



Rheological Evaluation of Bio-Based Synthetic Fluids as Sustainable Alternatives to Diesel: A Case Study of Soybean Oil Methyl Ester (SOME) and Melon Seed Oil Methyl Ester (MOME)

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Abstract

To address the environmental and toxic liabilities of diesel-based drilling fluids, this study investigates the technical suitability of transesterified soybean oil methyl ester (SOME) and melon seed oil methyl ester (MOME) as biodegradable, non-aqueous alternatives. Both oils were recovered via Soxhlet extraction with n-hexane, chemically transesterified into fatty acid methyl esters (FAMES), and characterized using FTIR spectroscopy. MOME exhibited a high crude volumetric yield of 73.5% (vol/wt) compared to 46.5% for SOME. Formulated synthetic-based muds (SBMs) were evaluated across key parameters. Both SOME SBM (508.5 V) and MOME SBM (485.5 V) displayed excellent electrical stability break voltages exceeding the diesel control (474 V) before and after dynamic aging at 300°F. Rheological testing revealed shear-thinning thixotropy, with SOME and MOME maintaining higher plastic and apparent viscosities across tested temperatures. Under HPHT filtration at 250°F and 500 psi differential pressure, both bio-synthetic formulations showed superior fluid loss control (SOME = 6.6 mL, MOME = 6.7 mL) and thinner filter cakes (1.5–2.0 mm) than the diesel control (7.5 mL, 2.0 mm). These results confirm that SOME and MOME are viable, sustainable continuous phases that maintain high physical performance while aligning with strict modern zero-discharge environmental standards.

Keywords: Synthetic-Based Mud (SBM); Biodegradable Drilling Fluid; SOME; MOME; HPHT Filtration; Rheology

Introduction

Drilling fluids are indispensable to rotary drilling operations, cooling the drill bit, suspending and transporting rock cuttings, maintaining wellbore integrity, and providing hydrostatic pressure control [1,2]. Among available systems, non-aqueous fluids (NAFs) are heavily preferred for challenging offshore, deepwater, and high-pressure high-temperature (HPHT) applications due to their superior shale inhibition, lubricating capacity, and thermal stability compared to water-based muds [3]. Conventionally, diesel oil has served as the continuous phase in oil-based muds

(OBMs) because of its lower price and predictable flow characteristics [4]. However, diesel oil contains hazardous polycyclic aromatic hydrocarbons (PAHs) that pose carcinogenic risks to drilling rig crew and severely pollute marine and terrestrial environments when waste drill cuttings are discharged [5]. Stricter regulatory mandates enforced by global agencies, such as the U.S. Environmental Protection Agency (EPA) and European REACH protocols, impose severe environmental and waste-treatment liabilities on operations utilizing conventional diesel continuous phases [6].

To mitigate these environmental challenges, the petroleum industry has focused extensively on bio-based plant oils as sustainable, non-toxic, and renewable continuous phases [7]. Although raw vegetable oils exhibit high lubricity and excellent biodegradability, their high native viscosities, poor cold-flow properties, and chemical susceptibilities to downhole thermal oxidation restrict their direct field application. Chemical transesterification converts triglycerides into fatty acid methyl esters (FAMES), significantly reducing base oil viscosity, expanding the hydrophobic character, and elevating thermal stability to standard operating levels [8]. While soybean oil has been widely proposed as an alternative, egusi melon seed oil (*Citrullus lanatus*) remains virtually unexplored as a transesterified base fluid, despite its massive agricultural abundance in West Africa [9]. No systematic comparative study exists that directly benchmarks SOME, MOME, and diesel continuous phases under a unified, identical mud additive formulation. This investigation closes this technical gap through laboratory-scale characterization, formulating high-performance SBMs and systematically evaluating their physical, viscometric, thixotropic, and HPHT filtration performance against conventional diesel controls.

Literature Review of Sustainable Drilling Fluids

Formulating eco-friendly drilling fluids requires base oils that maintain high lubricity, thermal stability, and shale inhibition [10]. Historically, Caenn, et al. established that oil-based muds outperform water-based muds in reactive shale zones by utilizing a stable water-in-oil emulsion to restrict hydration and prevent wellbore collapse [3]. However, the persistence of diesel-coated cuttings in surrounding ecosystems outweighs these operational advantages, prompting an industry-wide transition toward synthetic-based muds (SBMs) [11]. Plant-derived esters have emerged as prime candidates due to their inherent biodegradability and low toxicity, but their high-temperature stability remains a critical concern [12]. Recent advances focus on transesterification to optimize the rheological performance of plant oils under extreme downhole stress [13,14]. The chemical interaction of ester polar carbonyl groups with the surfaces of organophilic clay viscosifiers promotes platelet exfoliation, facilitating the development of robust thixotropic gel structures that optimize cuttings transport while managing circulating friction pressures downhole [15].

Materials and Methods

Raw soybean and egusi melon seeds were sourced from regional agricultural markets in Ibadan, Nigeria. Chemical reagents (n-hexane solvent, methanol reactant, NaOH catalyst, and anhydrous Na_2SO_4 drying agent) were obtained in high chemical purities from certified laboratory

suppliers. High-grade commercial mud additives consisted of a polyaminated fatty acid-based surfactant (primary emulsifier), a modified amidoamine derivative (secondary emulsifier), a dimethyl dihydrogenated tallow ammonium bentonite (organophilic clay viscosifier), and an organophilic lignite derivative (filtration control agent). Base weighting was conducted using API-grade barite and calcium chloride brine as the internal phase.

Oil extraction was conducted by grinding dried seed materials into fine powders and extracting with n-hexane solvent in a Soxhlet extractor operating at 68–70°C for 6–8 hours. Solvent recovery was executed using a rotary evaporator operating under a conservative temperature of 40°C under reduced pressure to protect the unsaturated aliphatic chains from early thermal oxidation and polymerization. For chemical transesterification, the recovered crude oils were reacted with methanol at a volumetric ratio of 0.25:1 in the presence of 6–12 g/L of NaOH catalyst at 55–60°C for 90 minutes. The separated FAME layers were washed thoroughly with warm distilled water, dried over anhydrous Na_2SO_4 , and characterized using Fourier Transform Infrared Spectroscopy (FTIR). The synthesized esters (SOME and MOME) were formulated into non-aqueous fluids (NAFs) utilizing a 70:30 oil-to-water ratio. The mixtures were prepared by blending components sequentially on a high-speed multimixer at 11,000 rpm for 30 minutes, maintaining the exact additive dosages across all three systems to ensure a unified, unbiased comparison against the diesel OBM control.

Results

Soxhlet extraction yielded 465 mL of crude soybean oil (46.5% volumetric yield) and 735 mL of crude egusi melon seed oil (73.5% volumetric yield) per 1000 g of dry seed powder. The exceptionally high yield of MOME represents a major economic advantage, indicating lower raw feedstock demands per barrel of formulated base fluid. The crude volumetric yields represent direct liquid extracts containing trace residual solvent fractions, as the rotary evaporator was run under a conservative 40°C threshold. FTIR spectroscopy confirmed successful ester conversion for both base oils, showing strong, sharp absorption bands at approximately 1741 cm^{-1} (ester carbonyl C=O stretch) and 1170 cm^{-1} (C–O stretching vibration). The absence of unreacted triglyceride glyceride backbone peaks and the complete absence of broad hydroxyl absorption near 3300 cm^{-1} confirmed the synthesis of high-purity, dry hydrophobic base fluids.

Rheogram analysis conducted at 30°C revealed distinct flow behavior characteristics. The conventional diesel mud displayed a near-linear shear stress profile varying from 9 to 56 lb/100ft² ($R^2 = 0.991$), adhering closely to Newtonian

Bingham Plastic flow. In contrast, both SOME-based SBM (33 to 282 lb/100ft²) and MOME-based SBM (35 to 273 lb/100ft²) exhibited pronounced non-Newtonian, shear-thinning (pseudoplastic) flow profiles. This behavior is highly modeled by the Herschel-Bulkley relation where the flow index (n) was consistently below 1.0. This pseudoplastic performance is operationally advantageous, providing high

annular viscosities to support cuttings during static rest while dropping viscosity rapidly at high drill string shear rates to minimize circulating pressure friction. The complete viscometric parameters (Plastic Viscosity, Yield Point, and Apparent Viscosity) across 30°C, 40°C, and 50°C are plotted in Figure 1 and summarized in Table 1.

Parameter	Fluid Continuous Phase	30°C	40°C	50°C
PV (cP)	Diesel (OBM)	17	8	4
	SOME (SBM)	110	86	81
	MOME (SBM)	103	82	67
AV (cP)	Diesel (OBM)	28	21	15.5
	SOME (SBM)	141	106	100
	MOME (SBM)	136.5	100	82.5
YP (lb/100ft ²)	Diesel (OBM)	22	26	23
	SOME (SBM)	62	40	38
	MOME (SBM)	67	36	31

Table 1: Viscometric Parameters of Formulations (Error: PV ± 0.5 cP, AV ± 0.75 cP, YP ± 1.0 lb/100ft²).

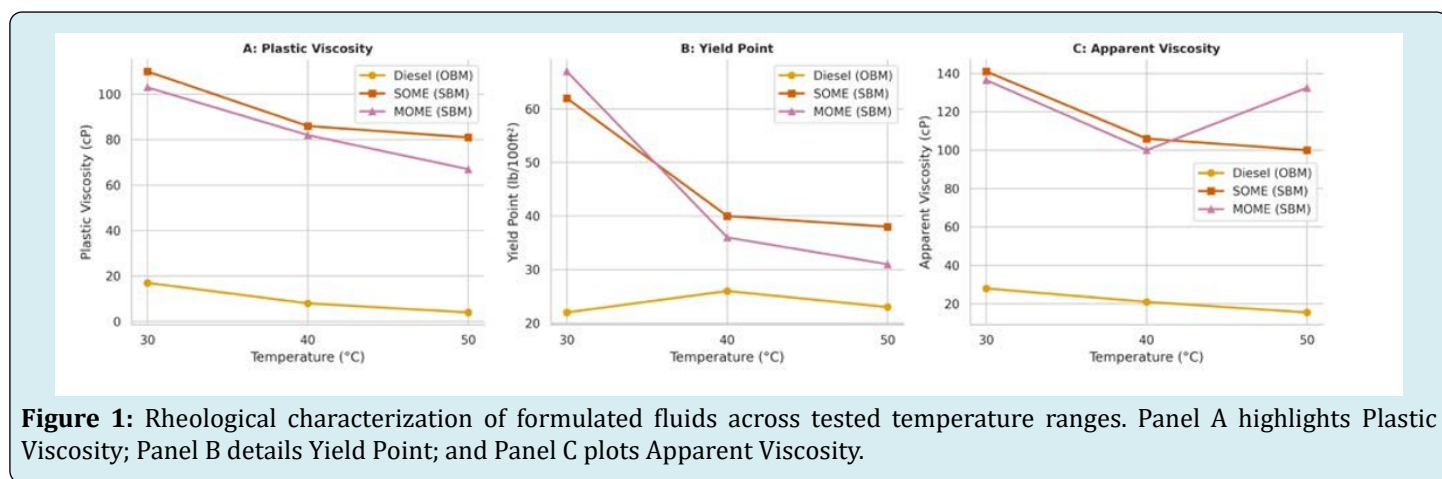


Figure 1: Rheological characterization of formulated fluids across tested temperature ranges. Panel A highlights Plastic Viscosity; Panel B details Yield Point; and Panel C plots Apparent Viscosity.

As plotted in Figure 1, the plastic and apparent viscosities of SOME SBM and MOME SBM are significantly higher than the diesel control. This is directly attributed to the greater molecular weight and robust intermolecular cohesion of transesterified FAME chains. Furthermore, both alternative muds maintained stable yield points under rising thermal stress. The high, non-progressive gel strengths of SOME and MOME SBMs (Figure 2B) confirm excellent thixotropic

cuttings suspension capacities, which minimize gravitational solids settling and the risk of barite sag. In contrast, the diesel control exhibited a marked, thermal-induced viscometric collapse, dropping to a PV of 4 cP at 50°C and a weak gel strength (10m = 1 lb/100ft²), representing severe downhole hole-cleaning liabilities. The base oil kinematic viscosities and the dynamic mud emulsion voltages are shown in Figure 2.

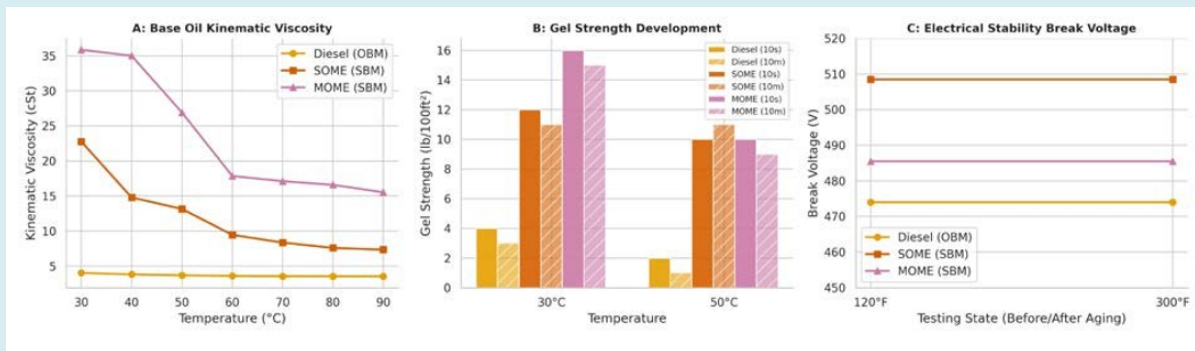


Figure 2: Thermal stability and emulsion integrity evaluation. Panel A illustrates Base Oil Kinematic Viscosity; Panel B details Gel Strength development; and Panel C plots Electrical Stability break voltage.

Kinematic viscosity values (Figure 2A) show that SOME and MOME maintain higher viscometric profiles than diesel across the 30–90°C range. This facilitates the formation of a durable, continuous lubricating film on the drill string and casing surfaces, minimizing mechanical friction under extreme downhole stress. Electrical stability break voltages (Figure 2C) show that both bio-synthetic muds safely exceed the standard API minimum limit of 300 V. SOME SBM achieved the highest electrical resilience (508.5 V), followed

by MOME SBM (485.5 V), outperforming the diesel mud (474 V). Dynamic hot-rolling at 300°F for 16 hours resulted in statistically identical ES break voltages, demonstrating that the emulsifier–base oil interfacial films experienced zero thermal degradation. This outstanding thermodynamic stability is attributed to the polar ester linkages of FAME molecules, which enhance surfactant adsorption. Physical density and mud-weight retention profiles under thermal stress are illustrated in Figure 3.

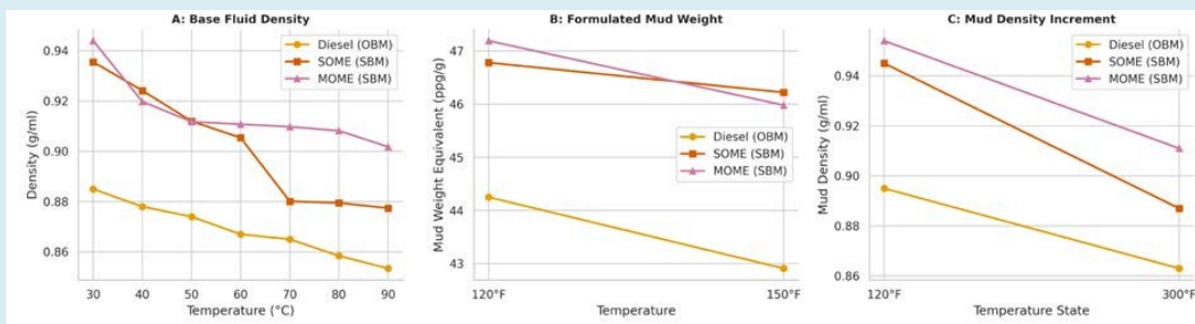


Figure 3: Physical density and mud weight characteristics under temperature stress. Panel A plots Base Fluid Density; Panel B shows Formulated Mud Weight; and Panel C details the Mud Density Increment.

Both SOME and MOME maintained higher native base densities compared to diesel across 30–90°C (Figure 3A). The polar ester functional groups and longer aliphatic chains provide a high molecular density that contributes passively to finished mud weight. Operationally, this higher density minimizes the concentration of barite weighting agents required to achieve target mud densities, lowering

raw chemical material costs, reducing solids loadings, and mitigating downhole barite sag risks. High-temperature filtration control represents another vital parameter. Under HPHT filter press testing at 250°F and 500 psi differential pressure, both bio-synthetic formulations significantly outperformed the diesel control (Table 2).

Mud Formulation System	HPHT Filtrate Loss (mL)	Filter Cake Thickness (mm)
Diesel OBM (Control)	7.5	2
SOME SBM	6.6	1.5
MOME SBM	6.7	2

Table 2: HPHT Filtration Performance of Formulations at 250°F and 500 psi (Error: Volume ± 0.1 mL).

SOME SBM exhibited a minimized fluid loss volume of 6.6 mL and built a thin, highly compact filter cake of 1.5 mm, which substantially reduces the risk of differential pipe sticking in highly permeable reservoir sections. MOME SBM achieved a favorable filtrate loss of 6.7 mL with a standard 2.0 mm filter cake, confirming the excellent fluid loss control and

wall-building efficiency of transesterified ester mud systems. A comprehensive, integrated performance assessment of the main technical, economic, and environmental parameters evaluated across all three fluid systems is summarized in Table 3.

Performance Parameter	Diesel (OBM)	SOME (SBM)	MOME (SBM)	Best Performer
Oil Extraction Yield	Moderate	Moderate	Highest (73.5%)	MOME
Plastic Viscosity	Lowest (Ideal)	Highest	Moderate	SOME
Yield Point	Lowest	High	Highest (67 lb/ft ²)	MOME
Gel Strength (10s)	Lowest	High	Highest (16 lb/ft ²)	MOME
Emulsion Stability	Lowest	Highest (508.5 V)	High	SOME
HPHT Fluid Loss Control	Lowest	Highest (6.6 mL)	High	SOME
Base Density (30°C)	Lowest	High	Highest (0.9440 g/ml)	MOME

Table 3: Integrated Performance Matrix of Evaluated Non-Aqueous Mud Systems.

Discussion

Practical Field Applicability and Viscosity Optimization

The experimental results demonstrate that SOME SBM and MOME SBM offer outstanding environmental, thixotropic, and fluid loss control benefits. However, a key operational challenge identified is their significantly elevated plastic viscosity (>100 cP at 30°C) relative to conventional diesel. In field deployments, such high viscosities would lead to excessive equivalent circulating densities (ECDs) and high frictional pump pressure losses, posing severe risks of hydraulically fracturing weak, shallow formations. To successfully manage and mitigate this risk, the rheological profiles of SOME and MOME muds must be optimized. This can be achieved by: (1) raising the oil-to-water ratio (OWR) from 70:30 to 80:20 or 90:10 to reduce internal phase droplet concentrations; (2) optimizing the organophilic clay concentration; or (3) incorporating specialized polymeric thinners and low-viscosity ester diluents. This optimization will lower the plastic viscosity to standard operational limits (typically 30–45 cP) while preserving sufficient cuttings transport and suspension capacities.

Limitations and Future Directions

Several study limitations should be highlighted. All viscometric evaluations were conducted under ambient pressure up to 50°C, which does not capture full HPHT rheology. In actual deep wellbores, extreme pressures can compress the organoclay network and base oil, while temperatures exceeding 150°C (300°F) can cause severe thermal thinning and ester degradation. Because high-

pressure, high-temperature (HPHT) viscometers (such as the Fann 50) were unavailable for this study, these results should be interpreted as an essential ambient-pressure viscometric baseline assessment. Furthermore, while the formulations demonstrated high thermal integrity during a standard 16-hour aging window, they remain vulnerable to base-catalyzed hydrolysis (saponification) and oxidative degradation across multi-week drilling campaigns. Future research must focus on long-duration aging trials, evaluating specialized chemical antioxidants and hydrolytic stabilizers to ensure long-term base fluid reliability.

Conclusion & Recommendations

This investigation successfully formulated and evaluated transesterified SOME and MOME SBMs as sustainable, high-performance continuous phases, directly benchmarked against conventional diesel muds. Both bio-synthetic formulations exhibited excellent physical, rheological, and thixotropic properties. They achieved superior emulsion stability break voltages (>480 V) and outstanding HPHT filtration control, significantly reducing filtrate losses (6.6–6.7 mL) and building thin, protective filter cakes compared to the diesel control. Comparing the two green formulations, MOME SBM represents the optimal candidate for raw feedstock yield, native base density, and initial cuttings suspension, while SOME SBM remains the premium choice for emulsion stability and minimized filtrate volumes. Based on these findings, we recommend: (1) deploying transesterified SOME and MOME as sustainable replacements for diesel in environmentally sensitive drilling zones; (2) executing HPHT rheological testing using Fann 50 systems to characterize pressure-dependent viscosity profiles; and (3) conducting long-duration aging studies to optimize specialized

antioxidants and chemical stabilizers for extended deepwell campaigns.

Conflicts of Interest

The authors declare no conflict of interest.

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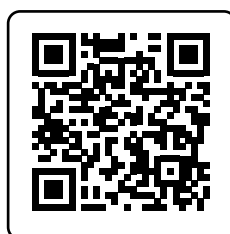
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