 0.5, 1, 1.5, and 2 hours. The nanofluid was prepared by dispersing nanoparticles in a base fluid (water, oil) and stirring the mixture continuously to ensure a homogeneous mixture. Subsequently, the initial spectral characteristics of the nanofluid were measured using electrophoretic light scattering ELS to assess the velocity of particles moving in an electric field using laser light scattering. The zeta potential is calculated from the electrophoretic mobility of the particles. G-FQDs were combined with three different surfactants of Sodium Dodecyl Sulfate (SDS), sodium cetyl sulfate (SCS), and ammonium lauryl sulfate (ALS) stabilizer, at different mass concentrations of G-FQDs were tested (0.1, 0.3, 0.5, and 1 wt%). The samples were subjected to ultrasonic agitation for 2 hours to ensure proper dispersion. Following this, the samples were allowed to settle for 6 months, during which observations were conducted weekly to assess the stability of the suspension layer. The zeta potential was measured using the Malvern Zetasizer Nano ZS based on the principles of the electrophoretic method. These procedures were conducted in accordance with standard protocols [27,28].

Contact Angle Measurement

Contact angle measurements were performed to assess the changes in wettability of glass slides, which served as analogs for carbonate rock cores. Initially, the glass slides were aged in mineral oil for 48 hours to establish an oil-wet surface. Subsequently, these oil-wet slides were immersed in different fluids, including various concentrations of the prepared nanofluids for 24 hours. The contact angle of an oil droplet on the glass slides was measured using the sessile drop method, as illustrated in Fig 1. During testing, the glass slides

were placed inside a visual cuvette filled with brine, and a crude oil droplet was injected through an inverted needle, allowing it to rest on the underside of the slide. Magnified side-view images of the oil droplet were then captured, analyzed using advanced software to determine the contact angle, and processed for further evaluation.

However, the density of nanofluids containing varying concentrations of graphene/ferrite quantum dots (G-FQDs) and different surfactant ratios (CSC, SDS, and ALS) was measured at room temperature. This assessment aimed to investigate the effect of incorporating G-FQDs into the nanofluid formulations and how the combination with various surfactants influences the overall fluid density.

Results and Discussion

Characteristics of G-FQDs

UV-Visible Analysis

Plant extracts generally display multiple UV absorption peaks between 250 and 400 nm, reflecting the presence of unsaturated groups and heteroatoms as indicated in Fig 4. These peaks indicate that the extract contains bioactive compounds such as phenolics and flavonoids, which can act as natural surfactants or wettability modifiers to facilitate oil displacement. This synthesis approach aligns with the methodology of Esegbe *et al.* [34], as depicted in Fig 2. Graphene oxide (GO) typically exhibits a distinct absorption peak between 450 and 540 nm, signaling the partial restoration of the sp^2 carbon network and the development of amphiphilic properties, which is consistent with results reported by Nouri Mollalar *et al.* [35]. This amphiphilicity is essential for interfacial activity, allowing graphene-based nanofluids to effectively reduce interfacial tension and modify wettability, thereby enhancing oil recovery at low concentrations.

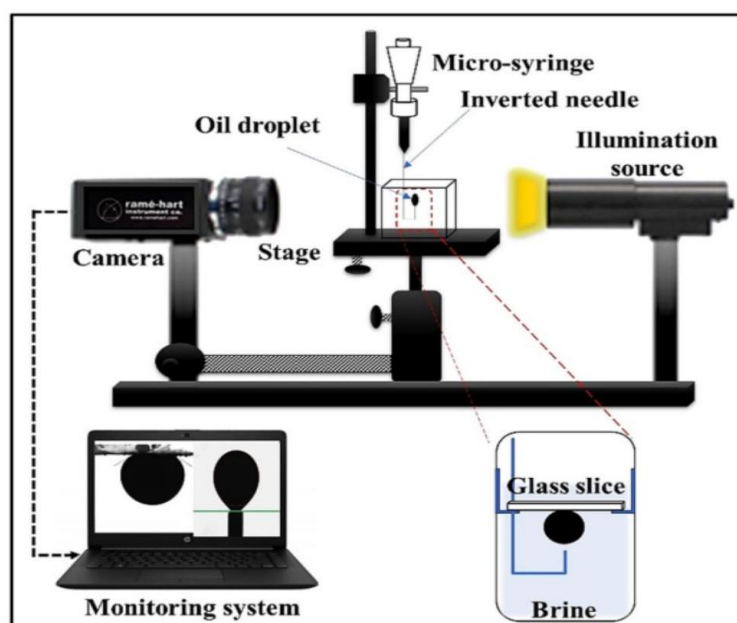


Fig 1. Goniometer utilized for contact angle measurements and IFT [33]

This synthesis is in agreement with Burresi *et al.* [36]. CoFe₂O₄ nanoparticles are characterized by UV-

Vis absorption in the visible range, often presenting broad bands due to d transitions and charge transfer between metal ions.

The observed absorption confirms both the presence and stability of these nanoparticles. Their unique optical and magnetic properties make them suitable for enhanced oil recovery (EOR), as they can be magnetically tracked, manipulated, or recovered, and may improve oil displacement through several mechanisms [37].

Carbon quantum dots (CQDs) typically show strong UV absorption between 480 and 580 nm, with a prominent peak around 540 nm.

These features indicate the presence of surface functional groups that improve CQD solubility and stability in water and brine. CQDs with such optical properties demonstrate excellent colloidal stability, low retention on reservoir rocks, and are effective in altering wettability and boosting oil recovery, even at very low concentrations [38].

FTIR Analysis

The FT-IR spectra for the extract, GNPs, CQD, and FQDs, nanocomposite are shown in Fig 3. The

spectra exhibit a broad absorption band between 3,000 and 3,600 cm^{-1} , along with distinct peaks in the 1,400–1,649 cm^{-1} range, which likely correspond to the stretching vibrations of O-H groups from water molecules adsorbed on the catalyst surface. For GNPs, a peak at 891 cm^{-1} is attributed to the stretched mode of O-H bond vibrations. Additionally, a peak at 1,495 cm^{-1} indicates the stretching vibration of Co in a metal-organic chelate, formed during the synthesis of CoFe_2O_4 (ferrite) due to the chelation of ethylene glycol and metal ions. The peaks in the 1,380–1,390 cm^{-1} range could be related to C-O-H formation in the in-plane band, resulting from the interaction between CoFe_2O_4 and GNPs. Furthermore, the absorption peak at 575 cm^{-1} likely reflects Fe-O and Co-O bond vibrations within CoFe_2O_4 . The comparative analysis of peaks between synthesized samples supports the successful synthesis of the composite material and agrees with the results reported by Ahmed *et al.* [39].

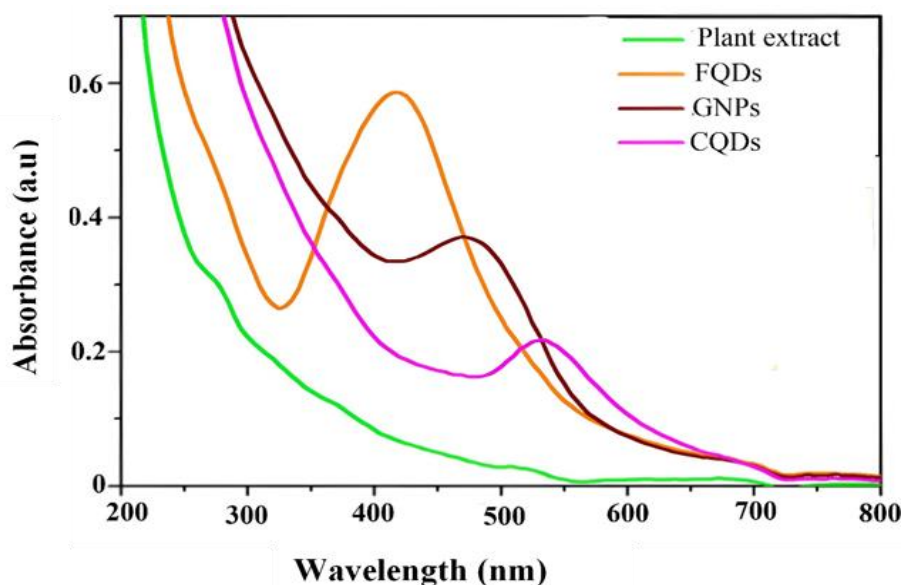


Fig 2. UV-Vis analysis of the prepared extract, GNPs, CQD, and FQDs

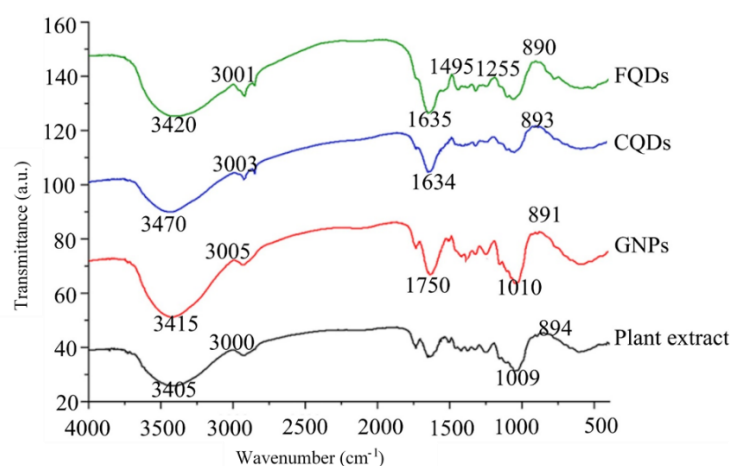


Fig 3. FTIR analysis of the prepared extract, GNPs, CQDs, and FQDs

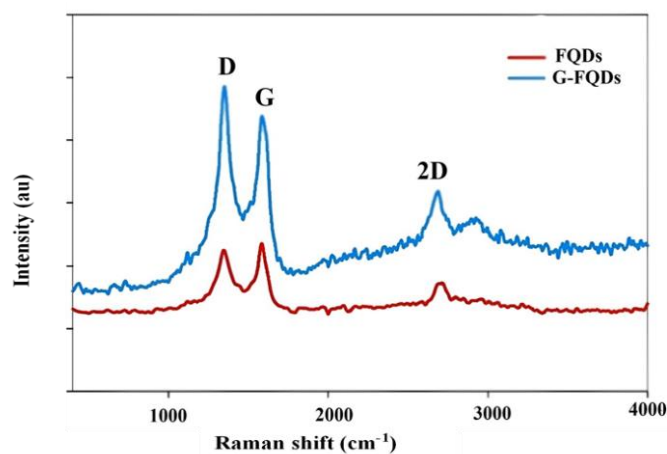


Fig 4. Raman spectroscopy of FQDs and G-FQDs

Raman Spectroscopy

Raman spectroscopy is a nondestructive analytical technique that is essential for evaluating the crystal structure quality of graphene before and after treatments. It provides information about the number of layers, crystallinity, defects, and impurities present in the material. Fig 4 presents the Raman spectra of graphene nanoparticles (GNPs), showing the characteristic main peaks. The D band at $1,360\text{ cm}^{-1}$ is associated with structural disorder and defects, while the prominent G band at $1,595\text{ cm}^{-1}$, which corresponds to the sp^2 bonded graphitic carbon.

In comparison, the FQDs-G powder exhibits the D and G bands at $1,369\text{ cm}^{-1}$ and $1,598\text{ cm}^{-1}$, respectively, with the D band being more dominant. The

intensity ratio of the D to G bands (I_D/I_G) for the grafted FQDs-G is higher than that of the pristine GNPs. This increased disorder ratio in the exfoliated graphene results from the conversion of carbon hybridization from sp^2 to sp^3 , due to the presence of functional polymer groups attached to the basal plane. This change provides clear evidence of the non-covalent functionalization of graphene. These observations are consistent with previous reports by Khan *et al.* [40]. The high absorption of the dispersant solvent with GNPs creates a protective shield, permitting to the peeling of the GNP layers under the high stress of the ultrasonication process into intact and thin graphene. Hence, the grafted graphene has a structure with a low ratio of defects.

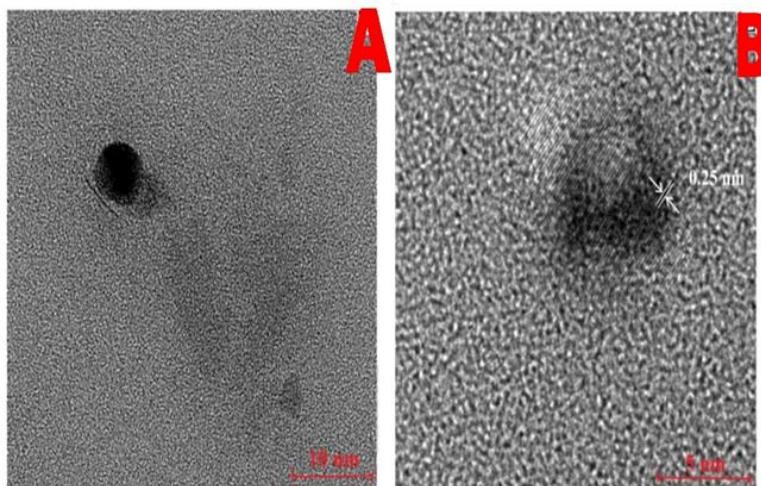


Fig 5. HRTEM analysis of G-FQDs nanohybrid

HRTEM Analysis

HRTEM is advanced imaging technique that allows us to visualize materials at the atomic level, providing critical insights into their structural and functional properties. Images of G-FQDs, along with the droplet size distribution, are presented in Fig 5. The HRTEM images reveal that the average droplet sizes of G-FQDs, determined using Digimizer image analysis software, range from 5 to 10 nm. Additionally, the droplets are uniformly dispersed in solution without any signs of agglomeration. The absence of agglomeration suggests that the nanoparticles are uniformly distributed. This consistency is essential for maximizing the surface area available for interactions with oil and enhancing the efficiency of recovery processes. When particles are well dispersed, they can more effectively interact with the oil, leading to improved recovery rates.

Alternation of Wettability and IFT Reduction

Wettability alteration is an essential enhanced oil recovery (EOR) strategy that transforms the reservoir rock surface properties to favor water over oil, thereby increasing the efficiency of oil displacement. By changing rock wettability from oil-wet to water-wet, this technique lowers residual

oil saturation and enhances the movement of hydrocarbons through mechanisms like capillary action and spontaneous imbibition. Interfacial tension (IFT) plays a pivotal role in EOR by affecting how easily trapped oil can be mobilized within reservoir rocks. Elevated IFT between oil and water strengthens capillary forces, making it more difficult for injected fluids to displace oil. Reducing IFT facilitates the release of trapped oil, improving recovery efficiency [30,35].

Impact of G-FQDs Size on Wettability Alteration

Contact angle measurements were performed to evaluate the oil flow rate in the presence of various nanofluids, with deionized water (DW) serving as the control. As demonstrated in Fig 6, the contact angle of oil on DW was recorded at 21.0 degrees, indicating that the carbonate slabs displayed water-wet characteristics. The introduction of 0.5 hydrothermal carbonization Times-G-FQDs significantly increased the oil contact angle from 21.0 degrees to 78.5 degrees, representing the most pronounced wettability change observed among all tested G-FQDs. This indicates that the presence of 0.5-G-FQDs shifted the carbonate slabs toward a water-wet condition. Furthermore, larger G-FQDs produced oil contact angles closer to the original water-wet state (with-

out G-FQDs). Smaller G-FQDs proved more effective in modifying surface properties due to their ability to better penetrate and interact with both the rock surface and oil droplets, leading to higher disjoining pressures [42].

Structural disjoining pressure is a phenomenon predictable in numerous studies, explaining the alteration of wettability in oil-wet rocks upon exposure to nanoparticles (NPs) [37,38]. This pressure represents the force needed to overcome the adhesion between the oil and the solid surface of the rocks, facilitating the fluid's detachment. According to this concept, NPs form a wedge-like film at the oil/water/rock interface, making both the size and concentration of NPs crucial in influencing the surface disjoining pressure.

As the size of the NPs decreases, the effects of Brownian motion become more pronounced. Consequently, increasing the concentration of NPs enhances the repulsive forces, leading to an elevated structural disjoining pressure [45].

The Stokes-Einstein equation supports the idea that decreasing the size of nanoparticles enhances Brownian motion [46].

$$D_B = \frac{K^B T}{3\pi\mu^f D_p} \quad (1)$$

Where, D_B is the Brownian diffusion coefficient (m^2/s), K_B is the Boltzmann constant (J/K), T is the

temperature (K), μ^f is the viscosity of the fluid ($\text{N}\cdot\text{s}/\text{m}^2$), and D_p is the diameter (m) of the NP.

Impact of G-FQDs Size on IFT

IFT between oil and water is a crucial factor in enhanced oil recovery (EOR), as lower IFT values generally facilitate increased oil extraction. The impact of the size of graphene/ferrite quantum dots (G-FQDs) on n-decane/water IFT was investigated. Similar to the wettability results presented in Fig 7, the application of 0.5-G-FQDs led to a significant reduction in n-decane/water IFT, which fell from 46.6 mN/m to 24.3 mN/m. The G-FQDs with the smallest sizes G-FQDs yielded the lowest IFT values, while those with the largest sizes resulted in the highest IFT values. Generally, our measurements show that larger (G-FQDs) promoted higher IFT. These findings align with existing literature reported by Lee *et al.* [47]; similar to how surfactants function, nanoparticles (NPs) gather at the oil-water boundary and lower interfacial tension (IFT). This IFT reduction is more noticeable with smaller NPs because a higher quantity can pack into the interface. Furthermore, smaller NPs provide a larger surface area for contact with the oil phase, enhancing asphaltene adsorption onto the NP surface.

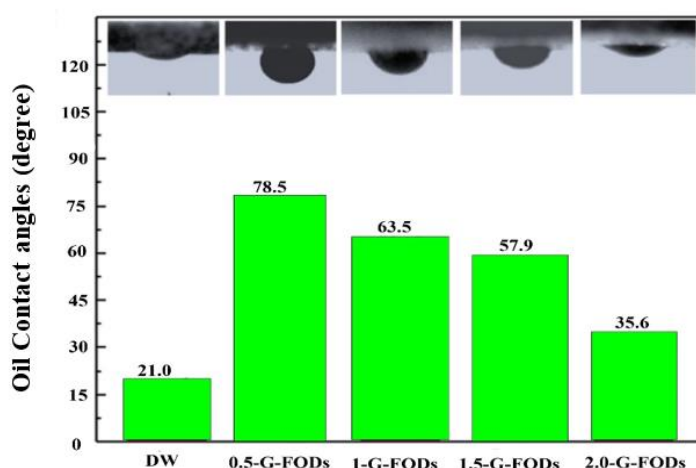


Fig 6. Contact angle after the treatment with carbonate rock of different nanofluids

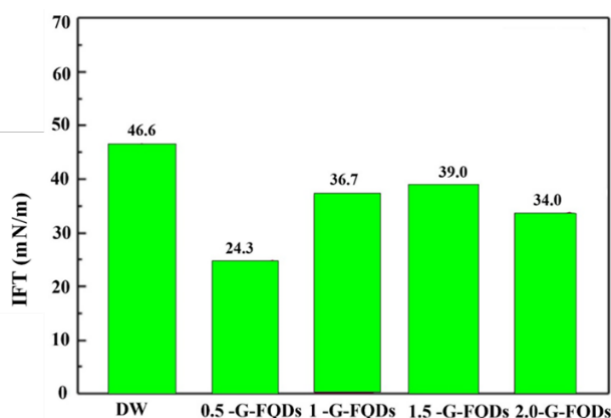


Fig 7. IFT alterations between n-Decane/fluids (water and nanofluids)

Stability of Nanofluids

Surfactants were incorporated into the nanofluids following specific G-FQD to surfactant ratios to enhance stability. After adding the surfactants, mechanical stabilization was achieved by probe sonication for 30 minutes, a process that increases the repulsive forces among G-FQDs, thereby improving particle dispersion and reducing aggregation. At a G-FQD to surfactant ratio of 1:0.2, the nanofluids displayed instability, with marked precipitation of G-FQDs observed across all surfactant types after 48 hours. Raising the ratio to 1:0.5 led to a substantial improvement agglomeration was significantly reduced and dispersion enhanced as illustrated in Fig 8. Specifically, the SDS-based nanofluid at this ratio exhibited only minimal agglomeration after three months, whereas nanofluids stabilized with SCS and ALS remained homogeneous and well-dispersed. Long-term stability testing over six months revealed that nanofluids with SCS and ALS surfactants sustained excellent stability, whereas approximately half of the G-FQDs in the SDS sample aggregated, as shown in Fig 9(a & b). Increasing the G-FQD to surfactant ratio further to 1:1 enhanced the stability for all surfactant types, maintaining homogeneous dispersion for at least six months, as depicted in Fig 10. These results indicate that G-FQD to surfactant ratios of 1:0.5 and 1:1 is optimal for long-term nanofluid stability and warrant further experimental verification. Notably, using only 0.5 wt% SCS was sufficient to achieve stable

nanofluid dispersions for over six months at a G-FQD concentration of 0.1 wt%. Additionally, stability assessments under heating and stirring conditions demonstrated superior stability for nanofluids with SCS and ALS surfactants. To support these findings, zeta potential measurements were performed at room temperature, with values provided in Table 1 for all surfactant types across three different ratios. The 1:0.5 ratio yielded the highest zeta potential for all surfactants, while the values decreased at the 1:1 ratio. Among the surfactants, the SDS sample showed comparatively higher zeta potential values. In the context of nanofluid stability, zeta potential values outside the range of +30 mV to -30 mV typically indicate strong stability and minimized aggregation tendency [48]. Enhancing the surfactant ratio from 1:0.2 to 1:0.5 increased the zeta potential, while further increasing the ratio to 1:1 reduced the zeta values. It is believed that the high negative surface charge of the nanoparticles is closely related to the good dispersion stability of the nanofluids [49]. This stability results from particle repulsive forces that balance particle attraction and inhibit assembly. Meanwhile, with the increase in G-FQDs concentration, the average size of the particles tends to increase. This emphasizes the need for an optimal surfactant-to-G-FQD balance to achieve the best possible stability, as excessively high surfactant concentrations may reduce the effectiveness of the surface charge and compromise stability.



Fig 8. The stability results of nanofluids after 48 hrs for 0.5 wt% of G-FQDs with a ratio of 1:0.2

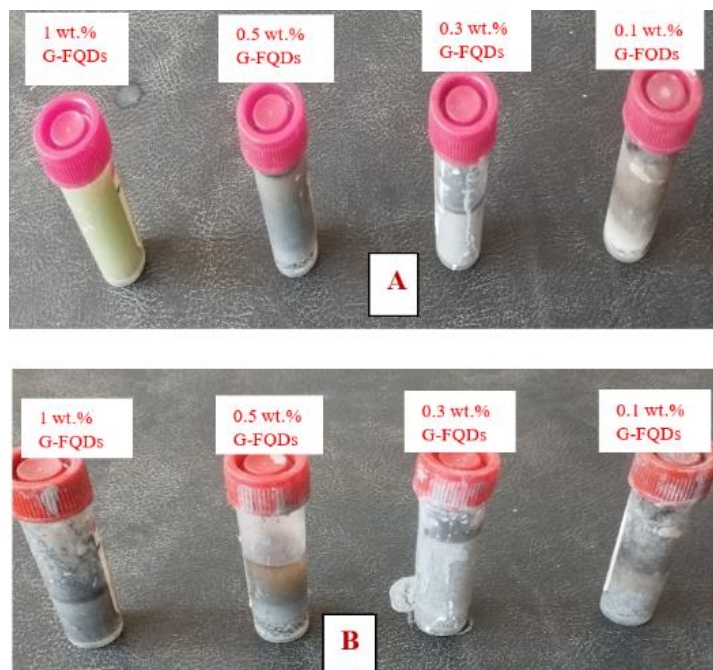


Fig 9. a and b: The stability results after 6 months of nanofluids at different G-FQDs concentrations with a ratio of 1:0.5 (C:S), where A and B are CSC and ALS, respectively



Fig 10. Stability results after 6 months of nanofluids at different G-FQDs concentrations with a ratio of 1:1.0 (C:S) using SDS surfactant

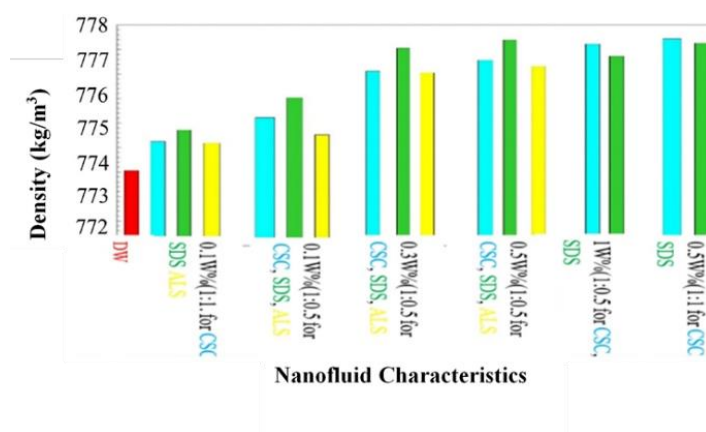


Fig 11. Density values of nanofluids at different concentrations, ratio of G-FQDs to surfactant and types of surfactants

Table 1. Zeta potential measurement for different surfactant

G-FQDs (ratio)	SDS	CSC	ALS
1:0.2	-52.7	-48.7	-44.2
1:0.5	-62.1	-49.2	-47.1
1:1.0	-56.0	-50.1	-47.8

Density of Nanofluid

Fig 11 illustrates the density of nanofluids at various G-FQD concentrations and surfactant ratios, measured at room temperature. The incorporation of G-FQDs into the water resulted in only slight changes in density, likely due to the relatively small amounts of G-FQDs added, which contributed minimally to the overall fluid density. For example, the density of CSC-based nanofluids increased by just 0.12% when 0.1 wt% of G-FQDs was used with a 1:0.5 surfactant ratio. When the G-FQD concentration was raised to 1 wt% at a 1:1 surfactant ratio, the density increase was still modest, at only 0.65%. It is important that nanofluids formulated with SDS surfactants exhibited higher densities compared to those with ALS and CSC surfactants. These findings align with the observations reported by Teng *et al.* [50], who noted a density increase ranging from approximately 0.02% to 0.5% with 0.04 wt% CNT additions.

Conclusion

This study demonstrates that Graphene-Ferrite Quantum Dots (G-FQDs) present a promising and

cost-effective approach for enhanced oil recovery by effectively addressing common issues of nanoparticle stability and agglomeration in harsh reservoir environments. Significantly lowering the oil-brine interfacial tension and, more importantly, drastically changing the wettability from oil-wet to water-wet conditions, the synthesized G-FQDs demonstrated exceptional stability in high-salinity and high-temperature conditions. Even at very low concentrations of nanofluid, the results show that altering wettability is more important for enhancing oil recovery than reducing interfacial tension. Therefore, under reservoir conditions, nanofluids based on G-FQDs have a great potential to improve residual oil displacement and mobility in porous media. Although these nanofluids induce only slight density changes with minimal effects on bulk fluid flow and pressure during reservoir injection, their primary advantage lies in interfacial property modification. Nevertheless, translating laboratory results to field-scale remains challenging due to reservoir heterogeneity, temperature, pressure variations, and chemical complexity affecting nanoparticle behavior and recovery efficiency. There-

fore, further research is needed to improve nanoparticle stability, concentration optimization, precise characterization, and scaling strategies before practical field deployment can be realized.

Authors' Contribution

Surajudeen Otolowo Azeez, Oluwaseun Adedokun, and Sarafadeen Ayinde Azeez contributed to the study design. Akeem Adekunle Adewale, Khadijat Kuburat Babalola, and Kamaldeen Olanikanmi Suleman participated in data collection. Data analysis was performed by Surajudeen Otolowo Azeez and Oluwaseun Adedokun. The manuscript was written by Surajudeen Otolowo Azeez, while Taofik Adewale Adedosu, Yekinni Kolawole Sanusi, and Qasim Abolanle Adeniji contributed to the manuscript editing and review. Lukman Ayobami Sunmonu served as the supervisor.

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