



Performance Evaluation of Esters Extracted from Waste Cooking Palm Oil on the Rheology, Filtration and Mud Cake Properties of Water Based Drilling Mud

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ABSTRACT

The synthesis of high-purity biodegradable esters from Waste Cooking Palm Oil (WCPO) represents a transformative shift toward sustainable drilling operations. By utilizing acid-catalyzed transesterification, this research successfully converts a low-value waste stream into a functional chemical additive capable of enhancing Water-Based Mud (WBM) performance. A critical aspect of this innovation is the achieved chemical purity of 98.8%, which ensures the bioester remains stable under high-shear environments. While commercial ester benchmarks at 4% concentration resulted in 15 mL fluid loss, the synthesized WCPO ester achieved a 61.5% improvement in fluid loss compared to the base mud, reducing loss to 10 mL and forming an ultra-thin 2/32-inch mudcake. Furthermore, rheological analysis confirmed that the ester stabilizes the Yield Point (YP) and Plastic Viscosity (PV) within operational limits, maintaining a predictable density range (7.7 to 8.5 ppg) compared to the erratic fluctuations observed in commercial alternatives. Although current results validate performance under Low-Pressure Low-Temperature (LPLT) conditions, this work establishes a foundation for future High-Pressure High-Temperature (HPHT) thermal stability validation. Therefore, this study demonstrates a viable waste-to-value pathway that supports the Malaysian circular economy and local SME scalability by providing a low-energy (65°C), cost-effective alternative to synthetic lubricants.

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1. INTRODUCTION

The global energy sector is undergoing a profound transition toward environmentally responsible and low-carbon oilfield operations, driving the development of sustainable alternatives to conventional petroleum-based drilling fluid additives [1]. Historically, oil-based mud (OBM) systems were favored due to their superior lubricity, thermal stability, and shale inhibition. However, increasingly stringent environmental regulations, elevated waste management costs, and growing societal pressure for greener technologies have accelerated the shift toward water-based mud (WBM) systems [2]. Despite their environmental advantages, WBMs inherently exhibit limitations in lubricity and filtration control, particularly in complex well architectures and high-pressure, high-temperature (HPHT) environments. These shortcomings necessitate the development of high-performance,

biodegradable mud systems. additives derived from renewable resources to ensure operational reliability without compromising environmental compliance [3].

The performance of bio-based additives in WBM is fundamentally governed by their chemical purity, molecular structure, and interfacial interactions with clay minerals. In aqueous systems, maintaining rheological stability while minimizing excessive filtrate invasion into permeable formations remains a critical challenge. Bioesters synthesized from waste-derived feedstocks often contain residual free fatty acids (FFAs), mono-/diglycerides, and unreacted glycerol, which can destabilize mud density and induce erratic viscosity profiles [1,4]. Such compositional inconsistencies weaken the electrochemical interactions between additive molecules and negatively charged bentonite platelets, thereby compromising dispersion stability and filtration performance.

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Achieving high chemical purity is therefore essential to promote consistent polar attraction and adsorption onto clay surfaces [5]. Strong molecular anchoring enhances platelet alignment and interparticle bridging, facilitating the formation of a compact and ultra-thin mudcake. This structure acts as an effective permeability barrier, reducing filtrate loss, mitigating differential sticking, and improving wellbore stability [2, 6].

In this context, the present study introduces a high-purity bioester synthesized from waste cooking palm oil (WCPO) as a sustainable drilling fluid additive. This approach embodies a waste-to-value strategy that diverts low-value organic waste from landfills while generating a high-quality, renewable raw material for upstream oil and gas applications [7]. Such valorization aligns with circular economy principles and contributes to carbon footprint reduction within Malaysia's oilfield service sector [8]. This research aims to systematically evaluate the effectiveness of synthesized WCPO-derived esters in stabilizing key rheological parameters, namely plastic viscosity (PV) and yield point (YP), while enhancing filtration control and mudcake quality in water-based drilling mud systems.

2. METHODOLOGY

A. Synthesis of WCPO Ester

The production of the WCPO ester followed a rigorous multi-stage acid-catalyzed transesterification process to ensure maximum conversion efficiency [4, 14]. For each experimental batch, a volume of 100mL of raw WCPO underwent a comprehensive pre-treatment phase. The feedstock was first filtered to remove food residues and suspended solids that could interfere with reaction kinetics and reduce final purity [15]. The filtered oil was then transferred to a 500mL beaker and heated gradually on a magnetic stirring hotplate, warming first to 60°C before increasing to 105°C for 1 hr. This dehydration step is critical to remove moisture that could otherwise deactivate the sulfuric acid catalyst, weaken the reaction efficiency, or promote undesirable soap formation [10, 16].

Once the oil cooled to approximately 50 to 60°C, the esterification reaction was initiated to enhance miscibility [18]. The catalyst mixture was prepared separately by adding 0.8mL of concentrated sulfuric acid (H_2SO_4) dropwise into 26.5mL of methanol while stirring for 3 min to manage the exothermic effect [5, 17]. The preheated WCPO was then combined with the methanol-acid mixture and the reaction was maintained at 60 to 65°C for 3 hr under continuous stirring. This temperature range provided the necessary activation energy for triglyceride conversion while preventing methanol loss due to excessive evaporation [17, 19]. The synthesis temperature of 65°C was selected because it is close to the boiling point of methanol (64.7°C), which enhances transesterification reaction kinetics while minimizing excessive alcohol evaporation. At this temperature, sufficient activation energy is available to accelerate ester formation without promoting side reactions such as soap formation or thermal decomposition. Previous biodiesel synthesis studies have similarly identified temperatures near 60–65°C as optimal [32, 33].

After the reaction, the mixture settled for 24 hr in a separatory funnel for phase separation. The crude ester was washed with 150mL of distilled water at 50°C until a neutral pH was achieved to remove residual catalyst and unreacted

methanol [19, 21]. Final drying was performed using 5 grams of anhydrous calcium chloride for 3 hr followed by double filtration to ensure a moisture-free product [21]. Anhydrous calcium chloride was used during the final drying stage due to its strong hygroscopic properties and ability to efficiently absorb residual moisture from the washed ester layer. Moisture removal is essential because water can promote ester hydrolysis, reduce storage stability, and negatively affect compatibility with drilling mud systems. Therefore, the use of $CaCl_2$ helps preserve ester purity and final product quality [34].

B. Characterization of Synthesized WCPO by GC-FID

The analysis was conducted using a DB 5 capillary column and an FID detector maintained at 300°C. The sample was diluted at a 1:100 ratio in n-hexane, followed by peak area integration via ChemStation software to determine its chemical composition [10, 21].

C. Formulations, Testing and Statistical Validation

The WBM was formulated by dispersing 22.5g of pre-hydrated bentonite into 350mL of deionized water, followed by the addition of 50g of barite to achieve the required density [22, 23]. The synthesized WCPO ester was integrated at concentrations of 1% (3.5 mL), 2% (7.0 mL), 3% (10.5 mL), and 4% (14.0 mL) by volume and blended at 10,000 rpm for 30 min to ensure a stable micro-emulsion [3, 23]. Performance testing was conducted in accordance with API RP 13B-1 standards. The mud weight was measured using a calibrated mud balance, where the cup was filled with the sample and the rider moved along the graduated beam until the level bubble settled at the center. Rheological properties were evaluated using a Fann 35 rotational viscometer. The rheological properties of the formulated mud samples were measured using a 6-speed rotational viscometer. To provide a precise technical framework for petroleum engineering readers, the dial readings at 600 rpm and 300 rpm were utilized to derive fundamental performance indicators based on the Bingham Plastic model. Specifically, the overall flow resistance of the mud during circulation was determined through the calculation of AV as shown in Equation (1). To assess the internal mechanical friction between solids and the liquid phase, which is critical for minimizing parasitic pressure losses, the PV was calculated using Equation (2).

Furthermore, the fluid's ability to suspend cuttings and maintain wellbore cleanliness under flow conditions was evaluated through the YP as defined in Equation (3). This parameter is essential for quantifying the electrochemical attractive forces within the mud system. To ensure scientific rigor and data reliability, all experiments were performed in triplicate, with three readings recorded for each measurement.

$$AV = \frac{\theta_{600}}{2} \in \text{centipoise}(cP) \quad (1)$$

$$PV = \theta_{600} - \theta_{300} \in \text{centipoise}(cP) \quad (2)$$

$$YP = \theta_{300} - PV \left(\in \frac{lb}{100ft^2} \right) \quad (3)$$

Filtration control was evaluated using an LPLT filter press at 100 psi for 30 min to measure filtrate volume and mudcake thickness [10, 12].

3. RESULT AND DISCUSSION

D. Analysis of Synthesized WCPO Ester using GC-FID

The resulting chromatogram displayed a singular, dominant peak at an elution time of 18.175 min, with negligible secondary peaks as shown in Figure 1. By integrating the peak areas, the chemical purity was determined to be 98.8 %, exceeding the general requirements for industrial-grade bio-lubricants [10]. This high purity level is a significant technical advantage; unreacted triglycerides or Free Fatty Acids (FFAs) in lower-purity esters can react with the calcium or bentonite in the WBM to form insoluble soaps [13, 21]. Such reactions can cause erratic fluctuations in 300 rpm and 600 rpm readings and destabilize the mud weight. Therefore, the 98.8% purity achieved in this study ensures that the WCPO ester acts as a passive, high-performance lubricant that enhances lubricity without interfering with the primary rheological functions of the drilling fluid [10, 25].

In a nutshell, the collective data obtained from GC-FID characterizations provide a robust scientific foundation for the technical viability of the synthesized lubricant. The convergence of these analytical results confirms that the chemical modification process effectively transformed WCPO into a high-purity FAME with the molecular integrity required for harsh oilfield environments [10, 14].

The high ester purity of 98.8% is important to ensure stable drilling fluid performance. If the synthesized ester contained lower purity levels, residual FFAs, mono-/diglycerides and unreacted triglycerides could remain in the product. These impurities may react with alkaline components or divalent ions such as Ca²⁺ present in bentonite or weighting materials and leading to soap formation through saponification reactions. The resulting soaps can destabilize the mud system by promoting foaming, altering emulsion behaviour, increasing viscosity unpredictably and affecting filtration performance. Therefore, high-purity ester is preferred to maintain chemical compatibility and rheological consistency [27,28].

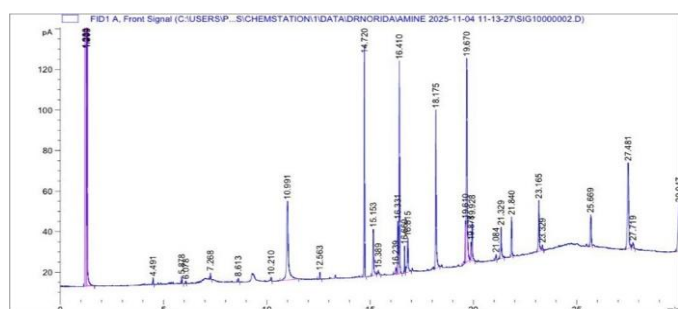


Fig. 1. GC-FID Spectrum of Synthesized WCPO Ester

E. Analysis of Mud Weight Stability

The management of fluid density, specifically the mud weight measured in pounds per gallon (ppg), serves as the primary mechanism for maintaining wellbore stability and managing hydrostatic pressure. During the experimental phase, the base WBM exhibited an initial density of 9.1 ppg, which served as the control benchmark for both the synthesized WCPO ester and the commercial lubricant. As shown in Table 1. Upon the introduction of a 1% concentration of the synthesized WCPO ester, a notable decrease in mud weight to 7.7 ppg, mirroring a similar decline in the commercial counterpart which dropped to 7.6 ppg. This initial reduction is technically justified by the partial substitution of the high-

density aqueous phase with lower-density organic esters. Because FAME possess a lower specific gravity than water, their introduction into the system naturally lightens the overall fluid column. This behaviour is a critical operational consideration, as it highlights the necessity of monitoring density to ensure that the fluid provides sufficient hydrostatic head to prevent underbalanced drilling conditions.

As the concentration of the additives was further increased from 2% to 4%, a distinct recovery and stabilization trend emerged, particularly within the synthesized WCPO formulations. The density of the WCPO-modified mud exhibited a steady climb to 8.1 ppg at a 2% concentration before reaching a plateau at 8.5 ppg for both the 3% and 4% concentrations. In contrast, the commercial lubricant displayed a more erratic density profile, fluctuating significantly before ending at a much higher value of 9.3 ppg at the 4% mark. The gradual rise and subsequent stabilization of the WCPO mud weight at 8.5 ppg suggest the formation of a superior and more uniform micro-emulsion within the bentonite-water matrix. This stability is scientifically justified by the high chemical purity of the synthesized ester. This high purity level minimizes the risk of phase separation or the formation of air pockets that often plague unrefined or lower-quality bio-additives, ensuring the fluid maintains a consistent internal structure.

Table 1. Mud Weight Comparison

Concentration (%)	Mud Weight (ppg)		
	Volume (mL)	Extracted	Commercial
0	0.0	9.1	9.1
1	3.5	7.7	7.6
2	7.0	8.1	8.7
3	10.5	8.5	8.2
4	14.0	8.5	9.3

The stabilization of mud weight at approximately 8.5 ppg at higher WCPO ester concentrations indicates that the system reached density equilibrium. Once the ester became uniformly dispersed within the continuous aqueous phase, further addition no longer caused significant density variation. This suggests the formation of a stable micro-emulsion or homogeneous dispersed phase with consistent bulk fluid properties [27].

F. Rheological Evaluation of WCPO Ester and Commercial

The rheological performance of the synthesized WCPO ester was evaluated against a standard commercial benchmark to determine its compatibility and structural influence on the WBM system. As shown in Table 2, the viscosity readings at 300 rpm and 600 rpm are important indicators of the fluid's shear stress response and overall flow behavior.

Table 2. Viscosity of Synthesized WCPO Ester and Commercial Ester

Concentration (wt%)	Extracted		Commercial	
	300 rpm	600rpm	300 rpm	600rpm
0	15.0 cP	30.0 cP	15.0 cP	30.0 cP
1	13.0 cP	24.0 cP	13.0 cP	24.5 cP
2	24.0 cP	30.0 cP	24.0 cP	29.0 cP
3	27.5 cP	30.0 cP	27.5 cP	32.0 cP
4	29.0 cP	35.0 cP	29.0 cP	36.0 cP

The results reveal a highly synchronized performance trajectory between the synthesized WCPO ester and the commercial. At a low concentration of 1%, both additives

induced a decrease in shear stress; specifically, the 600 rpm reading for the synthesized ester dropped from 30.0 to 24.0. This phenomenon is technically attributed to the adsorption of ester molecules onto the bentonite platelets, forming a microscopic lubricating film that significantly mitigates interparticle friction. In a real-world drilling scenario, this "thinning" effect at low concentrations is highly advantageous during the initial stages of drilling, as it reduces the equivalent circulating density (ECD) and lowers the energy required to pump the mud through the drill string.

However, as the concentration increased from 2% to 4%, a progressive upward trend in dial readings was observed for both systems. At the maximum 4% dosage, the synthesized WCPO ester reached a 600 rpm reading of 35.0, nearly identical to the 36.0 recorded for the commercial benchmark. This trend is scientifically significant; it demonstrates that at higher concentrations, the synthesized ester facilitates a robust structural matrix rather than causing excessive thinning. Operationally, this ensures the fluid retains sufficient carrying capacity to transport and suspend cuttings effectively. Without this strength, cuttings would settle at the bottom of the wellbore during pump shutdowns, leading to stuck pipe incidents and costly non-productive time (NPT).

The technical parity between the two additives, separated by only one dial unit at peak concentration, highlights the success of the synthesis process. While commercial formulations typically rely on specialized surfactants to stabilize the fluid under high solid loads, the WCPO ester achieves comparable stability through its 98.8% chemical purity. By matching the mechanical intensity of a high-end commercial product while utilizing a waste to value feedstock, the synthesized WCPO ester proves to be a technically superior and sustainable alternative. This performance is particularly relevant for Malaysian offshore formations where maintaining precise rheological control is essential for protecting weak formations and ensuring wellbore stability in high torque environments.

G. Dynamic Profiling of AV Response

Table 3 shows that both the synthesized ester and the commercial exhibited similar rheological behavior as concentration increased.

Table 3. Calculated AV

Concentration (%)	Volume (mL)	Extracted	Commercial
0	0.0	15.0	15.0
1	3.5	12.0	12.25
2	7.0	15.0	14.5
3	10.5	15.0	16.0
4	14.0	17.5	18.0

The data indicates that both the synthesized WCPO ester and the commercial followed a comparable path as the concentration was adjusted from 0% to 4%. Initially at a 1% concentration both additives caused a decrease in AV where the synthesized ester dropped to 12.0 cP and the commercial lubricant reached 12.25 cP. This reduction is technically justified by the ability of the ester molecules to intersperse between hydrated bentonite platelets and reduce internal mechanical friction [1, 21]. At this lower concentration the methyl esters act as a molecular lubricant that coats the clay surfaces preventing the formation of a rigid house of cards structure which typically increases flow resistance [21, 22].

As the concentration progressed toward 4% a steady recovery and increase in AV were observed with the synthesized WCPO reaching 17.5 cP while the commercial benchmark reached 18.0 cP. This upward trend at higher concentrations is scientifically significant because it indicates that the lubricants contribute to the fluid internal structural matrix. As the oil to water ratio increases the droplet density within the micro emulsion rises which leads to increased particle interaction and internal shear stress [2, 23]. This ensures the mud does not become overly thin which is essential for the effective suspension of drill cuttings in high angle or horizontal wellbores [12, 24]. The proximity of these results justifies the technical viability of the synthesized ester as a high-performance alternative to synthetic products.

At an initial dosage of 1%, the ester acts primarily as a surface lubricant and dispersing agent. Polar ester groups adsorb onto bentonite particle surfaces, reducing interparticle friction and weakening attractive forces between clay platelets. This disrupts the initial flocculated structure of the mud and lowers resistance to flow, resulting in a temporary thinning effect. Similar viscosity reduction at low lubricant concentration has been reported in water-based drilling fluids containing fatty acid esters [27,29].

Therefore, high purity synthesized ester achieved in this study ensures that the WCPO ester acts as a passive high-performance lubricant that enhances lubricity without interfering with the primary rheological functions of the drilling fluid [10, 25]. Because the WCPO ester contains long chain fatty acids it provides a more robust liquid film around the barite and bentonite solids compared to unrefined waste oils [3, 11]. Consequently, the AV data justifies that WCPO ester provides a reliable balance of lubrication and viscosity control while matching the operational efficiency of industrial synthetic lubricants. This behavior confirms that the synthesized ester can be successfully integrated into water-based systems to optimize hydraulics while maintaining the necessary hydrostatic control required for modern drilling operations.

H. Structural Profiling of Plastic Viscosity Response

Based on the values presented in Table 4, the PV for both the synthesized ester and the commercial lubricant showed a distinct decreasing trend until reaching an optimum concentration. The data indicates that both lubricants effectively reduced the internal friction of the mud system as the concentration increased from 0% to 3%. Specifically, the PV for the synthesized ester significantly dropped from 15.0 cP to a minimum of 2.5 cP at 3%. This reduction is technically justified by the ability of the WCPO ester to act as a lubricant that coats the surfaces of clay platelets, allowing them to slide past each other with minimal mechanical interference. A lower PV is highly desirable in drilling operations because it minimizes pressure losses during circulation and allows for higher flow rates without exceeding pump capacity limits.

Table 4. Calculated PV

Concentration (%)	Volume (mL)	Extracted	Commercial
0	0.0	15.0	15.0
1	3.5	11.0	11.0
2	7.0	6.0	6.0
3	10.5	2.5	2.5
4	14.0	6.0	12.0

However, at a 4% concentration, the PV for the extracted ester increased to 6.0 cP, while the commercial lubricant rose more sharply to 12.0 cP. This rise at higher concentrations is scientifically significant as it reflects the "emulsion limit" where the high density of oil droplets begins to increase the overall fluid resistance. Interestingly, the synthesized ester maintained a lower PV at 4% compared to the commercial alternative, which suggests it is less likely to cause excessive thickening at higher dosages. At a dosage of 4%, the drilling fluid likely approached an emulsion saturation limit, where the number of dispersed ester droplets increased substantially within the continuous water phase. As droplet concentration rises, droplet–droplet interactions and internal friction also increase, causing greater resistance to flow. This behavior explains the increase in Plastic Viscosity (PV) observed at higher additive concentration [28, 35].

The significant reduction in YP at 4% concentration for the commercial lubricant may be attributed to over-dispersion of clay particles caused by excessive surfactant content. At elevated dosage, the additive may weaken electrochemical attractive forces between solids, causing breakdown of the particle network responsible for cuttings suspension. As a result, the fluid exhibits lower carrying capacity and reduced YP values [27,30].

I. Analytical Evaluation of Yield Point Dynamics

The YP represents the electrochemical or attractive forces between particles under flowing conditions, which is crucial for the ability of the drilling fluid to lift and transport drill cuttings to the surface. According to the Bingham Plastic model, a stable YP is necessary to maintain the carrying capacity of the mud without requiring excessive pump pressure. Based on the Table 5, the YP for both the synthesized ester and the commercial lubricant exhibited a significant upward trend as the concentration increased.

Table 5. Calculated YP

Concentration (%)	Volume (mL)	Extracted	Commercial
0	0.0	0.0	15.0
1	3.5	2.0	11.0
2	7.0	18.0	6.0
3	10.5	25.0	2.5
4	14.0	23.0	12.0

Both lubricants effectively improved the structural integrity of the mud system. Specifically, the YP for the synthesized ester sharply increase from 0.0 lb/100ft² to a peak of 25.0 lb/100ft² at 3%. This increase is technically justified by the chemical interaction between the ester functional groups and the clay particles, which promotes the formation of a stronger flocculated network while the fluid is in motion. A higher YP is desirable because it prevents the settling of heavy cuttings during drilling, which reduces the risk of pipe sticking and hole cleaning issues.

However, at a 4% concentration, the YP for the extracted ester slightly decreased to 23.0 lb/100ft², while the commercial lubricant experienced a drastic drop to 6.0 lb/100ft². This sharp decline in the commercial sample suggests a possible destabilization of the fluid matrix at higher dosages, whereas the synthesized ester remained robust. This stability is scientifically significant as it demonstrates that the synthesized

ester maintains its carrying capacity even at higher concentrations.

In bentonite-based water mud systems, clay platelets tend to form a flocculated edge-to-face network known as a "house-of-cards" structure due to electrostatic attraction between positively charged edges and negatively charged faces. The introduction of methyl esters disrupts this structure through adsorption onto particle surfaces, reducing charge imbalance and weakening interparticle attraction. In addition, the hydrocarbon chains of the ester create steric separation and a lubricating film between particles. Consequently, the clay system becomes more dispersed and exhibits lower internal resistance to flow [36, 37].

J. Advanced Evaluation of Fluid Loss and Sealing Mechanism

Filtration volume or fluid loss is a critical performance metric measuring the ability of drilling mud to form a low permeability filter cake on the wellbore wall. Effective filtration control is essential to prevent excessive water influx into the formation, which triggers borehole instability and formation damage. Figure 2 represents the mean filtration volumes for the synthesized WCPO ester and commercial.

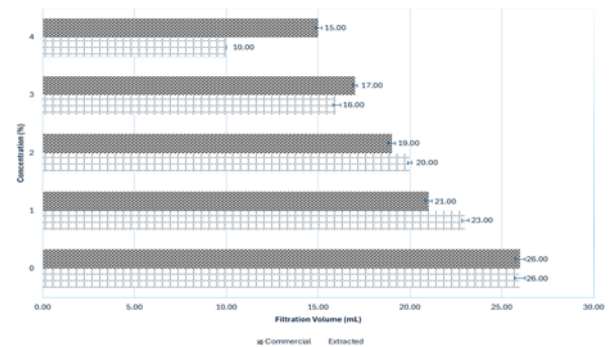


Fig. 2. Comparison between WCPO Ester vs Commercial

The WCPO ester reduced fluid loss from 26.0 mL to 10.0 mL at a 4% concentration, marking a significant 61.5% improvement over the base mud. This result shows that it allows the bio lubricant droplets to effectively plug the microscopic pore throats of the bentonite filter cake. In a real-world drilling operation, this level of filtration control is vital for protecting sensitive reservoir zones. By minimizing the invasion of filtrate into the formation, the WCPO ester reduces the risk of clay swelling and migration, which are primary causes of permanent formation damage and reduced oil productivity.

The comparative evaluation reveals significant differences in the fluid loss control mechanisms between the two additives. While both initially exhibit a reduction in filtrate volume from 0% to 2%, a critical performance divergence occurs at higher dosages. The commercial ester reached a minimum fluid loss of 15.0 mL at 4%, whereas the extracted WCPO ester demonstrated an accelerated sealing efficiency, reaching 10.0 mL at the same concentration. This performance gap indicates that the high purity synthesized ester possesses superior surface-active properties that allow it to more effectively densify the filter cake structure compared to the commercial alternative.

Operationally, the resulting ultra-thin 2/32-inch mudcake produced by the WCPO ester at 4% concentration provides a

critical advantage over the commercial ester, which produced a thicker 5/32-inch cake at the same dosage. In the real world, a thinner and tougher filter cake reduces the contact area between the drill string and the wellbore wall, significantly lowering the risk of differential pipe sticking in high torque Malaysian offshore wells. These findings confirm that the synthesized WCPO ester provides a technically superior and more reliable seal, establishing it as a high performing, sustainable "Gold Standard" alternative for industrial application.

K. Comprehensive Analysis of Mudcake Thickness and Texture

Figure 3 represents the comparison between extracted ester and commercial ester performance towards mudcake. The mechanical safety of the operation is significantly enhanced by the physical properties of the filter cake. The reduction of mudcake thickness to a mere 2/32 inch at a 4% concentration directly relates to the prevention of differential pipe sticking. In deep well environments, a thick sticky mudcake such as the 5/32 inch observed with the commercial benchmark can act as a suction cup, trapping the drill string against the wellbore wall under high pressure. The thin and exceptionally smooth film formed by the high purity WCPO ester minimizes the contact area and reduces the coefficient of friction, allowing the drill pipe to rotate and move freely. This step-by-step improvement from high purity chemical synthesis to optimized filtration and enhanced mechanical lubricity confirms that the synthesized ester is a robust industrial ready solution capable of outperforming petroleum derived standards in complex real world drilling environments.

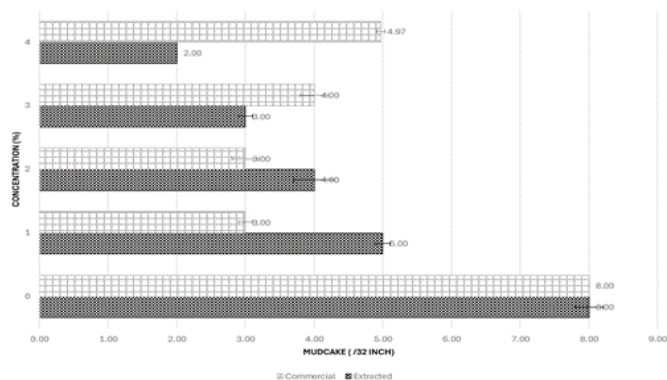


Fig. 3. Mudcake between WCPO Ester vs Commercial

4. CONCLUSION

The valorization of WCPO into a high-purity ester represents a significant advancement in sustainable drilling fluid technology. This study demonstrated that the synthesized ester, which achieved a peak purity of 98.8% through optimized transesterification, significantly outperforms commercial benchmarks by facilitating a 61.5% reduction in fluid loss and an optimized mudcake thickness of 2/32". These findings directly address critical petroleum engineering challenges, such as preventing formation damage in sensitive reservoirs and mitigating the risk of differential pipe sticking in highly permeable zones. By achieving these superior benchmarks at a moderate synthesis temperature of 65°C, the research proves that waste-derived products can match or even exceed the performance of virgin vegetable oils and traditional synthetic additives.

Furthermore, the synthesized ester provides a technically robust rheological profile essential for wellbore stability. The AV of the system reached an optimized value of 17.5 cP at 4% concentration, ensuring consistent flow resistance vital for preventing surge and swab pressures during tripping operations. Crucially, the YP reached a stable value of 6.0 lb/100ft², which confirms that the fluid maintains a superior carrying capacity.

The stable mud weight readings, which remained between 7.6 and 9.3 ppg, are scientifically justified for primary well control in Malaysian offshore operations. For offshore Malaysian drilling operations, especially deep and high-temperature wells in the South China Sea region, drilling fluids are typically required to remain stable at temperatures of 120–180°C and pressures ranging from 500 to 1000 psi. Acceptable performance targets include HPHT fluid loss below 15 mL, minimal rheological deviation after thermal aging, stable density without barite sag, and sufficient lubricity under high torque conditions. These criteria should be considered in future validation of the synthesized WCPO ester system [31, 38]. In the Malay Basin, the best operational range for the top hole and intermediate sections is usually between 8.5 ppg and 10.0 ppg. This keeps the necessary overbalance against pore pressures while avoiding losses in weak, normally pressured formations [26].

Future studies should evaluate the synthesized ester under HPHT conditions to confirm field applicability. Recommended tests include dynamic thermal aging using a roller oven at 120–180°C for 16 hours, followed by rheological measurements, HPHT filtration tests at pressures up to 500 psi, and emulsion stability analysis. These tests are necessary to assess thermal degradation resistance and performance retention under deep-well drilling conditions [31].

Ultimately, this research offers a robust, cost-effective, and ecologically sound solution for modern wellbore challenges, positioning waste cooking oil as a cornerstone of the next generation of green drilling fluids.

5. ACKNOWLEDGEMENT

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