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Investigation of the Effects of Multi-Walled Carbon Nanotubes Concentration and Sonication Time on the Performance of EOR Nanofluids

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ABSTRACT - The rising global energy demand drives the development of more efficient and environmentally friendly enhanced oil recovery (EOR) technologies. Nanofluids based on multi-walled carbon nanotubes (MWCNTs) stabilized by the surfactant sodium dodecyl sulfate (SDS) can improve oil recovery by altering rock wettability and increasing the viscosity of the injected fluid. This study investigates the effects of two synthesis parameters of the MWCNT/SDS nanofluid in two stages: MWCNT mass concentration and sonication time. In the first stage, nanofluids were synthesized at varied MWCNT concentrations (0.0002–0.001 g/100 mL) under 20 minutes of sonication. In the second stage, the best-performing concentration was used while the sonication time was varied (10–60 minutes). Nanofluid performance was evaluated through contact angle, viscosity, and colloidal stability tests. The results show that increasing the MWCNT concentration decreased the contact angle from 47.73° to 31.22° and increased the viscosity from 0.9414 to 1.0384 cP. At the best-performing concentration (0.001 g/100 mL), prolonging the sonication time reduced the contact angle to 19.22° at 60 minutes, increased the viscosity to 1.0770 cP, and improved the colloidal stability (stable up to 36 hours). The combination of an MWCNT concentration of 0.001 g/100 mL and a sonication time of 60 minutes produced the MWCNT/SDS nanofluid with the best characteristics within the tested range for EOR applications.

Keywords: enhanced oil recovery; Multi-Walled Carbon Nanotubes; nanofluid; sodium dodecyl sulfate; sonication time.

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1. Introduction

Energy is an essential element in nearly all aspects of human life and the main driver of industrial and economic activity. According to the International Energy Agency (IEA), global dependence on fossil fuels remains significant. Oil demand is projected to approach 105.7 million barrels per day, driven by the petrochemical and transportation sectors [Eckhouse 2025](#). This condition demands innovative strategies to improve the efficiency of crude oil recovery from existing reservoirs. A large fraction of the original oil in place remains trapped in reservoir pores after conventional production because of unfavorable rock wettability, strong capillary forces, and poor mobility control, so technologies that can modify these rock–fluid interactions are increasingly required.

Enhanced oil recovery (EOR) is an advanced recovery method that enables extraction of additional crude oil beyond what primary and secondary recoveries can produce, with recovery factors reaching 30–60% of the original oil in place [\(Kandiel et al., 2025\)](#). EOR methods are generally grouped into thermal injection, gas injection, chemical injection, microbial, and nanofluid use [\(Malozyomov et al., 2023\)](#). Among these methods, chemical EOR is widely investigated because chemical agents can modify rock fluid interactions and improve the displacement of residual oil. In particular, surfactants can reduce interfacial tension and alter rock wettability, while nanoparticles can provide additional surface interactions and improve the properties of the injected fluid. Recent studies published in *Scientific Contributions Oil and Gas* have demonstrated the potential of these approaches. [Rowi et al \(2025\)](#) reported that a combination of nano silica and anionic surfactants improved the wettability and interfacial properties of the injected fluid and showed potential for enhanced oil recovery in sandstone reservoirs. Similarly, [Ridaliani et al \(2025\)](#) demonstrated that palm oil based methyl ester sulfonate (MES) could improve oil displacement during laboratory scale surfactant flooding in berea sandstone. These studies show that the formulation and interaction of chemical EOR fluids with rock and oil are important factors in improving recovery performance.

Among emerging EOR approaches, nanotechnology through nanofluids is considered promising because it can effectively modify the rock–fluid interfacial properties while potentially being more environmentally friendly [\(Maia et al., 2024; Tong et al., 2023\)](#). Nanotechnology can improve crude oil recovery through several mechanisms, including wettability alteration, increased mobility of trapped oil, structural disjoining pressure, and interfacial tension reduction [\(El-Masry et al., 2023; Tong et al., 2023\)](#). Nanoparticles with diameters of 1–100 nm possess a large specific surface area and a high surface-area-to-volume ratio, which strongly influence fluid properties such as heat transfer, viscosity, and surface activity. Nanoparticles with diameters of 1–100 nm possess a large specific surface area and a high surface-area-to-volume ratio, which strongly influence fluid properties such as heat transfer, viscosity, and surface activity. Compared with conventional chemical EOR agents, nanofluids offer distinct advantages: nanoparticles can penetrate small pore throats, adsorb onto rock surfaces to alter wettability toward a more water-wet state, reduce residual oil saturation, and moderately increase the viscosity of the injected fluid, thereby improving the mobility ratio and sweep efficiency [\(El-Masry et al., 2023; Kandiel et al., 2025\)](#). Laboratory and pilot studies of nanofluid flooding have reported incremental oil recoveries of roughly 5–20% over conventional water flooding, depending on the nanoparticle type, concentration, and rock properties [\(El-Masry et al., 2023; Tong et al., 2023\)](#). In particular, a reduction in contact angle reflects wettability alteration toward a more water-wet state, which weakens oil adhesion to pore walls, lowers residual oil saturation, and thus increases oil recovery [\(Ebrahimi et al., 2025; Taheri et al., 2025\)](#), while an increase in the viscosity of the injected nanofluid improves the water–oil mobility ratio and volumetric sweep efficiency, which also contributes to higher oil recovery [\(Kandiel et al., 2025; Yousefrouz et al., 2025\)](#). Combining nanofluids with surfactants can further improve oil recovery efficiency by taking advantage of the complementary effects of nanoparticles and surfactants [\(Maia et al., 2024; Ridaliani et al., 2025; Rowi et al., 2025\)](#).

Multi-walled carbon nanotubes (MWCNTs) are among the most widely studied nanomaterials owing to their high thermal conductivity, chemical stability, and superior mechanical properties [\(Esfe et al., 2021; Yahyazadeh et al., 2024\)](#). However, MWCNTs are hydrophobic and difficult to disperse in water due to their large surface area and strong interparticle van der Waals forces, which cause them to agglomerate and settle. The main challenge in utilizing MWCNTs is obtaining a uniform and stable dispersion in the liquid phase [\(Kim et al., 2023; Yahyazadeh et al., 2024\)](#).

To overcome this challenge, surfactants and sonication are employed. The surfactant sodium dodecyl sulfate (SDS) reduces interfacial tension and maintains colloidal stability. Its amphiphilic structure binds MWCNT particles, preventing agglomeration and ensuring uniform dispersion (Heris et al., 2024). Sonication (ultrasonication) provides mechanical energy that breaks particle clusters and distributes them evenly in the carrier liquid (Asadi & Alarifi 2020). The sonication duration strongly influences dispersion quality. An adequate duration improves homogeneity and stability, whereas excessive duration may damage the nanoparticle structure (Jalilov et al., 2026; Razavifar et al., 2025).

Most previous studies have examined the use of MWCNT-based nanofluids for EOR in general (Belhaj et al., 2019; El-Masry et al., 2023), but few have systematically investigated the influence of key synthesis parameters, particularly MWCNT mass concentration and sonication time, on nanofluid performance. Therefore, this study investigates these two parameters in two stages. The first stage identifies the best-performing MWCNT mass concentration by varying the concentration at a fixed sonication time, and the second stage evaluates the effect of sonication time at the best concentration obtained. Nanofluid performance is assessed using contact angle (wettability) measurements, viscosity, and colloidal stability tests, yielding the MWCNT/SDS nanofluid formulation best suited for EOR applications within the tested range. The MWCNT concentration range (0.0002–0.001 g/100 mL) was selected based on previous reports that very low nanoparticle loadings are sufficient to alter wettability while minimizing the risk of agglomeration and pore plugging at higher concentrations (Belhaj et al., 2019; El-Masry et al., 2023), and the sonication window (10–60 minutes) follows studies showing that dispersion quality improves with sonication time up to a limit beyond which the nanoparticle structure may be damaged (Jalilov et al., 2026; Razavifar et al., 2025). Contact angle, viscosity, and colloidal stability were chosen as evaluation parameters because they directly represent three key requirements of an EOR nanofluid: wettability alteration, mobility control, and stability during injection.

2. Methodology

2.1 Materials

This research was carried out at the Nanotechnology Laboratory and the Integrated Laboratory, Universitas Diponegoro, Semarang. The materials were sodium chloride (NaCl, Merck, Germany), multi-walled carbon nanotubes (MWCNT) produced by the Nanotechnology Laboratory of Universitas Diponegoro, sodium dodecyl sulfate (SDS, Merck, Germany), distilled water, light synthetic hexadecane oil (Merck, Germany), and Berea sandstone core as the wettability test medium.

2.2 Laboratory facilities and data reproducibility

The experiments were conducted at the Nanotechnology Laboratory and Laboratorium Terpadu, Diponegoro University (UNDIP), Semarang City, Central Java, Indonesia. These laboratories are part of Diponegoro University and provide facilities for nanomaterial preparation, sample analysis, and physicochemical measurements. The MWCNT used in this study was produced by the Nanotechnology Laboratory of UNDIP. Laboratorium Terpadu was used for the experimental measurements and laboratory analysis. The nanofluids were prepared using a magnetic stirrer at 500 rpm and an ultrasonic probe homogenizer with a power of 1200 W, as described in the experimental procedure. Contact angle measurements were carried out using the reverse sessile drop method, while viscosity was measured using an Ostwald viscometer. The stability of the nanofluids was evaluated by visual observation during heating at 40 °C.

To ensure data reproducibility, the same experimental conditions were maintained for all samples, including MWCNT concentration, SDS concentration, stirring speed, sonication power, sonication time and temperature. We repeated viscosity measurements under the same experimental conditions and present the results as the mean $\pm$ standard deviation (SD). The contact angle measurements and stability observations were also conducted using the same measurement procedure for each sample. Consistent experimental conditions and measurement procedures were applied throughout the study to minimize experimental variation and improve result reproducibility.

2.3 Synthesis of MWCNT/SDS nanofluid

Synthesis began with the preparation of a 1% NaCl brine as the solvent medium. SDS at 0.1% was dispersed into the brine by stirring at room temperature at 500 rpm until homogeneous. MWCNT was then weighed according to the predetermined variation and slowly added to the brine–SDS solution while stirring continuously for 5 minutes. The mixture was sonicated using an ultrasonic probe homogenizer at 1200 W. The resulting MWCNT/SDS nanofluid colloid was stored at room temperature before analysis. The overall synthesis procedure is summarized in Figure 1. This study was conducted in two sequential stages, as illustrated in Figure 1.

2.4 Variation of MWCNT mass concentration

In the first stage, the sonication time was fixed at 20 minutes while the MWCNT mass concentration was varied into five levels: 0.0002, 0.0004, 0.0006, 0.0008, and 0.001 g/100 mL. The SDS (0.1%) and brine NaCl (1%) concentrations were kept constant. This stage aimed to determine the MWCNT concentration that produced the best wettability change and fluid characteristics.

2.5 Variation of sonication time

In the second stage, the best MWCNT concentration from Stage I (0.001 g/100 mL, equivalent to 0.005 g MWCNT and 0.250 g SDS in 500 mL of solvent) was used as a fixed parameter, while the sonication time was varied to 10, 20, 30, 45, and 60 minutes. A non-sonicated sample (0 minutes) was used as a comparison in the contact-angle test.

2.6 Characterization and testing

Contact angle testing was performed to evaluate alterations in rock wettability using the reverse sessile drop method. Berea cores were first saturated by immersion in 1% brine for 30 minutes at 40 °C, then rinsed with distilled water. The core was immersed in the MWCNT/SDS nanofluid, and a hexadecane oil droplet was injected from below using a size-25 needle so that it rose and touched the rock surface. The droplet image was captured with a macro-lens camera and processed using image-analysis software (ImageJ) to determine the contact angle. Viscosity was measured with an Ostwald viscometer by recording the efflux time of the fluid through the capillary, with brine as the reference. Stability was assessed visually. The nanofluid was continuously heated to 40 °C and observed every 12 hours to monitor agglomeration and sedimentation.

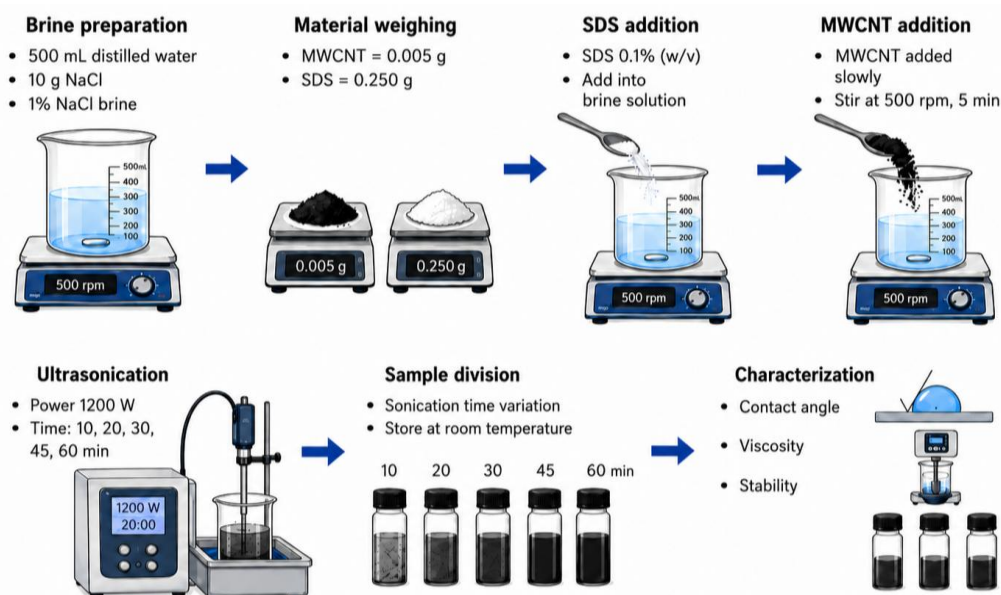


Figure 1.
Synthesis scheme of the MWCNT/SDS nanofluid.

2.7 Research variables

The independent variables were the MWCNT mass concentration and the sonication time. The dependent variables were the contact angle, viscosity, and visual stability of the nanofluid. The fixed variables in the stability test were the SDS concentration (0.1%), brine NaCl concentration (1%), stirring speed (500 rpm), sonication power (1200 W), and heating temperature (40 °C).

3. Result and discussion

3.1 Effect of MWCNT Mass Concentration

Five MWCNT concentrations were evaluated at a fixed 20-minute sonication time. The contact angle and viscosity results are summarized in Table 1.

Contact angle analysis is a primary parameter for determining the wettability of a fluid on a rock surface. Reservoir rocks are generally water-wet, but prolonged contact with oil turns them oil-wet, causing oil to adhere to the rock surface and lowering recovery efficiency. As shown in Table 1 and Figure 2, the contact angle decreased almost linearly with increasing MWCNT mass concentration, from 47.73° at 0.0002 g/100 mL to 31.22° at 0.001 g/100 mL.

Table 1.
Contact angle and viscosity of MWCNT/SDS nanofluid at various MWCNT mass concentrations (20-minute sonication).

MWCNT concentration (g/100 mL)	Contact angle (°)	Viscosity (cP)
Brine	–	0.8901 ± 0.0002
0.0002	47.73	0.9414 ± 0.0003
0.0004	45.00	0.9546 ± 0.0004
0.0006	38.74	0.9875 ± 0.0006
0.0008	37.12	1.0141 ± 0.0001
0.0010	31.22	1.0384 ± 0.0003

All measured contact angles lie below 90°; the decrease does not represent a transition from oil-wet to water-wet conditions; rather, it indicates that increasing the MWCNT concentration shifts the wettability of the Berea core sample from moderately water-wet toward strongly water-wet conditions. This change results from the synergistic effect between the nanoparticle charge and the presence of surfactant in the nanofluid. Adsorption of MWCNTs on the rock surface alters the rock's free surface energy, so the oil droplet wets the surface less and detaches more easily. The higher the MWCNT concentration, the more particles are adsorbed, and the greater the wettability change (Ebrahimi et al., 2025; Taheri et al., 2025). It should be noted that no surfactant-free nanofluid was tested as a baseline, so the individual contribution of SDS to the contact-angle reduction cannot be isolated in this study; the observed reduction is therefore attributed to the combined MWCNT/SDS system, in which SDS is known to lower interfacial tension and assist nanoparticle dispersion and adsorption (Heris et al., 2024; Maia et al., 2024). A surfactant-free control experiment is recommended for future work.

Viscosity is an important nanofluid property because it affects pumping power, the pressure drop in laminar flow, and the mobility ratio of the injected fluid to oil. Table 1 and Figure 3 show that the viscosity increased with MWCNT concentration, from 0.8901 cP (brine) to 1.0384 cP at the highest concentration. The added particles increase flow resistance because MWCNTs disrupt the motion of water molecules, thereby increasing solution viscosity (Abdolahi et al., 2025; Kanti et al., 2024).

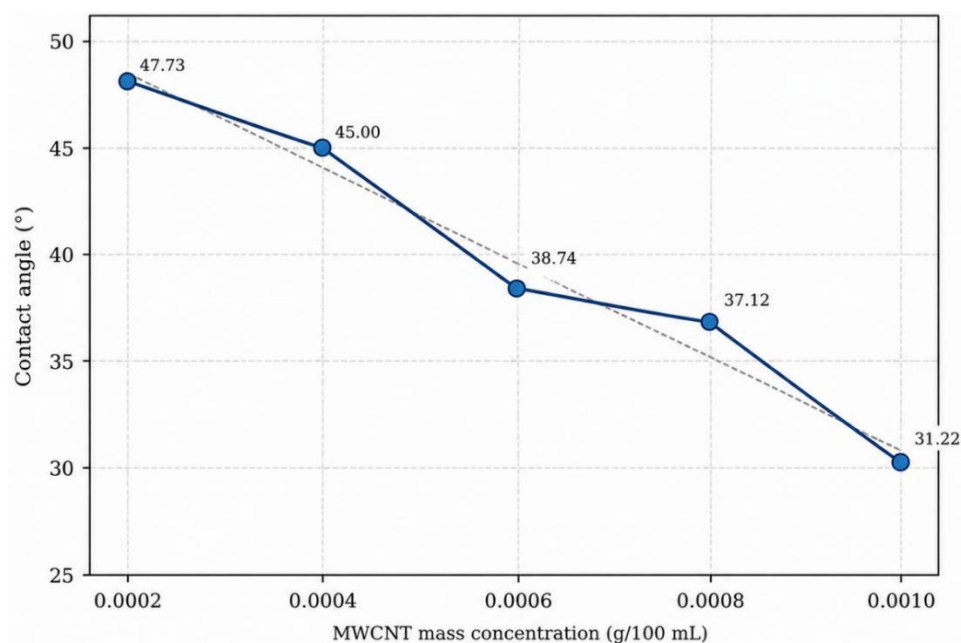


Figure 2.
Effect of MWCNT mass concentration (0.0002-0.001 g/100 mL) on the contact angle of MWCNT/SDS nanofluids at a fixed SDS concentration of 0.1% and sonication time of 30 min.

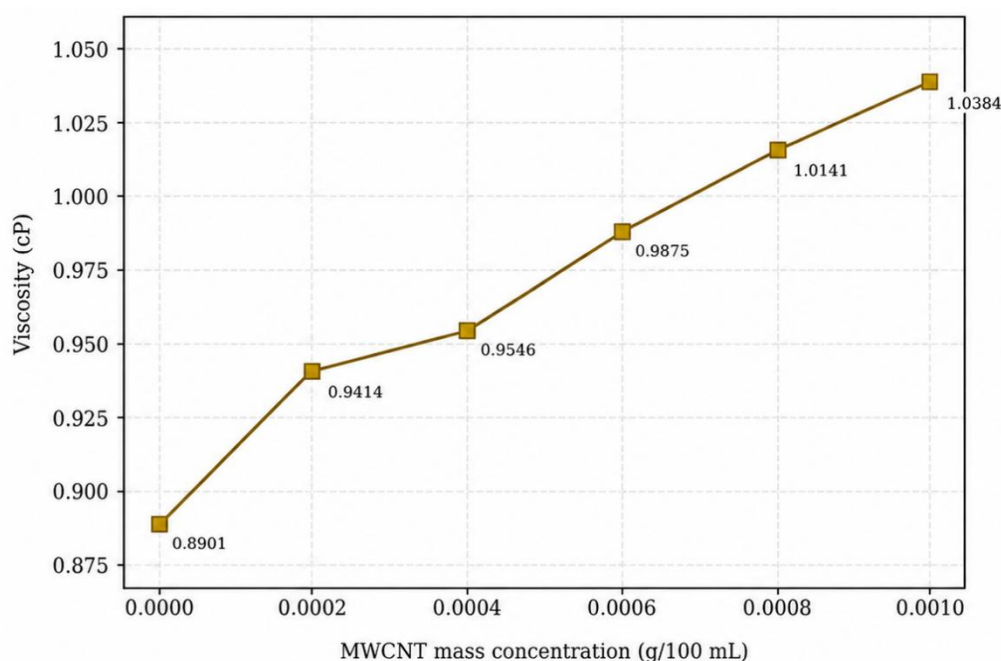


Figure 3.
Effect of MWCNT mass concentration (0.0002-0.001 g/ 100 mL) on the viscosity of MWCNT/SDS nanofluid at a fixed SDS concentration of 0.1% and sonication time of 30 minute.

The viscosity difference between the nanofluid and brine was small (0.0513–0.1483 cP). A slightly higher viscosity than brine is advantageous for EOR because it improves the mobility ratio without causing excessive injection resistance, making oil displacement in porous media more efficient (Kandiel et al., 2025; Tong et al., 2023). Nevertheless, viscosity increases of this magnitude (about 0.05–0.15 cP) are too small to establish effective mobility control by themselves; confirming a mobility-control benefit would require displacement (core-flooding) experiments and a more comprehensive assessment of nanofluid-based mobility control in EOR (Kandiel et al., 2025).

Stability was observed for up to 48 hours at 40 °C. Visually, increasing the MWCNT concentration made the fluid appear more concentrated but also increased the amount of sediment formed. The most agglomeration was observed at the highest concentration. Time-series photographs of these observations are presented in Figure 6a. According to DLVO theory, when the van der Waals attraction exceeds the electrostatic repulsion, particles tend to agglomerate and eventually settle (Javadipour et al., 2023). In Stage I, colloidal stability was still limited because the dispersion produced at 20-minute sonication was not optimal (Jalilov et al., 2026; Javadipour et al., 2023). Considering the balance between the largest wettability change (the smallest contact angle of 31.22°) and an adequate increase in viscosity, the concentration of 0.001 g/100 mL was selected as the best-performing concentration within the tested range. Because the contact angle decreased and the viscosity increased continuously over the concentrations tested, these data do not conclusively establish an optimum concentration; additional experimental points at higher concentrations would be required for that purpose.

3.2 Effect of sonication time

In the second stage, nanofluids were synthesized at the best-performing concentration of 0.001 g/100 mL (0.005 g MWCNT and 0.250 g SDS in 500 mL of solvent) with sonication times ranging from 0 to 60 minutes. The contact angle and viscosity results are summarized in Table 2.

Table 2.
Contact angle and viscosity of MWCNT/SDS nanofluid at various sonication times (0.001 g/100 mL concentration).

Sonication time (min)	Contact angle (°)	Viscosity (cP)
0	39.44	—
10	38.93	—
20	37.16	1.0384 ± 0.0003
30	28.98	1.0607 ± 0.0004
45	21.39	1.0715 ± 0.0006
60	19.22	1.0770 ± 0.0001

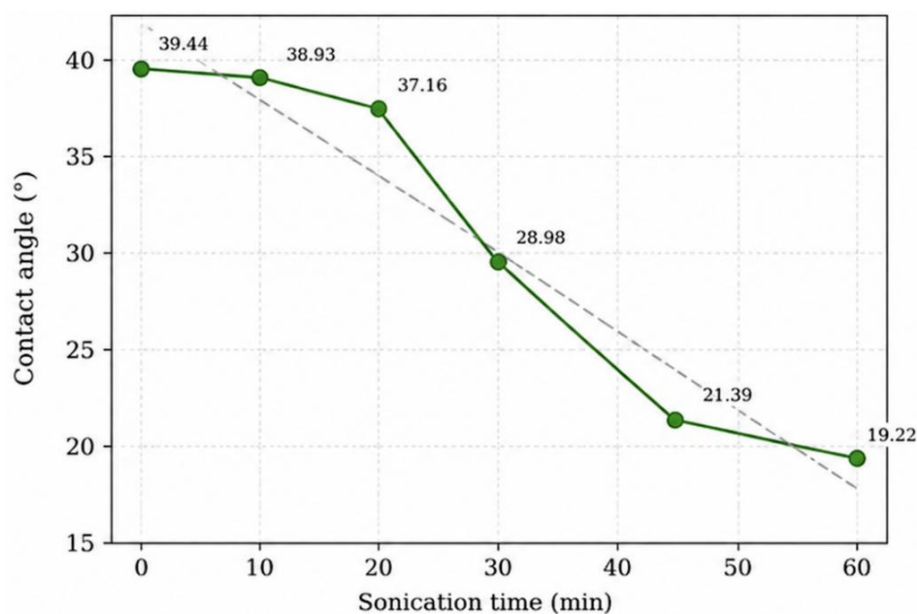


Figure 4.
Effect of sonication time (10-60 minute) on the contact angle of the MWCNT/SDS nanofluid containing 0.001 g/ 100 mL MWCNT at a fixed SDS concentration of 0.1%.

The contact-angle results (Table 2 and Figure 4) show a consistent decrease as sonication time increases. Without sonication, the contact angle was 39.44° ; it decreased to 37.16° at 20 minutes, 28.98° at 30 minutes, 21.39° at 45 minutes, and reached a minimum of 19.22° at 60 minutes, indicating a progressively stronger shift toward strongly water-wet conditions.

Longer sonication improves MWCNT dispersion, so that more particles are evenly distributed and available for adsorption on the rock surface, thereby increasing surface modification and lowering the contact angle. These results are consistent with previous studies showing that ultrasonic-assisted nanofluids can enhance wettability and oil-recovery efficiency (Bathali et al., 2026; Qu et al., 2024; Razavifar et al., 2025). It should be noted that the contact angle measured at 0.001 g/100 mL and 20 minutes of sonication in Stage II (37.16° , Figure 4) differs from that obtained in Stage I (31.22° , Figure 2). The two values were obtained in separate experimental campaigns using freshly prepared nanofluid batches and different Berea core surfaces, and contact-angle measurements on natural rock are sensitive to local surface roughness and mineral heterogeneity, which explains the discrepancy. Importantly, the decreasing trends with MWCNT concentration and with sonication time remain consistent in both campaigns.

The nanofluid viscosity increased steadily with sonication time (Table 2 and Figure 5), from 1.0384 cP at 20 minutes to 1.0607 cP (30 min), 1.0715 cP (45 min), and a peak of 1.0770 cP at 60 minutes. This increase reflects an increasingly homogeneous particle dispersion: a more even MWCNT distribution enlarges inter-particle interactions and internal fluid resistance, raising the viscosity (Asadi & Alarifi 2020; Kanti et al., 2024). The rates of contact-angle reduction (Figure 4) and viscosity increase (Figure 5) tend to level off at longer sonication times, suggesting that an optimum is being approached; however, additional experimental points beyond 60 minutes are required to establish this optimum conclusively.

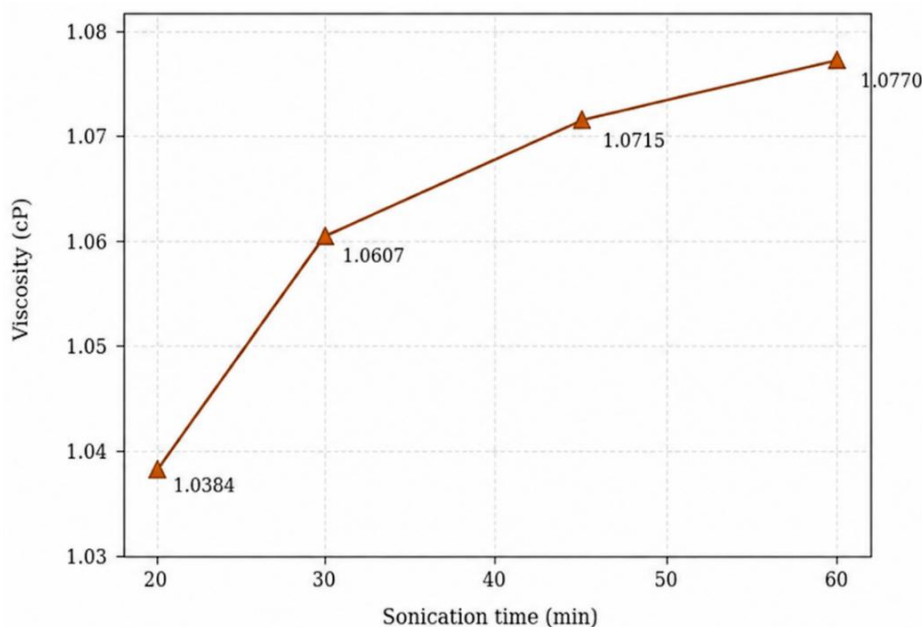


Figure 5.
Effect of sonication time (10-60 minutes) on the viscosity of the MWCNT/SDS nanofluid containing 0.001 g/ 100 mL MWCNT at a fixed SDS concentration of 0.1%.

This controlled viscosity increase is beneficial for EOR because it improves the mobility ratio and oil-sweep efficiency during injection without causing excessive flow resistance in porous media (Yousefrouz et al., 2025).

The colloidal stability results in Stage 1 are presented in Figure 6. The stability observations showed that the longer the sonication time, the greater the stability of the MWCNT/SDS nanofluid, as evidenced by reduced sedimentation and a more uniform particle distribution. After 12 hours, all samples sonicated for 10–60 minutes showed relatively little sedimentation. After 24 hours, samples with shorter sonication times began to show more

sediment, whereas the 45- and 60-minute samples remained stable. At 36 hours, the 60-minute sample retained the best stability. SDS plays a key role here: its amphiphilic structure binds the non-polar MWCNT and prevents agglomeration, keeping the dispersion even (Heris et al., 2024; Jalilov et al., 2026; Javadipour et al., 2023). The initial dispersions immediately after each sonication treatment are shown in Figure 7, and time-series photographs of these observations are presented in Figure 8.

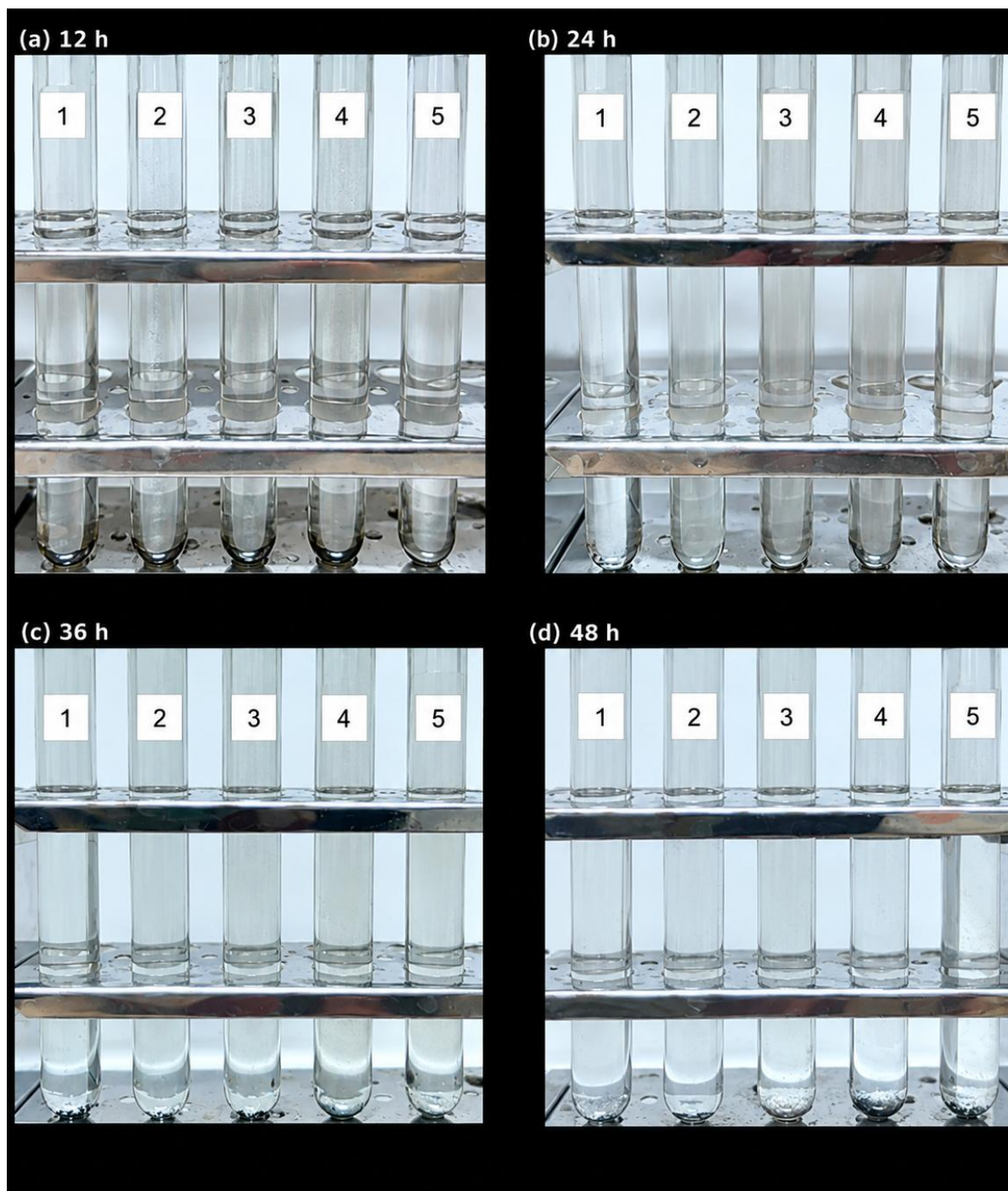


Figure 6.

Visual observation of the colloidal stability of the MWCNT/SDS nanofluids at different MWCNT mass concentrations during Stage I: nanofluids containing (a) 0.0002; (b) 0.0004; (c) 0.0006; (d) 0.0008; and (e) 0.001 g/100 mL MWCNT were observed after 12, 24, 36, and 48 hours.

The images show the progressive formation of sediment with increasing MWCNT concentration and observation time.

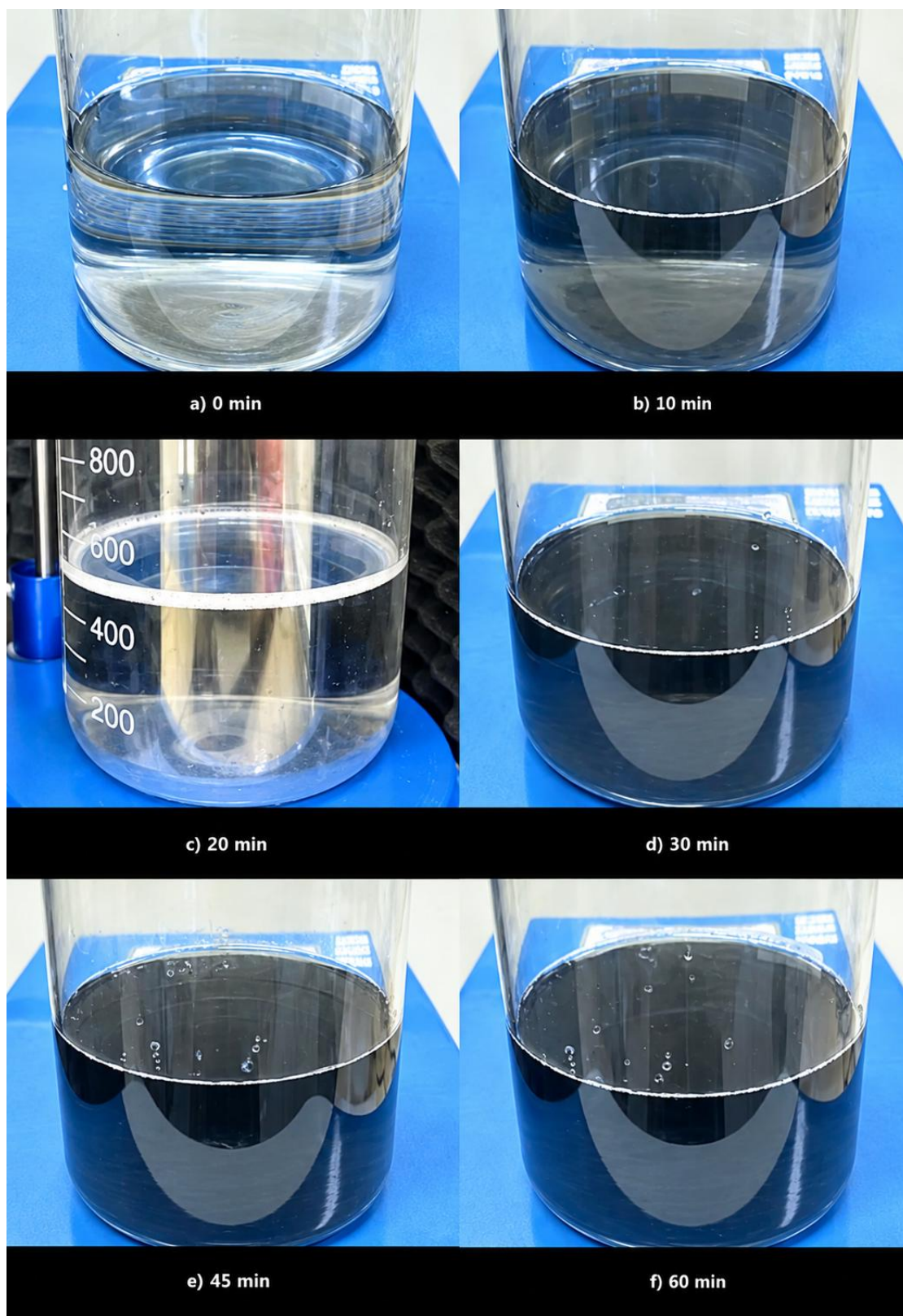


Figure 7.

Initial visual appearance of MWCNT/SDS nanofluids containing 0.001 g/ 100 mL MWCNT after different sonication times during Stage II, (a) 0; (b) 10; (c) 20; (d) 30; (e) 45; and (f) 60 minute.

The image illustrate the initial dispersion state of the nanofluids immediately after sonication.

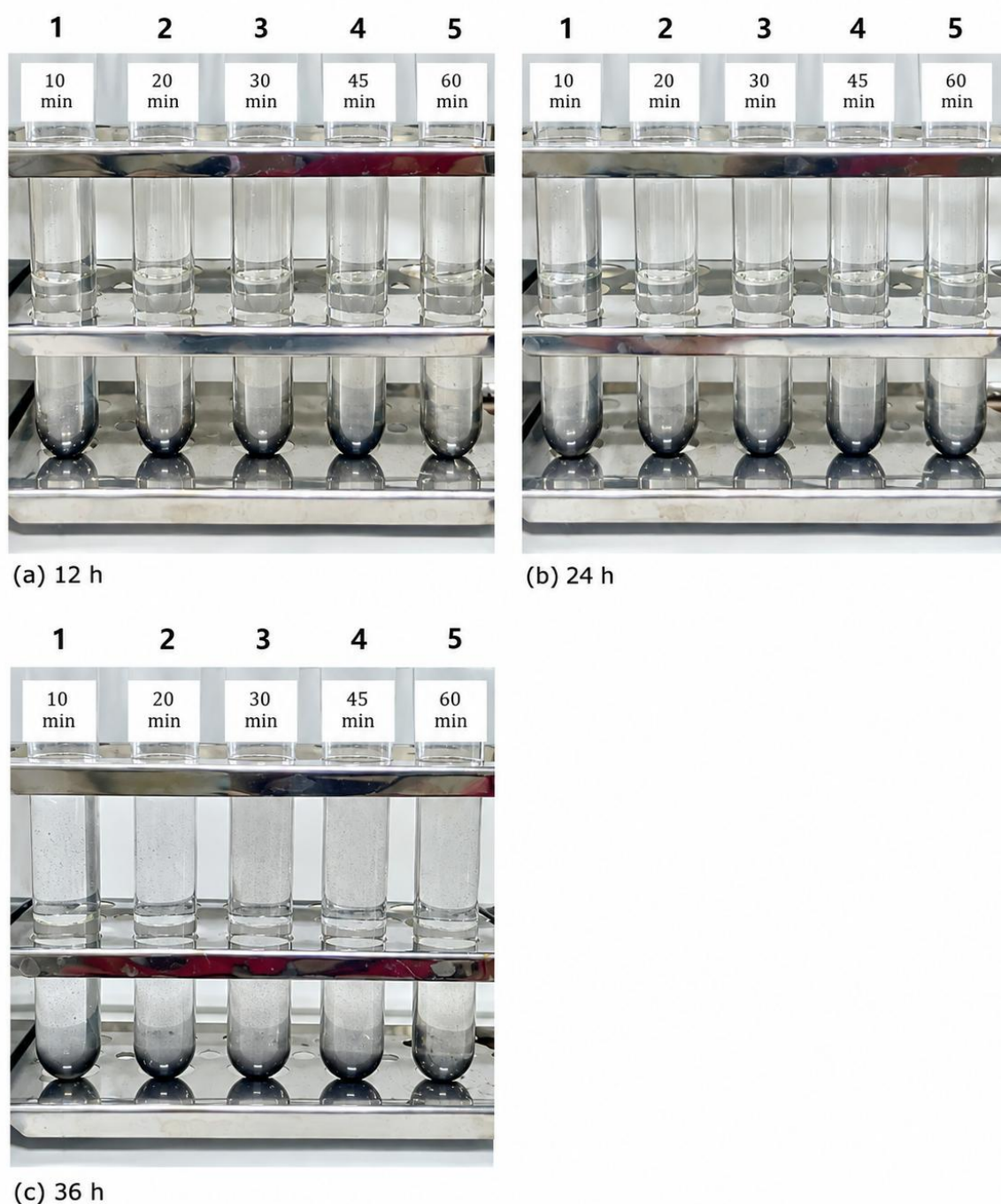


Figure 8.

Visual observation of the colloidal stability of MWCNT/SDS nanofluids containing 0.001 g/100 mL MWCNT after different sonication times during Stage II, nanofluids sonicated for 0, 10, 20, 30, 45, and 60 minute were observed after 12, 24, and 36 hours.

The images show improved dispersion stability with increasing sonication time, with the longest sonication time providing the most stable visual dispersion within the observation period.

Overall, the results show that an MWCNT concentration of 0.001 g/100 mL, sonicated for 60 minutes, yields the MWCNT/SDS nanofluid with the smallest contact angle (19.22°), a favorable viscosity (1.0770 cP), and the best colloidal stability among the tested conditions. The combination of MWCNT and SDS is effective in reducing interfacial tension and improving oil recovery by reducing the residual oil trapped in porous media (Maia et al., 2024; Soleimani & Sadeghi 2025; Taheri et al., 2025).

4. Conclusion

The synthesis of MWCNT/SDS nanofluid for enhanced oil recovery (EOR) was successfully investigated through two sequential stages by evaluating the effects of MWCNT concentration and sonication time. Increasing the MWCNT concentration improved the nanofluid properties by reducing the contact angle from 47.73° to 31.22° and increasing the viscosity to 1.0384 cP, with 0.001 g/100 mL identified as the best-performing concentration within the tested range. At this concentration, extending the sonication time to 60 min further enhanced the nanofluid performance by decreasing the contact angle to 19.22°, increasing the viscosity to 1.0770 cP, and maintaining colloidal stability for up to 36 h. These findings demonstrate that the combination of 0.001 g/100 mL MWCNT and 60 min sonication produces a stable nanofluid with improved wettability and rheological properties, which are essential for enhancing oil displacement efficiency. Therefore, the resulting MWCNT/SDS nanofluid shows strong potential as a chemical agent for EOR applications. It should be emphasized that these findings were obtained on initially water-wet Berea sandstone at 40 °C and ambient pressure; the two-stage screening approach used here is generally applicable to other nanofluid systems, but the specific values reported are valid only within the tested range and should not be extrapolated directly to reservoir conditions. Future research should evaluate the performance of MWCNT-based nanofluids using initially oil wet rock samples (contact angle >90°) initially, conduct additional experiments to determine the optimal MWCNT concentration and sonication time, and investigate interfacial tension reduction, transport behavior in porous media, and oil recovery performance through core-flooding experiments under reservoir conditions.

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6. Declarations

6.1 Author contributions

Heydar Ruffa Taufiq: conceptualization; writing original draft; investigation. Ngurah Ayu Ketut Umiati: review & editing; methodology; Validation. Diah Ayu Purbowati: data curation; Visualization. Eva Fariha Sal Shabillah: software; Formal analysis. Khasan Rowi: Investigation; Validation. Nesti Dwi Maharani: Writing - Review & Editing; Visualization. Agus Subagio: Supervision; Funding acquisition; Resources.

6.2 Funding statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

The authors did not use generative AI or AI-assisted technologies in the preparation of this manuscript

7. Glossary of terms and symbols

Terms and Symbols	Definition	Unit
C	MWCNT mass concentration	g/mL
m	Mass of MWCNT	g
θ	Contact angle	°
μ	Dynamic viscosity	cP
S	Colloidal stability	h
SDS	Sodium Dodecyl Sulfate	-
$\Delta\theta$	Change in contact angle	°
$\Delta\mu$	Change in viscosity	cP

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