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Full Length Research

Experimental investigation of the viability of biodiesel synthesized from moringa seed oil in oil based drilling mud formulation

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ABSTRACT: The environmental and regulatory pressures associated with petroleum diesel-based drilling fluids have accelerated the search for sustainable alternatives in oil and gas operations. This study evaluates *Moringa oleifera* seed oil biodiesel as a substitute base fluid in oil-based mud (OBM) formulations. Moringa seeds were sourced locally in Lagos, Nigeria, prepared through dehulling and grinding, and subjected to Soxhlet extraction using ethanol. The crude oil was pre-treated via acid esterification to reduce free fatty acids, followed by alkaline-catalyzed transesterification to synthesise fatty acid methyl esters (FAME). Physicochemical characterisation of raw oil, biodiesel, and petroleum diesel was conducted, assessing parameters such as viscosity, density, acid value, flash point, cloud point, and pour point. Two mud systems, Moringa biodiesel-based mud (MBM) and petroleum diesel-based mud (PDM), were formulated with identical additives and tested for rheological, static, and filtration properties under varying thermal conditions. Results showed that Moringa seeds yielded 29.45% oil, with a biodiesel conversion efficiency of 91.37%. Biodiesel exhibited reduced viscosity (5.303 mm^2/s) and acid value (1.336 mgKOH/g) compared to raw oil, and a higher flash point (121°C vs. 71°C for diesel), confirming enhanced safety and stability. Mud performance tests revealed comparable densities (9.0 ppg) and phase stability across MBM and PDM, with MBM showing slightly higher alkalinity (pH 8.7 vs. 8.09) and marginally elevated fluid loss (3 mL/30 min vs. 2 mL/30 min). Gel strength and rheological profiles demonstrated MBM's ability to maintain structural integrity across elevated temperatures (up to 170°F), with shear stress and yield point values closely matching those of PDM.

Keywords: Moringa biodiesel oil-based mud, physicochemical properties, rheological performance, sustainable drilling.

INTRODUCTION

Drilling fluids are indispensable in oil and gas exploration and production operations because they perform critical functions necessary for efficient and safe drilling activities. These functions include cooling and lubricating the drill bit, transporting drill cuttings to the surface, stabilising the wellbore, and controlling formation pressure during drilling operations. Drilling fluids are generally classified into water-based muds (WBMs), oil-based muds (OBMs), and synthetic-based muds (SBMs). Among these categories, oil-based drilling muds are widely preferred in complex drilling environments due to their superior thermal stability, lubricity, shale inhibition capacity, and enhanced performance under high-pressure and high-temperature conditions (Adesina *et al*., 2012). Despite these advantages, conventional oil-based muds commonly utilise diesel, mineral oils, and other petroleum-derived fluids as the continuous phase, which pose significant environmental and ecological concerns because of their toxicity, poor biodegradability, and disposal challenges.

The increasing global emphasis on environmental sustainability and stricter regulations governing drilling waste disposal have stimulated research into the development of environmentally friendly drilling fluids. In this regard, biodiesel has emerged as a promising

alternative base fluid for oil-based drilling mud systems. Biodiesel is a renewable and biodegradable fuel composed mainly of fatty acid methyl esters produced from vegetable oils, animal fats, or waste oils through transesterification processes (Balat, 2007; De Paola *et al*., 2021). Compared with conventional petroleum-derived oils, biodiesel exhibits lower toxicity, improved biodegradability, and reduced environmental impact, making it attractive for sustainable drilling operations. Previous studies have demonstrated the feasibility of utilising locally synthesised biodiesel in drilling fluid formulations with encouraging rheological and lubricating properties (Duru *et al*., 2022). Similarly, Bataee *et al*. (2024) reported the successful application of palm oil biodiesel as a replacement for diesel oil in drilling mud systems, further supporting the potential of bio-based drilling fluids.

Among the numerous vegetable oils explored for biodiesel production, *Moringa oleifera* seed oil has attracted considerable attention because of its unique physicochemical properties and high oil yield. *Moringa oleifera*, commonly referred to as the “miracle tree” or “tree of life,” is a fast-growing and drought-resistant plant widely cultivated in tropical and subtropical regions of Africa and Asia (Pareek *et al*., 2023; Cao *et al*., 2023). The plant possesses extensive nutritional, medicinal, industrial, and environmental applications due to its rich composition of bioactive compounds (Gopalakrishnan *et al*., 2016). The seeds of *Moringa oleifera* contain substantial quantities of oil, ranging from approximately 30–40%, with a high proportion of oleic acid that contributes to excellent oxidative stability and desirable fuel characteristics (Leone *et al*., 2016; Idris *et al*., 2020). Studies have shown that moringa seed oil possesses favourable physicochemical properties suitable for biodiesel production and other industrial applications (Orhevba *et al*., 2013; Garba *et al*., 2024).

The suitability of moringa seed oil as a biodiesel feedstock has been investigated by several researchers. Abdulkareem *et al*. (2011) optimised the extraction of oil from *Moringa oleifera* seeds as an alternative feedstock for biodiesel production, while Abdu and Fatima (2014) identified moringa oilseed as a viable biodiesel feedstock in Northern Nigeria. Additionally, the optimisation of biodiesel production from different vegetable oils has demonstrated the growing potential of renewable feedstocks in sustainable energy development (Hadiyanto *et al*., 2020; Abdullahi *et al*., 2022). The high oxidative stability, biodegradability, and renewable nature of moringa seed oil-derived biodiesel make it a promising candidate for environmentally friendly oil-based drilling mud formulations.

Furthermore, the increasing interest in green and sustainable oilfield chemicals has encouraged the exploration of bio-based additives and surfactants for drilling fluid systems. Hafshejani *et al*. (2016) developed a novel bio-based deflocculant for bentonite drilling mud, while Obeta *et al*. (2025) synthesised green surfactants from underutilised plant seeds for oilfield applications. These studies highlight the growing shift toward renewable and biodegradable materials in drilling fluid technology. Nevertheless, despite the increasing attention given to biodiesel-based drilling fluids, limited information is available regarding the application of biodiesel synthesised from moringa seed oil in oil-based drilling mud formulations.

Therefore, this study experimentally investigates the viability of biodiesel synthesised from *Moringa oleifera* seed oil as a substitute for conventional diesel in oil-based drilling mud formulation. The research evaluated key parameters such as rheological properties, lubricity, stability, and environmental impact to determine the feasibility of MSOB as a sustainable component in drilling muds. The findings from this research are expected to contribute to the development of sustainable, eco-friendly, and biodegradable drilling fluid systems capable of reducing the environmental footprint associated with conventional oil-based drilling muds while promoting the industrial utilisation of renewable agricultural resources.

MATERIALS AND METHODS

Seed sample preparation

The moringa seed (Figure 1) was acquired from a local market in Alimosho LGA (Latitude 6.5936ºN, Longitude 3.2612ºE), Lagos state, Nigeria. To prepare the moringa seeds for extraction, the good seeds were carefully selected from the seeds collected, and they were dried under the sun for a couple of days to reduce their moisture content. The seeds were then dehulled to remove the outer shell or coat and re-dried. After that, the seeds were ground into powder form using a manual grinder to allow for better extraction yield. The diesel was stored in an air-tight container in preparation for the experiment.

Seed oil extraction

The experiment was performed in a 1000 ml Soxhlet apparatus using ethanol as an extraction solvent. The setup consists of a reflux condenser, thimble, distillation flask, heating mantle, and a retort stand. The solvent (ethanol) was heated to evaporate, travelled up a distillation arm, and flooded into the thimble chamber, housing the solid sample tied in a sack. The condenser ensures that the solvent vapour cools and drips back into the chamber housing the solid material. The chamber, therefore, slowly fills with warm solvent and dissolves the oil in the solid sample. When the Soxhlet chamber was almost full of ethanol, it emptied by the siphon. The solvent was returned to the distillation flask with the dissolved oil from the sample. The thimble ensures that the rapid motion of the solvent does not transport any solid material to the

Figure 1. Moringa seed before and after dehulling: (a). Moringa seeds before dehulling, (b). Moringa seeds after dehulling.

Figure 2. Oil in the stirrer during transesterification and Biodiesel/glycerol after transesterification: (a) During transesterification, (b) Biodiesel/glycerol after transesterification.

still pot. This cycle was allowed to repeat many times over hours. After dewaxing, the sample was oven-dried at 60°C for 3 hours and kept in a bottle for the next stage of operation.

Extracted oil pre-treatment

Due to the high fatty acid content of the extracted oil, the oil was pre-treated by the acid esterification process before the transesterification process was carried out. About 200g of oil in a glass reactor was esterified with 25 wt% of methanol using 1.0 wt% H_2SO_4 as a catalyst to reduce the free fatty acids to less than 1% FFA. The mixtures were placed on a constant temperature magnetic stirrer set to heat at a constant temperature of 60°C for 1 hour transesterification reaction.

Synthesis of moringa oil biodiesel

The synthesis of moringa oil biodiesel was carried out using the transesterification process. The esterified moringa oil was converted into biodiesel using the following process (Figure 2). The synthesis of FAME from esterified triglyceride and methanol was carried out in a 250ml glass reactor placed on a constant temperature magnetic stirrer at atmospheric pressure. About 200 g of

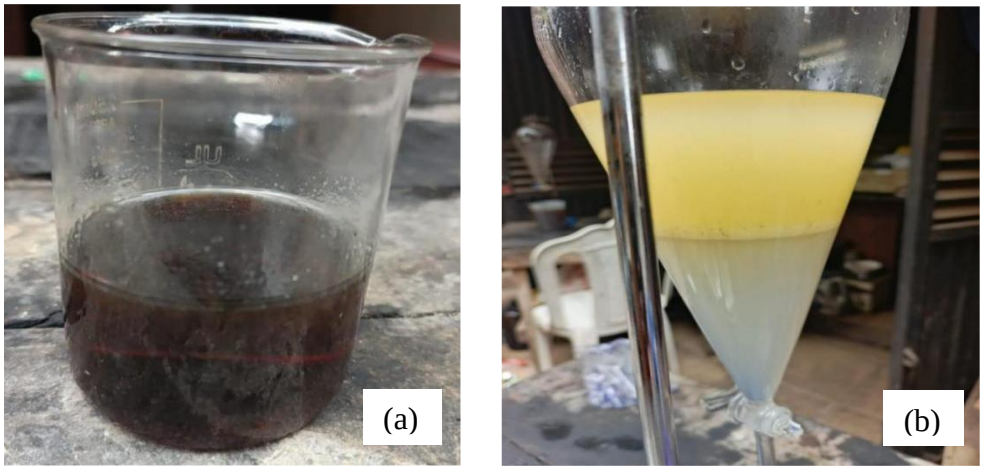

Figure 3. Separated glycerol & Biodiesel washing: (a)Separated glycerol, (b) Biodiesel washing.

the esterified oil was weighed into the glass reactor for the experiment. The oil was heated to a constant temperature of 60°C. The heat was added to a mixture of methanol, 23 wt% of oil and NaOH, 1 wt% of oil. The reaction was conducted with constant stirring of the mixture at about 450rpm for 60 minutes. After the reaction, the mixture was transferred into a 250ml separating funnel where the product was separated into two layers of FAME and glycerol (Figure 3). the glycerol was then removed leaving only the methyl esther which was mixed with warm deionized water at 50ºC using a stirrer to create a homogenous mixture after which the mixture is left to settle resulting in phase separation due to density differences, The water at the lower layer which now contains the excess methanol and catalyst was removed and the clean biodiesel at the upper layer was retrieved. All these purification processes is for ensuring a good quality biodiesel that meets fuel standards.

Characterisation of moringa raw oil, moringa biodiesel and traditional diesel

The physiochemical properties of the moringa oil (MO), moringa oil biodiesel (MOB) and the traditional diesel (TD) were determined in the laboratory to assess their quality and stability. The properties characterized includes: cloud point, pour point, flash point, acid value, free fatty acid, viscosity and density.

Acid value

Exactly 0.05M KOH solution was prepared by dissolving 2.805 g KOH (pellet) with 1000ml distilled water. Furthermore, a mixture of 99.7% pure ethanol and 98% pure benzene in a ratio of 1:1 by volume was prepared by mixing 50 ml benzene and 50 ml of ethanol. About 1g of the oil was weighed and dissolved in the mixture of ethanol and benzene. The solution was titrated with 0.1N KOH solution in the presence of 2 drops of phenolphthalein as an indicator until the endpoint with the appearance of a pale permanent pink. The titre volume of 0.1 N KOH (V) was noted. The total acidity (acid number) in mgKOH/g was calculated using the following equation.

$$AV = \frac{MW \times N \times V}{W} \quad (1)$$

Where: MW = Molecular weight of potassium hydroxide (56.1g), N = Normality of potassium hydroxide solution (0.1 N), V = Volume of potassium hydroxide solution used in titration, W = Weight of oil sample.

Free fatty acid

The FFA content was calculated from this equation;

$$\%FFA = \frac{AV}{2} \quad (2)$$

Where: AV = Acid Value

Flash point

The flash point of the MO, MOB, and TD were determined separately using recommendations from Garba *et al*. (2024) as cited in Abubakar *et al*. (2020) it involved pouring the oil sample into a 50 cm^3 beaker to about 10cm3 and then heating the sample in a hot plate at a controlled rate (5 - 6 °C/min) and stirring to ensure uniform heating of the sample and periodically introducing the ignition source into the vapor space above the liquid

sample and then observing for a flash indicated by a brief flame over the sample surface and the flash point was then recorded as the lowest temperature at which that brief flame was observed. This procedure was done about 3 times to ensure consistency with the recorded flash point.

Cloud point

The cloud point of the MO, MOB, and TD were determined separately using recommendations from Garba *et al*. (2024) as cited in Abubakar *et al*., (2020) it involved filling a cylindrical test tube with the sample at a desired volume and clamping the test tube with a clamp that contains a thermometer and then placing the sample in the test tube into a cooling bath, the temperature was monitored with the thermometer and the sample was visually inspected periodically for cloudiness and the temperature at which the first trace of cloudiness appeared in the test tube was recorded as the cloud point.

Pour point

The pour point of the MO, MOB, and TD was determined separately using the ASTM D97-17b method. The sample was poured into the cylindrical test tube and closed with a clamp containing a thermometer, it was then pretreated by heating to about 9°C above the expected pour point for each of the samples before being placed in a waterbath at temperature of 24°C, after the sample was cooled to a point where paraffin wax could form, the sample was then removed from the water bath and tilted on the clamp and observed various times (intervals of 3°C below the initial temperature) for any movement, if any movement was observed, the test was repeated, after several checks there was no flow or movement observed from the sample after tilting it horizontally for about five seconds then the temperature at which there was no flow of the sample was checked from the thermometer and recorded as the pour point of the sample (Analytical, n.d).

Density

The density of the MO, MOB, and TD were determined separately using recommendations from Garba *et al*., (2024) as cited in Abubakar *et al*., (2020) it involved washing and rinsing a substitute of a specific gravity bottle with acetone and drying it before placing in a dessicator to cool at room temperature and then placing it on a weighing scale to determine the weight of the bottle and then recording the measured weight and then the volumes of each sample were measured and recorded before pouring them into the bottle separately and measuring their weight on a weighing scale and recording that weight. The density of each sample was then calculated from the formula below.

$$\text{Density} = \frac{(Weight\ of\ the\ bottle + Sample) - (weight\ of\ the\ bottle\ only)}{Volume\ of\ sample} \quad (3)$$

Viscosity

The Brookfield NDJ-5S Rotary viscometer was used in the determination of viscosity. The appropriate spindle number was identified and selected for the test sample and gently mounted on the machine. A 250ml beaker was cleaned, and the sample was poured up to the 200ml mark. The beaker was then placed on a water bath with the temperature preset at a constant 30°C and allowed to equilibrate for 10 minutes. The spindle and the temperature sensor of the machine were then lowered into the sample, and the power button was turned on. The appropriate spindle number and speed were selected on the display screen, followed by the run button. The machine was then allowed to read the viscosity until a stable value was obtained and recorded.

Hydrogen peroxide value

The hydrogen peroxide of the MO, MOB, and TD was determined separately using the iodometric titration method based on a study by Garba *et al*. (2024). This procedure involves weighing a specific amount of the oil sample into a clean, dry conical flask and then dissolving the sample in a mixture of glacial acetic acid and chloroform, ensuring the mixture is completely dissolved. Potassium iodide solution is then added to the flask and swirled gently to mix. The mixture is then allowed to stand in the dark for a few minutes, so the peroxides in the oil react with potassium iodide to release iodine. After the reaction, distilled water is added to the flask to dilute the mixture and prevent iodine loss. Titration then begins by slowly adding sodium thiosulfate solution while swirling continuously. When the yellow colour of iodine becomes pale, starch is introduced into the solution as an indicator, which will turn the mixture blue. Titration is continued with sodium thiosulfate until the blue colour disappears completely, marking the endpoint. A blank test is then performed using the same steps but without the oil sample to determine the baseline. The peroxide value is calculated using the recorded titration volumes, the weight of the oil sample, and the normality of the sodium thiosulfate solution, which are incorporated into Equation 4.

$$\text{PV} = \frac{(V - Vb) \times N \times 1000}{W} \quad (4)$$

Where: PV = Peroxide value (milliequivalents of active oxygen per kg of oil), V = Volume of sodium thiosulfate used for the oil sample (mL), V_b = Volume of sodium thiosulfate used for the blank (mL), N = Normality of sodium thiosulfate solution.

Saponification value

The saponification value of the MO and MOB was determined separately using the ASTM D1962 titration method, which involves taking 2g of the oil sample in a beaker and dissolving it in 10 mL of ethanol solvent and then transferring 25mL of ethanolic 0.5 nomality of KOH to the oil solvent mixture and using the same procedure for a blank sample. Afterwards, the samples are attached to a reflux condenser and heated to the water boiling point for about 30 minutes, after which the samples are allowed to attain room temperature and then 2 drops of phenopthaelin indicator are added to the samples and titrated against 0.5 nomality of HCl. Finally, the saponification value can be estimated from Equation 5.

$$\mathrm{SV} = \frac{M_W \times N \times (V_{blank} \times V_{test})}{W_s} \quad (5)$$

Where: Mw = Molecular weight (g/mol) of KOH, Vblank = Volume (mL) of HCI for a blank sample, Vtest = Volume (mL) of HCl for the test sample, N = Normality(mol/mL) of KOH, W = Weight (g) of the sample.

Moisture content

The moisture content of the MO, MOB, and TD were determined separately by weighing a specific amount of each sample in pre weighed petri dishes and placing the samples in an oven and drying at 500℃ for about two hours and then taking the weight of the samples every thirty minutes and repeating the procedure until a constant weight is obtained, the sample is to be taken out of the oven after every thirty minutes and kept in a dessicator to cool before being reweighed, and the result of the dry sample is then determined and recorded. The moisture percentage can be calculated using Equation 6.

$$\mathrm{MC}\ (\%) = \frac{W_i \times W_d}{W_i} \times 100 \quad (6)$$

Where: W_i = Initial weight of the sample, and W_d = Weight of the sample after drying.

Kinematic viscosity

The kinematic viscosity of the MO, MOB, and TD at 40cp and 100cp and were determined separately using Equation 7.

$$\text{Kinematic viscosity (cSt)} = \frac{Dynamic\ Viscosity}{Density} \quad (7)$$

Formulation of drilling mud

Two separate drilling muds were formulated using moringa oil biodiesel (MOB) and traditional diesel (TD) as the base fluids. These muds were formulated by mixing the oil with various concentrations of chemicals and additives. Below is a list of the chemicals and additives used for the formulation of both muds in the order in which they were mixed and the amounts used.

1. Base fluid (Moringa biodiesel / Traditional diesel): 227ml each
2. Organophilic clay (Viscosifier): 15g
3. Primary Emulsifier (Dispersant): 2g
4. Secondary Emulsifier (Dispersant): 2g
5. Water: 70ml
6. $CaCl_2$ (Salinity and shale inhibition): 20g
7. Lime (pH Regulator): 5g
8. Saltex (Fluid loss Agent): 2g
9. Barite (Weighing agent): 50g
10. Deformer: 1 drop

The final muds (Biodiesel-based mud, Diesel-based mud) were formulated and mixed at a time range of 45 minutes, respectively, ensuring proper dispersion and emulsion stabilisation.

Performance tests on the formulated muds

Various performance tests were conducted for the formulated muds to determine their behaviour and performance under different conditions.

Rheological properties determination

The rheological measurements were made under different reservoir conditions. All the dial readings at (3RPM, 6RPM, 100RPM, 200RPM, 300RPM and 600RPM) were taken at various temperature conditions (80°F, 140°F and 170°F, respectively) during the test for the plastic viscosity, yield point and gel strength.

Plastic viscosity: The plastic Viscosity of the moringa oil biodiesel based drilling mud and the diesel based mud were both tested separately by pouring the mud sample into the fann vg viscometer cup and lowering the rotor sleeve into the mud sample in the cup and then setting the viscometer to 600rpm and recorded the dial reading, after letting the mud stabilize, the viscometer reading was then set to 300rpm and the dial reading was also recorded and the plastic viscosity was calculated from the following equation ;

$$PV = \theta 600 - \theta 300 \quad (8)$$

Note that the dial readings at 600rpm and 300rpm were taken under different reservoir conditions (80°F, 140°F and 170°F respectively)

Gel strength: The gel strength of the moringa oil biodiesel based drilling mud and the diesel based mud were both tested separately by transferring the mud sample into the

fann vg viscometer cup and placing the rotor sleeve into the cup ensuring that it contacts the mud sample and setting the viscometer to 3RPM for 10 seconds to break initial gel and then the mud was allowed to sit for 10 seconds before resetting the viscometer to 3RPM, then the highest dial reading was recorded as the rotor tried to break the gel which represented the gel strength at 10 seconds, After which the viscometer was turned off and the mud allowed to sit for 10 minutes. The viscometer was reset to 3 RPM, and the highest reading on the dial was recorded, representing the gel strength at 10 minutes. Note that the dial readings at 3 rpm were taken under different reservoir conditions (80°F, 140°F and 170°F, respectively)

Yield point: The yield point of the moringa oil biodiesel-based drilling mud and the diesel-based mud were both determined separately using the plastic viscosity calculated and the dial meter reading at 300 RPM, both gotten from the initial plastic viscosity test performed under different downhole conditions (80°F, 140°F and 170°F, respectively). The yield point in lb/1000ft^2 was then calculated using the following equation;

$$\text{Yield point (YP)} = \theta 300 - PV \quad (9)$$

Static properties analysis

Static properties such as mud density, PH, and phase stability were evaluated to assess the baseline characteristics of the formulated drilling muds.

pH

The pH of the moringa oil biodiesel-based drilling mud and the diesel-based mud was determined separately using a PH meter. It involved immersing the pH electrode into the mud sample and allowing the reading on the pH meter to stabilise, and then recording the pH value.

Density

The density of the moringa oil biodiesel based drilling mud and the diesel based mud were determined separately using a mud balance by filling the mud balance cup with the drilling mud sample and levelling it to remove any excess mud and then placing the lid on the cup ensuring it is secured tightly, afterwhich the mud balance is placed on a fulcrum and adjusting the counterweight until the beam is level and then reading the density directly from the scale on the mud balance.

Filtration performance measurement

The filtration properties of the moringa oil biodiesel based drilling mud and the diesel based mud were both determined separately using the standard API filter press, the filter press was assembled and a filter paper was placed on the filter press holder and the mud sample was poured into the filter press and it was closed and a graduated cylinder was placed under the filter press and a pressurized source was connected to filter press to apply pressure of about 100psi and the timing began with a stopwatch and the filtration test was conducted for 30 minutes and the volume of filtrate collected in the cylinder was recorded as the API filtrate volume. The filter press was opened, and the filter paper with the filter cake was retrieved. The filter cake thickness was measured with a Vernier calliper.

RESULTS AND DISCUSSION

Physiochemical properties

The physiochemical evaluation of Moringa oleifera oil and its biodiesel derivative demonstrates a clear transformation in properties that both validate its potential as a renewable fuel and highlight areas requiring optimisation (Table 1). The oil yield of 29.45% situates Moringa among the more promising non-edible feedstocks, consistent with Elsorady (2023) and Orhevba *et al*. (2013), and superior to neem (Garba *et al*., 2024) and Thevetia peruviana (Dhoot *et al*., 2011). This yield advantage underscores its viability for large-scale biodiesel production, particularly in resource-constrained regions where waste cooking oil (Aboelazayem *et al*., 2017) may be less reliable.

Conversion efficiency was equally impressive, with biodiesel yield reaching 91.37%. This surpasses sunflower oil (Mansourpoor, 2012) and aligns with the optimised alkaline-catalysed transesterification reported by Kafuku and Mbarawa (2010). Such efficiency confirms Moringa's suitability as a sustainable feedstock, echoing Omonhinmin *et al*. (2020), who emphasised its industrial potential.

The transformation from raw oil to biodiesel was accompanied by significant improvements in quality indicators. Moisture content dropped from 1.45% to 0.16%, a reduction critical for storage stability and microbial resistance, paralleling the findings of Fotouo-M *et al*. (2016). Similarly, viscosity decreased markedly, with kinematic values falling within ASTM standards and approaching petroleum diesel levels. This reduction, consistent with Rashid *et al*. (2008) and Idris *et al*. (2020), ensures compatibility with combustion engines and enhances fuel atomization.

Density changes were modest but meaningful: biodiesel's slightly lower density (0.8316 g/cm^3) compared to petroleum diesel (0.8532 g/cm^3) reflects typical transesterification outcomes and supports improved atomization, as noted by Leone *et al*. (2016). More striking was the reduction in acid value, from 16.342 mgKOH/g in

Table 1. Physiochemical properties.

Property	Moringa Oil	Biodiesel	Petrol-Diesel
Oil yield (%)	29.45	-	-
Biodiesel yield (%)	-	91.37	-
Moisture Content (℃)	1.45	0.16	0.01
Dynamic Viscosity (mPa.s)	7.960	4.410	3.370
Kinematic Viscosity (mm^2/s)	9.3361	5.3030	3.9498
Density (g/cm^2)	0.8526	0.8316	0.8532
Acid value (mgKOH/g)	16.342	1.336	1.483
Free Fatty Acid (%)	8.171	0.668	0.742
Flash Point (℃)	167	121	71
Cloud Point (℃)	7.81	2.51	-4.85
Pour Point (℃)	4.60	0.94	-11.32
Colour	Orange brown	Golden yellow	Light yellow

Table 2. Drilling mud properties result.

Properties tested	MBM	PDM
Density (ppg)	9.0	9.0
pH	8.7	8.09
Flud loss (ml/min)	3/30	2/30
Mud cake thickness	Thin and permeable	Thin and permeable
Phase Stability	No settling	No settling

Key: MBM = Moringa biodiesel based mud and PDM = Petrol diesel based mud.

oil to 1.336 mgKOH/g in biodiesel, comparable to petroleum diesel (1.483 mgKOH/g). This mirrors pretreatment strategies highlighted by Niju *et al*. (2019) and Orhevba *et al*. (2013), ensuring enhanced stability and reduced corrosion risks. Free fatty acid content followed a similar trajectory, dropping from 8.171% to 0.668%, thereby minimising soap formation during transesterification, consistent with Idris *et al*. (2020).

Safety properties were notably improved, with biodiesel exhibiting a flash point of 121°C compared to petroleum diesel's 71°C. This higher flash point, corroborated by Wai *et al*. (2016) and Wang *et al*. (2012), enhances handling safety and makes biodiesel particularly suitable for high-pressure, high-temperature drilling environments. However, cold flow properties remain a limitation: biodiesel's cloud and pour points (2.51°C and 0.94°C) are significantly higher than petroleum diesel (–4.85°C and –11.32°C), restricting performance in colder climates. This challenge, emphasised by Fotouo-M *et al*. (2016) and Knothe (2008), necessitates blending strategies or additive incorporation to improve operability.

Finally, the colour transformation from orange-brown oil to golden-yellow biodiesel reflects the removal of pigments and impurities, a change reported by Leone *et al*. (2016) and Lalas and Tsaknis (2002). This visual shift is not merely aesthetic but indicative of improved purity and fuel quality.

Drilling mud performance

The evaluation of Moringa biodiesel-based mud (MBM) relative to petroleum diesel-based mud (PDM) reveals that biodiesel substitution does not compromise the essential drilling fluid properties required for effective wellbore stability and operational performance (Table 2). Both mud systems recorded identical densities of 9.0 ppg, confirming that biodiesel maintains hydrostatic pressure equivalence with petroleum diesel. This finding is consistent with Wang *et al*. (2012) and Wai *et al*. (2016), who reported that biodiesel-based invert emulsions sustain stable density values under field conditions, thereby ensuring reliable pressure control.

The pH values highlight a subtle but meaningful distinction: MBM exhibited a slightly higher alkalinity (8.7) compared to PDM (8.09). This elevated alkalinity enhances compatibility with alkaline-tolerant additives, improves emulsion stability, and reduces microbial activity. Suhara *et al*. (2024) emphasised the buffering capacity of biodiesel systems, while Topare *et al*. (2021) noted that biodiesel formulations often exhibit higher alkalinity than fossil diesel. Thus, MBM's pH advantage contributes to both chemical stability and corrosion resistance in metallic drilling components.

Fluid loss control remains a critical parameter, and MBM recorded 3 ml/30 min compared to PDM's 2 ml/30 min.

Table 3. Gel strengths of the muds at different temperatures and time.

Temperature	MBM GS @10secs	MBM GS @10mins	PDM GS @10secs	PDM GS @10mins
80°F	8	18	11	18
140°F	14	18	18	32
170°F	29	33	31	38

Although MBM's value is marginally higher, it remains within acceptable industry limits. Duru *et al*. (2022) reported biodiesel-based muds with fluid loss values of 4.4 ml, demonstrating that biodiesel systems can effectively minimise filtrate invasion. Villada *et al*. (2017) further showed that additive optimisation (e.g., PAC, xanthan gum) can enhance fluid loss control, suggesting that MBM performance could be improved through similar strategies.

Mud cake thickness was comparable across both systems, with thin and permeable cakes observed. This outcome is desirable as it minimises formation damage and facilitates removal. The permeability, however, indicates potential filtrate invasion under certain downhole conditions. Importantly, MBM did not negatively affect solids deposition or cake quality. Tecla *et al*. (2019) demonstrated that Moringa oleifera derivatives can improve rheological properties of water-based muds, while Sulaimon *et al*. (2017) confirmed that vegetable oil-based muds maintain thin mud cakes while enhancing HPHT performance. These findings reinforce the potential of Moringa biodiesel to sustain desirable mud cake characteristics.

Phase stability was excellent in both MBM and PDM, with no evidence of settling or separation. This reflects strong emulsification and suspension properties, likely due to balanced emulsifiers and sufficient shear mixing. Wai *et al*. (2016) similarly reported robust stability in biodiesel-based invert emulsions, while Sun *et al*. (2018) highlighted that multiphase flow modelling confirms biodiesel muds' ability to resist gas intrusion and maintain phase integrity. The observed stability of MBM therefore validates its suitability for demanding drilling environments.

Rheological properties

The rheological properties of the formulated moringa biodiesel mud (MBM) and petroleum diesel mud (PDM) were evaluated at different simulated downhole temperatures of 80°F, 140°F, and 170°F. The dial readings obtained at varying rotational speeds are presented in Table 3. Generally, dial readings increased with increasing RPM and temperature for both mud systems, indicating an increase in shear stress with shear rate. However, PDM consistently recorded higher dial readings than MBM at elevated temperatures, particularly at 170°F. This suggests that PDM exhibited greater resistance to flow, while MBM showed improved shear-thinning behaviour and lower flow resistance under high-temperature conditions. Similar observations have been reported for biodiesel-based drilling fluids formulated from vegetable oils (Adesina *et al*., 2012; Bataee *et al*., 2024).

The plastic viscosity values presented in Table 4 showed that both mud systems had similar PV values at 80°F, but MBM exhibited a noticeable decrease in PV as temperature increased. In contrast, PDM maintained relatively higher PV values at elevated temperatures. The reduction in PV observed for MBM indicates lower internal friction and improved thermal thinning characteristics, which are beneficial for reducing pumping energy and improving circulation efficiency during drilling operations. The favourable rheological behaviour of MBM may be linked to the physicochemical properties and fatty acid composition of moringa seed oil (Leone *et al*., 2016; Idris *et al*., 2020).

The yield point values presented in Table 5 increased with temperature for both mud systems, although PDM consistently exhibited slightly higher values. The progressive increase in the yield point of MBM with temperature indicates improved structural integrity and enhanced cuttings carrying capacity under downhole conditions. Higher yield point values are advantageous for efficient hole cleaning and suspension of drilled cuttings during static conditions. This finding agrees with the report of Bataee *et al*. (2024), who observed that biodiesel-based drilling muds exhibited comparable rheological performance to conventional diesel muds.

Gel strength values presented in Table 6 increased with temperature for both mud systems. PDM consistently exhibited higher gel strengths than MBM, indicating stronger structural retention and suspension capability under elevated temperature conditions. However, MBM demonstrated considerable thermal responsiveness, particularly between 140°F and 170°F, suggesting that moringa biodiesel mud possesses acceptable suspension properties for drilling operations. Adequate gel strength is essential for preventing cuttings settlement during pump-off periods and maintaining mud stability under downhole conditions. Similar rheological behaviour has been reported for environmentally friendly biodiesel-based drilling muds formulated from vegetable oils (Adesina *et al*., 2012; Bataee *et al*., 2024).

The rheological behaviour of MBM was further evaluated using the Bingham Plastic, Power Law, and Herschel–Bulkley models. The shear stress and shear rate data used for the analysis are presented in Table 7, while the corresponding fitting plots are shown in Figures 4a–c.

Table 4. Shear stress and shear rate at different temperatures and RPM.

Temperature (°F)	RPM	Shear Rate (1/S)	Dial Reading	Shear Stress (lb/ft²)
80	3	5.11	9	4.60
	6	10.22	10	5.11
	100	170.3	20	10.22
	200	340.6	30	15.33
	300	510.9	38	19.42
	600	1012.8	63	32.19
140	3	5.11	11	5.62
	6	10.22	12	6.13
	100	170.3	24	12.26
	200	340.6	33	16.87
	300	510.9	43	21.97
	600	1021.8	62	31.68
170	3	5.11	26	13.29
	6	10.22	27	13.80
	100	170.3	38	19.42
	200	340.6	47	24.06
	300	510.9	53	27.08
	600	1021.8	69	35.26

Table 5. Dial readings for MBM and PDM under different temperature conditions.

Rotation speed	MBM @80°F	PDM @80°F	MBM @140°F	PDM @140°F	MBM @170°F	PDM @170°F
3RPM	9	9	11	16	26	28
6RPM	10	10	12	17	27	30
100RPM	20	23	24	33	38	50
200RPM	30	33	33	45	47	62
300RPM	38	42	43	55	53	72
600RPM	63	67	62	84	69	100

Table 6. Plastic viscosity of the muds at different temperatures.

Temperature	PV OF MBM (cp)	PV OF PBM (cp)
80°F	25	25
140°F	19	29
170°F	16	28

Table 7. Yield point of the muds at different temperature.

Temperature	YP OF MBM (lb/100ft²)	YP OF PBM (lb/100ft²)
80°F	13	17
140°F	24	26
170°F	37	44

Among the models evaluated, the Herschel–Bulkley model provided the best fit across all temperature conditions, with correlation coefficients (R^2) close to 1.00, indicating that MBM exhibits non-Newtonian shear-thinning behaviour with measurable yield stress characteristics. The Bingham Plastic model also produced good fitting results, although

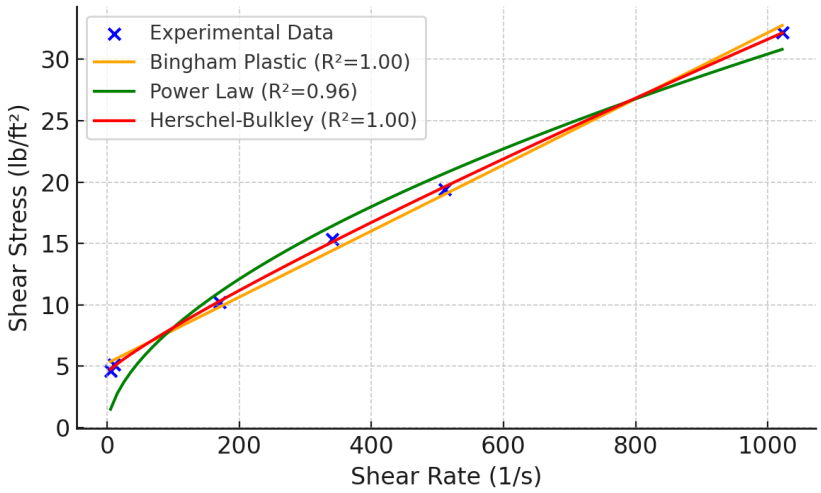

Figure 4a. Plot of rheological models fitting for MBM at 80°F.

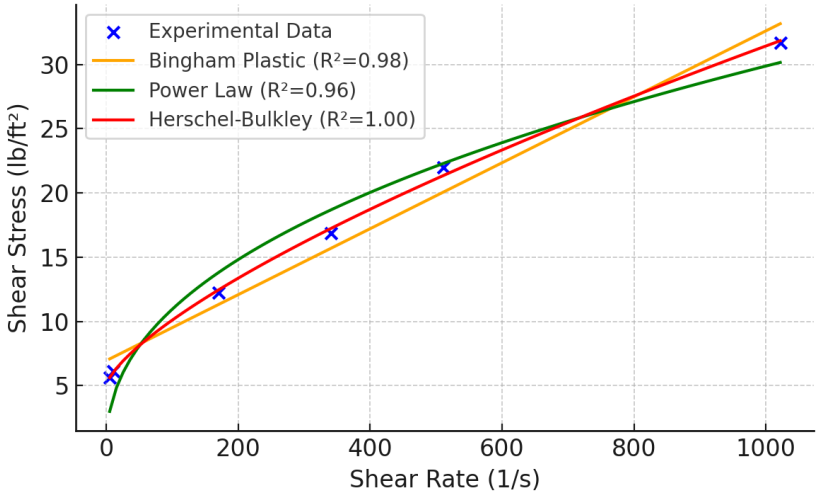

Figure 4b. Plot of rheological model fitting for MBM at 140°F.

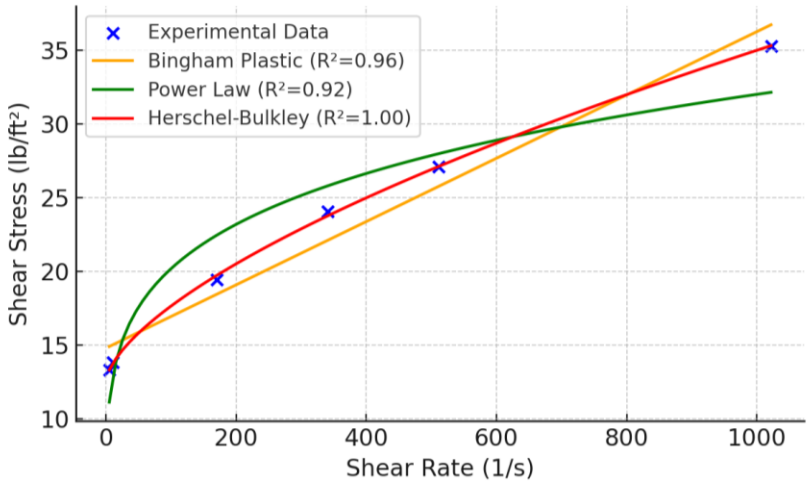

Figure 4c. Plot of rheological model fitting for MBM at 170°F.

its accuracy decreased slightly with increasing temperature, whereas the Power Law model produced the least satisfactory fit. Similar non-Newtonian rheological characteristics have been reported for oil-based biodiesel drilling fluids derived from vegetable oils (Adesina *et al*., 2012; Bataee *et al*., 2024).

Overall, the findings confirm the industrial potential of Moringa oleifera oil not only as a nutraceutical product with recognized pharmacological and health benefits but also as a renewable industrial feedstock suitable for biodiesel and drilling mud applications (Pareek et al., 2023). Nevertheless, optimization of Moringa-based drilling fluid formulations remains necessary to improve viscosity stability and thermal resistance under extreme downhole conditions.

Conclusion

This study demonstrates that biodiesel synthesised from *Moringa oleifera* seed oil is a viable and sustainable substitute for petroleum diesel in oil-based drilling mud formulations. The seeds yielded 29.45% oil with a biodiesel conversion efficiency of 91.37%, confirming their suitability as a renewable feedstock. The resulting biodiesel exhibited improved physicochemical properties, including reduced viscosity (5.303 mm²/s), lower acid value (1.336 mgKOH/g), and a significantly higher flash point (121°C compared to 71°C for diesel), enhancing both safety and stability. When applied in drilling mud systems, moringa biodiesel-based mud (MBM) maintained comparable density (9.0 ppg), rheological integrity under elevated temperatures (up to 170°F), and gel strength similar to petroleum diesel-based mud (PDM). Although MBM showed slightly higher alkalinity (pH 8.7 vs. 8.09) and marginally increased fluid loss (3 mL/30 min vs. 2 mL/30 min), these values remain within acceptable operational limits. Overall, the findings highlight moringa biodiesel as an eco-friendly, biodegradable alternative that aligns with sustainability goals in oil and gas operations, with future research needed to address cold-flow limitations and optimise additive formulations for broader field applications.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

Abdu, Z., & Fatima, S. I. (2014). *Moringa Oleifera* oilseed as viable feedstock for biodiesel production in Northern Nigeria. *International Journal of Energy Engineering, 4*(2), 21–25.

Abdulkareem, A. S., Uthman, H., Afolabi, A. S., & Awenebe, O. L. (2011). Extraction and optimization of oil from *Moringa oleifera* seed as an alternative feedstock for the production of biodiesel. *In: Sustainable growth and applications in renewable energy sources*, 243-268. Intech Open. https://doi.org/10.5772/25855.

Abdullahi, K., Ojonugwa, S. S., Yusuff, A. S., Umaru, M., Mohammed, I. A., Olutoye, M. A., & Aberuagba, F. (2022). Optimisation of biodiesel production from Allamanda seed oil using design of experiment. *Fuel Communications, 14*, 100081. https://doi.org/10.1016/j.jfueco.2022.100081.

Aboelazayem, O., Saha, B., & Gadalla, M. (2017). Biodiesel production from waste cooking oil via supercritical methanol: Optimisation and reactor simulation. *Renewable Energy, 124*, 144-154. https://doi.org/10.1016/j.renene.2017.06.076.

Adesina, F., Falode, O., Ako, C., Adeyemi, A., & Ameloko, A. Adesina, F., Falode, O., Ako, C., Adeyemi, A., & Ameloko, A. (2012). Environmentally friendly oil based drilling mud. In: *New Technologies in the Oil and Gas Industry*, 49. Intech Open. https://doi.org/10.5772/51236

Analytical (n.d.). ASTM D97-17b: Standard Test Method for Pour Point of Petroleum Products. Retrieved from https://ayalytical.com/methods/astm-d97/.

Balat, M. (2007). Production of biodiesel from vegetable oils: A survey. *Energy Sources, Part A: Recovery, Utilisation, and Environmental Effects, 29*(10), 895-913. https://doi.org/10.1080/00908310500283359.

Bataee, M., Wong, S., Khur, W. S., Bennour, Z., Mostofi, M., & Hamdi, Z. (2024, October). Performance analysis of eco-friendly palm oil biodiesel as a replacement for diesel oil in drilling mud applications. In *SPE Asia Pacific Oil and Gas Conference and Exhibition.* Paper Number: SPE-221346-MS. https://doi.org/10.2118/221346-ms.

Cao, J., Shi, T., Wang, H., Zhu, F., Wang, J., Wang, Y., Cao, F., & Su, E. (2023). *Moringa oleifera* leaf protein: Extraction, characteristics and applications. *Journal of Food Composition and Analysis, 119*, 105234. https://doi.org/10.1016/j.jfca.2023.105234.

De Paola, M. G., Mazza, I., Lopresto, C. G., Calabrò, V., & Paletta, R. (2021). Small-scale biodiesel production plants—An overview. *Energies, 14*(7), 1901. https://doi.org/10.3390/en14071901.

Dhoot, S. B., Jaju, D. R., & Deshmukh, S. A. (2011). Extraction of *Thevetia Peruviana* seed oil and optimisation of biodiesel production using alkali-catalysed methanolysis. *Journal of Alternate Energy Sources & Technology, 2*(2), 8–16.

Duru, U. I., Nduwuba, G. O., Onyejekwe, I. M., & Ikpeka, P. (2022). Experimental evaluation of locally synthesized biodiesel drilling fluid. *The Mining-Geological-Petroleum Engineering Bulletin*, *37*(1), 105–121. https://doi.org/10.17794/rgn.2022.1.10

Elsorady, M. E. (2023). Evaluation of Moringa oleifera seed oil extracted with different extraction methods. Croatian Journal of Food Science and Technology, 15(1), 1-7. https://doi.org/10.17508/cjfst.2023.15.1.01

Fotouo-M, H., Du Toit, E. S., & Robbertse, P. J. (2016). Effect of storage conditions on *Moringa oleifera* Lam. seed oil: Biodiesel feedstock quality. *Industrial Crops and Products, 84*, 80-86. https://doi.org/10.1016/j.indcrop.2016.01.032.

Garba, L., Mahmoud, A. A., Boryo, D. E. A., Abubakar, A., & Abdullahi, Z. A. (2024). Comparative analysis of oil obtained from *Moringa* and *Neem* seeds. *BIMA Journal of Science and Technology, 8*(1B), 170-185. https://doi.org/10.56892/bima.v8i1.624.

Hadiyanto, H., Budiman, A., Aini, A. P., Kusmiyati, K., Roesyadi, A., & Widayat, W. (2020). Multi-feedstocks biodiesel production

from esterification of *Calophyllum inophyllum* oil, castor oil, palm oil and waste cooking oil. *International Journal of Renewable Energy Development, 9*(1), 119-123. https://doi.org/10.14710/ijred.9.1.119-123

Hafshejani, K. S., Moslemizadeh, A., & Shahbazi, K. (2016). A novel bio-based deflocculant for bentonite drilling mud. *Applied Clay Science*, *127*, 23-34. https://doi.org/10.1016/j.clay.2016. 03.037

Idris, A. A., Nour, A. H., Ishag, O. A. O., Ali, M. M., Erwa, I. Y., & Nour, A. H. (2020). Physicochemical Properties and Fatty Acids Composition of Sudanese Moringa Oleifera Seed Oil. *Journal of the Turkish Chemical Society, Section A: Chemistry*, *7*(3), 911-920. https://doi.org/10.18596/JOTCSA.771260

Kafuku, G., & Mbarawa, M. (2010). Alkaline catalysed biodiesel production from *Moringa oleifera* oil with optimised production parameters. *Applied Energy, 87*(8), 2561-2565. https://doi.org/10.1016/j.apenergy.2010.02.026

Knothe, G. (2008). Designer" biodiesel: Optimising fatty ester composition to improve fuel properties. *Energy & Fuels, 22*(2), 1358-1364. https://doi.org/10.1021/ef700639e

Leone, A., Spada, A., Battezzati, A., Schiraldi, A., Aristil, J., & Bertoli, S. (2016). *Moringa oleifera* seeds and oil: Characteristics and uses for human health. *International Journal of Molecular Sciences, 17*(12), 2141. https://doi.org/10.3390/ijms17122141

Mansourpoor, M. (2012). Optimization of biodiesel production from sunflower oil using response surface methodology. *Journal of Chemical Engineering & Process Technology, 3*(5), 1-5. https://doi.org/10.4172/2157-7048.1000141

Niju, S., Raj, F. R., Anushya, C., & Balajii, M. (2019). Optimization of acid catalyzed esterification and mixed metal oxide catalyzed transesterification for biodiesel production from *Moringa oleifera* oil. *Green Processing and Synthesis, 8*(1), 756-775. https://doi.org/10.1515/gps2019-0045

Obeta, P. O., Ogbonna, J., Okoro, E. E., & John, A. (2025). Synthesis and characterisation of green surfactants from selected underutilised local plant seeds: A sustainable alternative for oilfield applications. *Direct Research Journal of Public Health and Environmental Technology*, *10*(1), 150–162.

Omonhinmin, C., Olomukoro, E., Egwim, E., & Ayoola, A. (2020). Utilisation of *Moringa oleifera* oil for biodiesel production: A systematic review. *AIMS Energy, 8*(1), 102–121. https://doi.org/10.3934/energy.2020.1.102

Orhevba, B. A., Sunmonu, M. O., & Iwunze, H. I. (2013). Extraction and characterization of Moringa oleifera seed oil. *Journal of Food and Dairy Technology, 1*(1), 22-27. http://irepo.futminna.edu.ng:8080/jspui/handle/123456789/4897

Pareek, A., Pant, M., Gupta, M. M., Kashania, P., Ratan, Y., Jain, V., Pareek, A., & Chuturgoon, A. A. (2023). *Moringa oleifera*: An updated comprehensive review of its pharmacological activities, ethnomedicinal, phytopharmaceutical formulation, clinical, phytochemical, and toxicological aspects. *International Journal of Molecular Sciences, 24*(3), 2098. https://doi.org/10.3390/ijms24032098

Rashid, U., Anwar, F., Moser, B. R., & Knothe, G. (2008). *Moringa oleifera* oil: A possible source of biodiesel. Bioresource Technology, 99(17), 8175-8179. https://doi.org/10.1016/j.biortech.2008.03.066.

Suhara, A., Karyadi, K., Veza, I., Hananto, A. L., Putra, N. R., Idris, M., Roslan, M. F., Tirta, A., & Herawan, S. G. (2024). Biodiesel sustainability: Review of progress and challenges of biodiesel as sustainable biofuel. *Clean Technologies, 6*(3), 886-906. https://doi.org/10.3390/cleantechnol6030045

Sulaimon, A. A., Adeyemi, B. J., & Rahimi, M. (2017). Performance enhancement of selected vegetable oil as base fluid for drilling HPHT formation. *Journal of Petroleum Science and Engineering, 152*, 49-59. https://doi.org/10.1016/j.petrol.2017.02.006

Sun, B., Fu, W., Wang, N., Wang, Z., & Gao, Y. (2018). Multiphase flow modelling of gas intrusion in oil-based drilling mud. *Journal of Petroleum Science and Engineering, 174*, 1142-1151. https://doi.org/10.1016/j.petrol.2018.12.018

Tecla, C., Biwott, O., Akaranta, O., Kiprop, A., & Boniface, O. (2019). Improving the rheological properties of water-based mud with *Moringa oleifera* leaves. *Chemical Science International Journal, 28*(4), 1-9. https://doi.org/10.9734/CSJI/2019/V28I430144

Topare, N. S., Jogdand, R. I., Shinde, H. P., More, R. S., Khan, A., & Asiri, A. M. (2021). A short review on approach for biodiesel production: Feedstock's, properties, process parameters and environmental sustainability. *Materials Today: Proceedings, 57*, 1605-1612. https://doi.org/10.1016/j.matpr.2021.12.216.

Villada, Y., Gallardo, F., Erdmann, E., Casis, N., Olivares, L., & Estenoz, D. (2017). Functional characterisation on colloidal suspensions containing xanthan gum (XGD) and polyanionic cellulose (PAC) used in drilling fluids for a shale formation. *Applied Clay Science, 149*, 59-66. https://doi.org/10.1016/j.clay.2017.08.020

Wai, L., Zhao, X., Ji, Y., Peng, H., Li, Y., Liu, L., & Han, X. (2016). An investigation on environmentally friendly biodiesel-based invert emulsion drilling fluid. *Journal of Petroleum Exploration and Production Technology, 6*(3), 505-517. https://doi.org/10.1007/s13202-015-0205-7

Wang, M., Sun, M., Shang, H., Fan, S., Liu, M., & Liu, F. (2015). Biodiesel-based drilling fluids. *SPE Journal,* 155578. https://doi.org/10.2118/155578-MS.